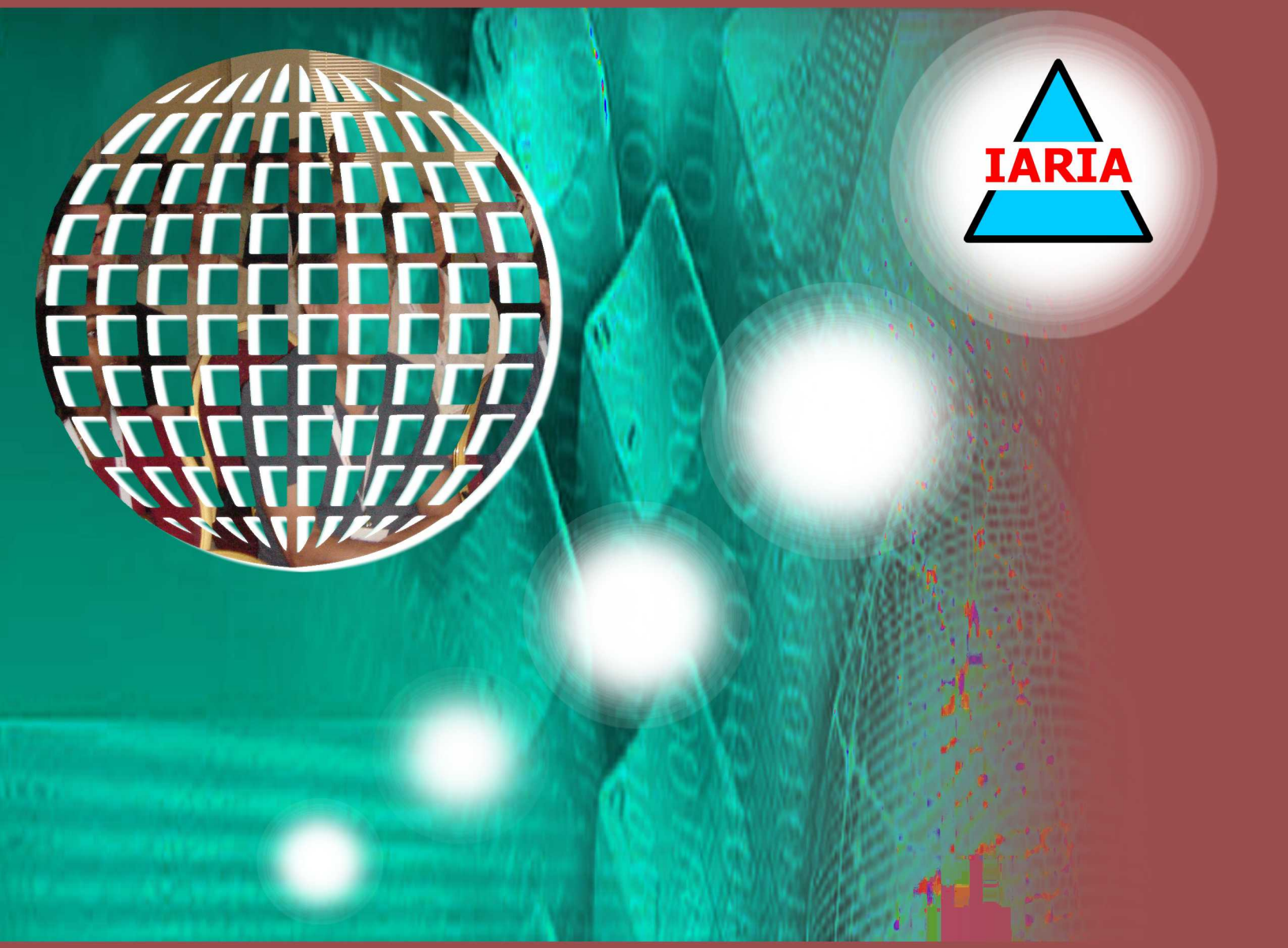
International Journal on Advances in Software



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CONTENTS

Components and Computational Modules for Knowledge Mapping: A Case of Spatial Knowledge

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***Abstract*—This paper presents the research results from an extended case study and implementation for the identification and spatial mapping of arbitrary non-georeferenced input data entities. The implemented components and methods are based on the methodology of knowledge mapping. The methodology enables to implement and realise methods for the creation of new context for objects and entities, e.g., creating support for the tasks of knowledge mining and decision making. The focus of the methodology is the mapping of knowledge and its facilities of creating substantially different practical method implementations for identical input objects while aiming on comparable tasks. The main goal of these case studies and implementations is to demonstrate how to create two different automatable methods for knowledge mapping to be applied on each input object, based on a functional architecture of sustainable long-term multi-disciplinary knowledge resources and components, which provide support for a wide range of flexibility for knowledge mapping and different computational solutions. The implementation cases are based on automated computational cases of spatial visualisation. In addition, the results from any of these realisations are used to further valorise new knowledge and continuously improve the contributing long-term knowledge resources.**

Keywords–Knowledge Mapping; Spatial Knowledge; Context Creation Algorithms; Universal Decimal Classification; Advanced Data-centric Computing.

I. INTRODUCTION

Knowledge Mining and decision making are facilities, which are required for a large number of application scenarios but which are, nevertheless, in practice widely based on plain methods of data mining only.

This extended research is based on the results from the collaborations on computation and Knowledge Mapping for data entities, which was presented at the INFOCOMP 2018 conference in Barcelona, Spain [1]. The methodology goes beyond creation of plain methods and the practically very limited view of 'data', which is commonly used. The paper illuminates the view of the Principles of Superordinate Knowledge [2], which is not restricted to a plain data view but focusses on advanced knowledge based context creation for arbitrary knowledge. The principles are general, compared to simpler approaches. Therefore, the principles should not be intermixed with 'data' based mining approaches.

There are no other, comparable realisations known so far, which use standardised, universal conceptual knowledge frameworks for creating context, e.g., spatial context.

This paper presents context-methods for multi-dimensional context creation based on the new methodology of Knowledge Mapping. The methodology allows to create knowledge mapping and new context for arbitrary objects, based on knowledge, e.g., conceptual knowledge. The results are methods based on an architecture allowing advanced knowledge mapping, including flexible deployment of computational sequences and an implementation of resources and application components.

This paper is organised as follows. Section II introduces to the motivation, state-of-the-art, and the base of the new approach. Section III presents the architecture, frame of universal knowledge, target input and associated universal knowledge. Section IV presents an exemplary approach, with the details of two well comparable but different case study implementations and all essential components. Section V discusses the results of the case studies, evaluates them based on the conceptual knowledge, computational sequences, and architectures and delivers a computational footprint in context with referred knowledge. Section VI summarises the results and lessons learned, conclusions, and future work.

II. MOTIVATION AND APPROACH

Resources of knowledge are steadily increasing in number and size and so is the complexity and heterogeneity of the associated knowledge. In most cases, it is not possible to find satisfying results even though the basis of data is rapidly growing. New approaches are needed in order to find answers to challenging knowledge mining requests.

Concepts used in the past mostly provided non consistent and insufficient approaches when dealing with the complexity of knowledge. In most cases, those concepts basically consider dealing with 'data' and claim to result in 'knowledge' or even 'wisdom' of some kind [3]. For example, the Data-Information-Knowledge-Wisdom (DIKW) approach widely used in Data Mining (DM) lacks an understanding of data being only one aspect of knowledge [4].

Implementations are mostly neglecting the knowledge associated with originary resources and referred knowledge and therefore deal with the applications and isolated technical features, which are neither able to be integrated for improving results and resources nor can they provide reasonable freedom of solutions.

Concepts like DIKW are lacking a profound relation of data and information [5]. Terms like “knowledge hierarchy” and “information hierarchy” are more misleading than constructive, especially when we have to deal with complex and long-term resources. Approaches used with data warehousing [6] on that basis, e.g., Extract, Transform, Load (ETL) and Extract, Load, Transform (ELT) for integrating data newly also resulted in requiring hybrid approaches but have not been based on a profound understanding of knowledge.

It should be explicitly stated, as commonly not sufficiently understood: The knowledge based concept is superior to a plain, data based concept. Mining and management based on the data concept is by far insufficient due to its most limited analysis approaches where accuracy is restricted to attributed data, e.g., simple data mining procedures and character string comparisons.

The described deficits are a major motivation for the long-term research presented in this paper. The fundaments of terminology and of understanding knowledge are layed out by Aristotle [7][8], being an essential part of ‘Ethics’ [9]. Information sciences can very much benefit from Aristotle’s fundaments and a knowledge-centric approach [10] but for building holistic and sustainable solutions they need to go beyond the available technology-based approaches and hypothesis [11] as analysed in Platons’ Phaidon.

Making a distinction and creating interfaces between methods and applications [12], the principles are based on the methodology of knowledge mapping [13], which fundaments are not outlined here again. The implementation can make use of objects and conceptual knowledge [14] and shows being able to build a base for applications scenarios like associative processing [15] and advanced knowledge discovery [16].

Considering this state-of-the-art, the methodology deployed in this research and the accompanying implementation of methods consequently focusses on the complex knowledge basis, which allows to integrate the different aspects of knowledge and the complexity of knowledge context. In result, the methodology allows to create methods focussing on alternative contexts based on a wide range of criteria and solutions provided by knowledge context. Implementations are considered knowledge-centric, with data being one complementary facet of knowledge. Therefore, the methodology and, in consequence, the method implementations based on this methodology, are vastly scalable. Scalability support ranges from fixed associations to arbitrarily fuzzy understanding.

III. Architecture and Universal Knowledge

An understanding of the essence and complexity of universal, multi-disciplinary knowledge can be achieved by taking a closer look on classification. The state-of-the-art of classifying ‘universal knowledge’ is the Universal Decimal Classification (UDC) and its solid background and long history. The LX knowledge resources’ structure and the classification references [17] based on UDC [18] are essential means for the processing workflows and evaluation of the knowledge objects and containers. Both components provide strong multi-disciplinary and multi-lingual support.

For this part of the research, all small unsorted excerpts of the knowledge resources objects only refer to main UDC-based classes, which for this publication are taken from the Multilingual Universal Decimal Classification Summary (UDCC Publication No. 088) [19] released by the UDC Consortium under the Creative Commons Attribution Share Alike 3.0 license [20] (first release 2009, subsequent update 2012). Nevertheless, the research conducted here in deploying knowledge provides a new solution not precedented by comparable approaches, from the view of methodology and implemented methods.

A. Architecture

The implementation architecture is shown in Figure 1.

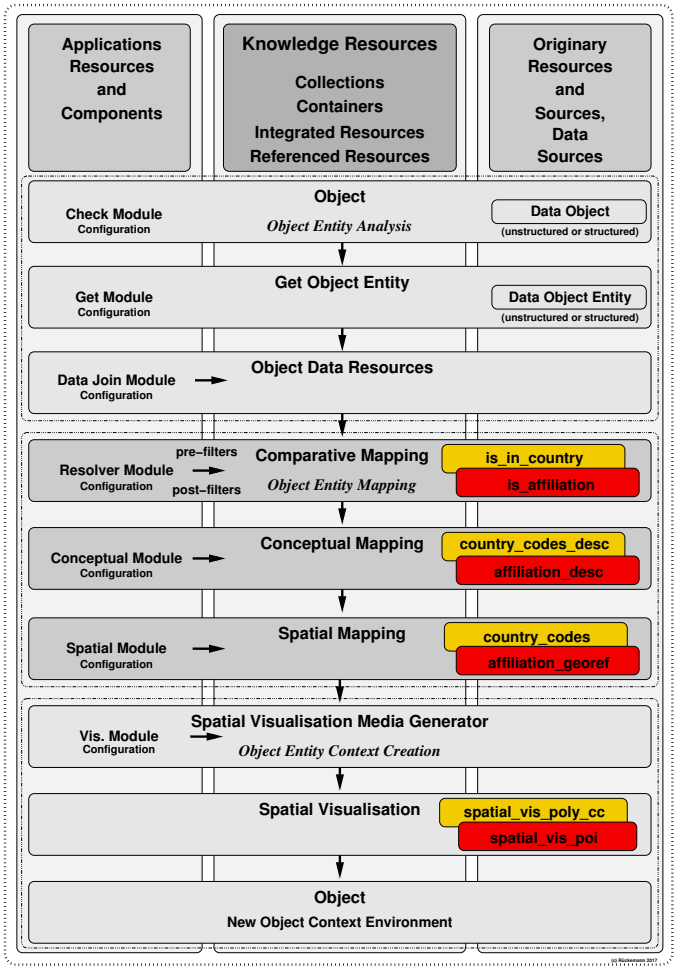

Figure 1. Architecture for mapping arbitrary objects / entities to new context environments, allowing different methods (yellow/red) for implementations.

The illustration of the architecture for knowledge mapping of arbitrary objects and entities to new object context environments also takes into account that the context of objects and their entities can contain many different facets and references from different origin.

The target for the case studies is a knowledge mapping providing two different mapping views. The spatial visualisation is an illustrative step, providing insights on new context.

Data and modules are provided by Knowledge Resources, originary resources, and application resources and components. The architecture is also aware of allowing different methods (e.g., highlighted in yellow/red) for implementations regarding the same resources and target.

The core of the knowledge mapping in this case consists of comparative mapping, conceptual mapping, and spatial mapping. All the examples in the case studies are based on the methodology of knowledge mapping [13]. The integration of originary sources provides a generic view for terms like 'knowledge integration' and 'knowledge representation' as such might be used in less generic approaches.

Here, in the mapping and the consecutive steps (here, a visualisation for illustration purposes), we do have the major differences of different methods for implementing alternative ways for the same resources and target.

The following case studies, all from real productive implementations, demonstrate the different characteristics of implementations based on the same universal knowledge. From a multitude of application scenarios, a term to location association providing ways of knowledge mapping of textual context to space and place were choosen for case studies.

B. Target Data and Universal Knowledge

The next passages show some major steps for creating spatially linked context from plain text, which were used in the workflows required for the cases.

For demonstration, a publicly available central target object was used for input to both implemented methods realised in this paper and for data entity analysis.

1) Target data: Natural language target: The single data object in this case study implementation (Figure 2) contains mostly unstructured text [21] markup, and formatting instructions.

```
1  <!DOCTYPE html PUBLIC "-//W3C//DTD XHTML 1.0 Transitional//EN" ... <title>
   GEOProcessing 2018 ...</title>
2  ..., Leibniz Universit&auml;t Hannover / Westf&auml;lische
   Wilhelms-Universit&auml;t M&uuml;nster / North-German Supercomputing Alliance
        (HLRN), Germany ...
3  ..., Technion - Israel Institute of Technology, Haifa,      Israel<br />
4  ..., Consiglio Nazionale delle Ricerche - Genova,      Italy <br />
5  ..., Centre for Research in Geomatics - Laval University,      Quebec, Canada <
   br />
6  ..., Curtin University, Australia <br />
7  ..., Lomonosov Moscow State University, Russia  <br />
8  ..., FH Aachen, Germany</p>
9  ...
10 ..., Erciyes University, Turkey <br />
11 ..., Synodon Inc., Canada<br />
12 ..., Royal Observatory of Belgium (ROB), Belgium<br />
13 ..., Oracle America Inc., USA  <br />
14 ..., Environmental Systems Research Institute (ESRI), USA<br />
15 ..., OSCARS, France<br />
16 ..., Geospatial technologies/Oracle Server Technologies      - Sophia Antipolis,
    France<br />
17 ..., University of Coimbra/INESC Coimbra, Portugal</p>
18 ...
19         <p>..., Universiti Tun Hussein Onm Malaysia, Malaysia<br />
20           ..., Cardiff University, Wales, UK<br />
21           ..., Universidade  Federal do Rio Grande, Brazil<br />
22           ..., GIS unit Kuwait Oil  Company, Kuwait<br />
23           ..., Middle East Technical  University, Turkey<br />
24           ..., University of  Sharjah, UAE<br />
25           ..., Georgia State University, USA<br />
26           ..., Centre for Research  in Geomatics - Laval University, Quebec,
              Canada<br />
27           ..., Environmental Systems  Research Institute (ESRI), USA<br />
28           ..., ORT University -  Montevideo, Uruguay<br /> ...
```

Figure 2. Mapping target: Single object, unstructured text containing various natural language references to locations (excerpt).

The sample object is the publicly available committees' page of the Tenth International Conference on Advanced Geographic Information Systems, Applications, and Services (GEOProcessing 2018), in Rome [21].

Large passages of text not relevant for demonstration of the principles were reduced to ellipses. The spatial visualisation can result from identifying and mapping entities in the text of an object to various knowledge context. The identification of entities is resulting from automated analysis.

2) Knowledge Resources: Location, integrated: Figure 3 shows the object content after automatically integrated with the Knowledge Resources via a join module.

```
1  GEOProcessing 2018 [...]: ...
2    ..., Leibniz Universität Hannover / Westfälische Wilhelms-Universität Münster
      / North-German Supercomputing Alliance (HLRN), Germany ...
3    ..., Technion - Israel Institute of Technology, Haifa, Israel
4    ..., Consiglio Nazionale delle Ricerche - Genova, Italy
5    ..., Centre for Research in Geomatics - Laval University, Quebec, Canada
6    ..., Curtin University, Australia
7    ..., Lomonosov Moscow State University, Russia
8    ..., FH Aachen, Germany
9    ...
10   ..., Erciyes University, Turkey
11   ..., Synodon Inc., Canada
12   ..., Royal Observatory of Belgium (ROB), Belgium
13   ..., Oracle America Inc., USA
14   ..., Environmental Systems Research Institute (ESRI), USA
15   ..., OSCARS, France
16   ..., Geospatial technologies/Oracle Server Technologies, Sophia Antipolis,
      France
17   ..., University of Coimbra/INESC Coimbra, Portugal
18   ...
19   ..., Universiti Tun Hussein Onm Malaysia, Malaysia
20   ..., Cardiff University, Wales, UK
21   ..., Universidade  Federal do Rio Grande, Brazil
22   ..., GIS unit Kuwait Oil  Company, Kuwait
23   ..., Middle East Technical  University, Turkey
24   ..., University of  Sharjah, UAE
25   ..., Georgia State University, USA
26   ..., Centre for Research  in Geomatics - Laval University, Quebec, Canada
27   ..., Environmental Systems  Research Institute (ESRI), USA
28   ..., ORT University -  Montevideo, Uruguay ...
```

Figure 3. Object instance representation after integration into knowledge resources, containing source references and locations (excerpt).

The Object Entity Mapping facilitates to associate relevant objects, e.g., via conceptual knowledge and comparative methods.

The objects and their entities can contain any knowledge, e.g., factual and conceptual knowledge. In this case, dealing with space and place data, the references, e.g., referred conceptual knowledge, carried in objects are most relevant.

The complement knowledge used with the mapping contains multi-disciplinary and multi-lingual knowledge, it can contain names, places, and synonyms in different languages as well as extensive context references, dynamically usable geo-coordinates, geo-classification, and so on. The complement knowledge is continuously improved and extended by manual means, integration of resources as well as by training procedures.

3) UDC: Place and Space: Tables I, II, and III show example excerpts of relevant main classification codes and details of the UDC references used for conceptual mapping. For conceptual knowledge of place and spatial context the implementations requires to provide references to classification codes. The UDC provides references based on the common auxiliaries of place of the UDC [22] as excerpted here for facets of place and space, physiographic designation, and places from ancient to modern world.

TABLE I. CONCEPTUAL MAPPING REFERENCES WITH UDC CODES OF SPATIAL FEATURES / PLACE: AUXILIARIES OF PLACE (EXCERPT).

UDC Code	*Description*
UDC:(1/9)	**Common auxiliaries of place.**
UDC:(1)	Place and space in general. Localization. Orientation
UDC:(100)	Universal as to place. International. All countries in general
UDC:(1-0/-9)	Special auxiliary subdivision for boundaries and spatial forms of various kinds
UDC:(1-0)	Zones
UDC:(1-1)	Orientation. Points of the compass. Relative position
UDC:(1-2)	Lowest administrative units. Localities
UDC:(1-5)	Dependent or semi-dependent territories
UDC:(1-6)	States or groupings of states from various points of view
UDC:(1-7)	Places and areas according to privacy, publicness and other special features
UDC:(1-8)	Location. Source. Transit. Destination
UDC:(1-9)	Regionalization according to specialized points of view

TABLE II. CONCEPTUAL MAPPING REFERENCES WITH UDC CODES OF SPATIAL FEATURES / PLACE: PHYSIOGRAPHIC DESIGNATION (EXCERPT).

UDC Code	*Description*
UDC:(2)	**Physiographic designation**
UDC:(20)	Ecosphere
UDC:(21)	Surface of the Earth in general. Land areas in particular. Natural zones and regions
UDC:(23)	Above sea level. Surface relief. Above ground generally. Mountains
UDC:(24)	Below sea level. Underground. Subterranean
UDC:(25)	Natural flat ground (at, above or below sea level). The ground in its natural condition, cultivated or inhabited
UDC:(26)	Oceans, seas and interconnections
UDC:(28)	Inland waters
UDC:(29)	The world according to physiographic features
UDC:(3/9)	Individual places of the ancient and modern world

TABLE III. CONCEPTUAL MAPPING REFERENCES WITH UDC CODES OF SPATIAL FEATURES / PLACE: PLACES (EXCERPT).

UDC Code	*Description*
UDC:(3)	**Places of the ancient and mediaeval world**
UDC:(4/9)	**Countries and places of the modern world**

The references, e.g., classification, facets, concordances, and textual description, are usable in all the procedures and steps and allow to consider and implement arbitrary flexibility of fuzziness. Entry points to relevant and associated knowledge may be in any disciplinary context due to the consistent framework of the UDC and the multi-disciplinary and multi-lingual Knowledge Resources. During the research, two computational sequences were implemented for illustration of such procedures. These sequences show different characteristics in content and context, as well as different characteristics in architecture and computational requirements.

IV. IMPLEMENTATION: MULTIPLE WAYS TO SPACE

The following case studies present two different methods for implementing object/entity knowledge mapping to space and place targets and discuss major insights. Computational knowledge mapping procedures are presented for both methods, as well as the visualisation of the results. The computational application components are part of the available resources.

The Generic Mapping Tools (GMT) [23] suite application components were used for handling the spatial data, applying related criteria, and for the visualisation. All provided spatial presentations in the following examples are using the same Mercator projection (region: -180/180/-60/84) in order to provide a common base for the comparison.

A. Space and place: Affiliation based knowledge mapping

This method implements the knowledge mapping based on affiliations. The implementation is done according to the implementation architecture (Figure 1).

1) Computational sequence: Table IV gives the computational sequence of the core computational procedures.

TABLE IV. AFFILIATION BASED MAPPING: COMPUTATIONAL SEQUENCE OF CORE COMPUTATIONAL PROCEDURES AND REFERRED MODULES.

Procedure	*Module*
Comparative Mapping Configuration	`is_affiliation`
Conceptual Mapping Configuration	`affiliation_desc`
Spatial Mapping Configuration	`affiliation_georef`

The means, regarding space and place: Affiliation mapping, affiliation association via conceptual knowledge and textual description, and affiliation georeferencing.

The module `is_affiliation` is responsible for the comparative mapping. The module `affiliation_desc` is responsible for the conceptual mapping. The module `affiliation_georef` is responsible for the spatial mapping.

For illustration, Figure 4 shows an excerpt of affiliation references from the Knowledge Resources as associated with the comparison.

```
...
-3.1788641 51.4866271 Cardiff University, Wales, UK
...
-71.2747424 46.7817463 Centre for Research in Geomatics, Laval University, Quebec, Canada
...
8.9011038 44.4086615 Consiglio Nazionale delle Ricerche (CNR), Genova, Italy
...
-117.195686 34.056077 Environmental Systems Research Institute (ESRI), USA
...
-84.3852819 33.753068 Georgia State University, USA
...
47.6598413 28.922652 Kuwait Oil Company, Kuwait
...
9.7196989 52.3829641 Leibniz Universitaet Hannover, Germany
...
32.7778538 39.8956446 Middle East Technical University, Turkey
...
-56.1905803 -34.9038526 ORT University, Montevideo, Uruguay
...
37.5286696 55.7039349 Moscow State University, Russia
...
7.6131826 51.9635705 Westfaelische Wilhelms-Universitaet Muenster
...
35.0231271 32.7767783 Technion, Israel Institute of Technology, Haifa, Israel
...
-51.2185702 -30.0338411 Universidade Federal do Rio Grande, Brazil
...
-61.5289325 16.2242724 Universite des Antilles - LAMIA, France, Guadeloupe
...
103.0855782 1.858626 Universiti Tun Hussein Onm Malaysia, Malaysia
...
55.4783714 25.2867708 University of Sharjah, United Arab Emirates
...
```

Figure 4. Knowledge Resources: Affiliation references used in comparative mapping (excerpt).

In practice, the number of such place references can be very large. In case of this study, the numbers are in the range of millions of places. Therefore, it is important to understand what the tasks of the modules are.

2) Module tasks:

- The first module creates possible entities, including a recoder for alternative re-coding of codepages, a corrector generating attempts for corrections of writing, and a comparator computing comparisons with known and available affiliation space and place in the resources and references, here on base of affiliations and distinctive locations.
- The second module identifies the resulting entities based on the fit, according to the conceptual knowledge relevant for the targeted knowledge mapping, here geospatial association and referencing.
- The third module creates the spatial mapping and visualisation, depending on the choosen base.

With all modules, functional code is generated for the respective steps. The generation ensures that appropriate implementations can be achieved depending on the computing resources and infrastructures, which are used for the computational tasks. This is important, especially for large numbers of target data sets because many millions of comparisons may be required for each step and, e.g., the computation be parallelised appropriately.

3) Output representation: The visualisation of the results (red bullets) from the affiliation based procedures was done on a spatial map (Figure 5).

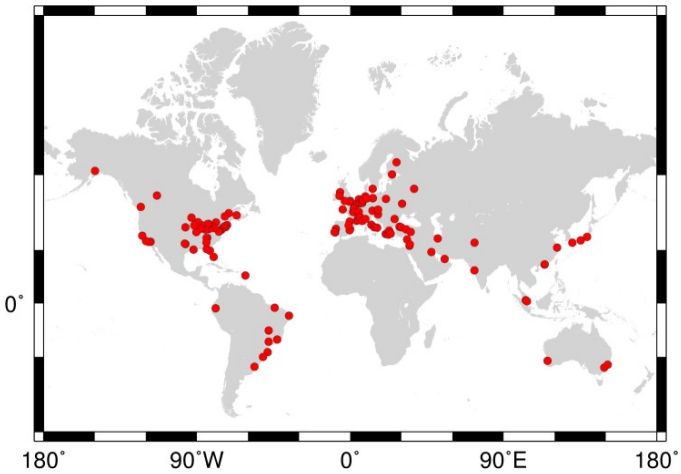

Figure 5. Visualisation of the result of affiliation based knowledge mapping: Geo-referenced place association (Mercator projection).

The computing task can be parallelised for objects and entities. For demanding application scenarios, e.g., dynamical implementations, this implementation benefits to a small extend from parallelisation.

B. Space and place: Country code based knowledge mapping

This method implements the knowledge mapping based on country codes. The implementation is done according to the implementation architecture (Figure 1).

1) Computational sequence: Table V gives the computational sequence of the core computational procedures.

That means, regarding space and place: Country mapping, association of country codes via codes description, and evaluation of country codes and visualisation.

TABLE V. COUNTRY CODE BASED MAPPING: COMPUTATIONAL SEQUENCE OF CORE COMPUTATIONAL PROCEDURES AND REF. MODULES.

Procedure	*Module*
Comparative Mapping Configuration	`is_in_country`
Conceptual Mapping Configuration	`country_codes_desc`
Spatial Mapping Configuration	`country_codes`

The module `is_in_country` is responsible for the comparative mapping. The module `country_codes_desc` is responsible for the conceptual mapping. The module `country_codes` is responsible for the spatial mapping.

2) Module tasks:

- The first module creates possible entities, including a recoder for alternative re-coding of codepages, a corrector generating attempts for corrections of writing, and a comparator computing comparisons with known and available country and country code space and place in the resources and references, here on base of countries and larger areas.
- The second module identifies the resulting entities based on the fit, according to the conceptual knowledge relevant for the targeted knowledge mapping, here geospatial association and referencing.
- The third module creates the spatial mapping and visualisation, depending on the choosen base.

Here, too, with all modules, functional code is generated for the respective steps. The generation ensures that appropriate implementations can be achieved depending on the computing resources and infrastructures, which are used for the computational tasks. This is important, especially for large numbers of target data sets because many millions of comparisons may be required for each step and, e.g., the computation be parallelised appropriately.

Figure 6 shows an excerpt of country code references from the Knowledge Resources as associated with the comparison.

In practice, the number of such country code references have several hundred pattern-code entities for a certain year

or era. In case of this study, the numbers are in the range of about 300 pattern rules per language. Resolving can be done automatically via geo-referencing and visualisation application components.

```
...
"Australia" lxcoco-AU
"Brazil|,_Brasil" lxcoco-BR
"Canada" lxcoco-CA
...
"Germany|Deutschland" lxcoco-DE
"Ghana"  lxcoco-GH
"Gibraltar" lxcoco-GI
...
"Great_Britain" lxcoco-GB3
...
"Greece" lxcoco-GR
"Greenland|Grønland" lxcoco-GL
"Grenada" lxcoco-GD
"Guadeloupe" lxcoco-GP
...
"Israel" lxcoco-IL
"Italy" lxcoco-IT
"Kuwait" lxcoco-KW
"Malaysia" lxcoco-MY
"Russian_Federation" lxcoco-RU1
"Russia" lxcoco-RU2
"Turkey" lxcoco-TR
"United_Arab_Emirates" lxcoco-AE1
"UAE|U\.A\.E\." lxcoco-AE2
"United_Kingdom" lxcoco-GB1
",_UK" lxcoco-GB2
"United_States_of_America|USA|U\.S\.A\.|U\.S\." lxcoco-US
"Uruguay" lxcoco-UY
...
```

Figure 6. Knowledge Resources: Country Codes used for comparative mapping (excerpt).

Due to the nature of arbitrary and heterogeneous input objects the corrector algorithms benefit from continuous training. An excerpt of the corrector algorithm is shown in a correcting code listing (Figure 7).

```
...
s+George Mason University.*?Romanian Academy, USA.*?Romania+George Mason University, USA\nRomanian Academy, Romania+g
s+UAP and SEU, Bangladesh.*Islamic University in Madinah, KSA+UAP and SEU, Bangladesh\nIslamic University in Madinah, KSA+g
s+Swiss National Science Foundation.*Oregon Health.*Science University, USA+Swiss National Science Foundation, Switzerland\nOregon Health \& Science University, USA+g
s+World Precision Instruments, Inc. USA; University of South Florida, USA+World Precision Instruments, Inc. USA\nUniversity of South Florida, USA+g
s+Bowie State University; University of Maryland, College Park, USA+Bowie State University, USA\nUniversity of Maryland, College Park, USA+g
s+Cardiff University School of Medicine,.*\|.*Welsh e-Science Centre+Cardiff University School of Medicine\nWelsh e-Science Centre+g
s+California NanoSystems Institute (CNSI), Brain Research Institute (BRI).*\|.*University of California at Los Angeles (UCLA), USA+California NanoSystems Institute (CNSI), Brain Research Institute (BRI)\nUniversity of California at Los Angeles (UCLA), USA+g
s+CEA-Leti\/DACLE\/LIALP Lab, Verimag Lab.*?Grenoble University, France+CEA-Leti\/DACLE\/LIALP Lab, Verimag Lab, France\nGrenoble University, France+g
s+CISTER, INESC/TEC.*\|.*Polytechnic Institute of Porto, Portugal+CISTER, INESC/TEC, Portugal\nPolytechnic Institute of Porto, Portugal+g
s+Instituto de Telecomunica<UTFSeq>es, Aveiro, Portugal.*University of Bradford, UK+Instituto de Telecomunica<UTFSeq>es, Aveiro, Portugal\nUniversity of Bradford, UK+g
s+Instituto de Telecomunica<UTFSeq>es, Aveiro, Portugal.*American University of Nigeria, Nigeria+Instituto de Telecomunica<UTFSeq>es, Aveiro, Portugal\nAmerican University of Nigeria, Nigeria+g
s+University of Pisa, Italy.*Leiden University, The Netherlands+University of Pisa, Italy\nLeiden University, The Netherlands+g
s+(University of Hamburg)/.*?(Regional Computer Center), Germany+<DSym>{1}, Germany\n<DSym>{2}, Hamburg, Germany+g
s+Defence R.*?D Canada, Valcartier.*?Univ. Laval.*?Univ. de Montr.*?al, Canada+Defence R\&D Canada, Valcartier, Canada\nUniv. Laval, Canada\nUniv. de Montreal, Canada+g
s+Defence R\&D, Canada+Defence R\&D Canada, Canada+g
s+Sensemaking-PACOM Fellowship \& AIRS, Swansea University/Hawaii Pacific University, UK/USA+Sensemaking-PACOM Fellowship \& AIRS, Swansea University\nHawaii Pacific University, UK/USA+g
s+Department of Computing Science and HPC2N.*+Department of Computing Science, Ume<UTFSeq> University, Sweden\nHigh Performance Computing Center North (HPC2N), Ume<UTFSeq> University, Sweden+
s+High Performance Computing Center North (HPC2N), Sweden+High Performance Computing Center North (HPC2N), Ume<UTFSeq> University, Sweden+g
s+California NanoSystems Institute (CNSI), Brain Research Institute (BRI) | University of California at Los Angeles (UCLA), USA+California NanoSystems Institute (CNSI), USA\nBrain Research Institute (BRI), USA\nUniversity of California at Los Angeles (UCLA), USA+g
s+Westf.*lische Wilhelms-Universit.*t M.*nster.*Leibniz Universit.*t Hannover.*North-German Supercomputing Alliance, Germany+Westfälische Wilhelms-Universität Münster, Münster, Germany\nLeibniz Universität Hannover, Hannover, Germany\nNorth-German Supercomputing Alliance, Germany+g
s+University Politehnica Bucharest, Romania.*?Texas A\&M University, USA+University Politehnica Bucharest, Romania\nTexas A\&M University, USA+g
s+Brown University, USA.*University of Saskatchewan, Canada+Brown University, USA\nUniversity of Saskatchewan, Canada+g
s+ICT-KTH, Sweden.*?IDI-NTNU, Norway+ICT-KTH, Sweden\nIDI-NTNU, Norway+g
s+Center for Service Research \(CfSR\)\/National Institute of Advanced Industrial Science and Technology \(AIST\), Japan+Center for Service Research (CfSR), Japan\nNational Institute of Advanced Industrial Science and Technology (AIST), Japan+g
s+Wirtschafts- und Sozialwissenschaftliches Institut, D.*?sseldorf, Karlsruhe Institute of Technology, Germany+Wirtschafts- und Sozialwissenschaftliches Institut, Düsseldorf, Germany\nKarlsruhe Institute of Technology, Germany+g
s+Colorado State University, USA.*Lancaster University, UK+Colorado State University, USA\nLancaster University, UK+g
s+University of Carthage, Tunis.*El Manar University, Tunisia+University of Carthage, Tunis, Tunisia\nEl Manar University, Tunisia+g
s+University of Carthage, Tunis<DSym>+University of Carthage, Tunis, Tunisia+g
s+The University of Melbourne, Australia+University of Melbourne, Australia+g
s+Ural Federal University.*Ekaterinburg, Russian Federation.*University of Peloponnese.*Tripolis, Greece+Ural Federal University, Ekaterinburg, Russian Federation\nUniversity of Peloponnese, Tripolis, Greece+g
s+University of Twente and University of Groningen.*,The Netherlands+University of Twente, The Netherlands\nUniversity of Groningen, The Netherlands+g
s+French National Institute of Geographic and Forest Information.*, France+IGN Institut National de l Information GÃ©ographique et ForestiÃ¨re, France+g
s+ForestiÃ¨re+Forestiere+g
...
```

Figure 7. Correcting code for the corrector algorithm (excerpt).

The examples from the Knowledge Resources are a small subset from hundreds of thousands of comparable entries. The entries are presented here in Perl Compatible Regular Expressions (PCRE) style [24] based on widely common Perl [25] conventions. For display, dollar symbols are substituted as `<DSym>`, various UTF sequences are substituted as `<UTFSeq>`.

After conceptual mapping, correcting algorithms, sorting, and removing duplicates a list of country codes can be generated using a country code container from the knowledge resources. Figure 8 shows the list of resulting country codes automatically generated for the target data.

```
AE,AT,AU,BE,BR,CA,CN,CY,DE,EC,ES,FI,FR,GB,GP,GR,HK,HR,IE,IL,IN,IR,IT,JP,KW,MY,NL,PK,PL,PT,RO,RU,SE,SG,TR,UA,US,UY
```

Figure 8. Knowledge Resources: Country Codes automatically generated for the target data (excerpt).

3) Output representation: The visualisation of the results (yellow country colourisation) from the country code based procedures was done on a spatial map (Figure 9). The country codes are based on the standard of the International Standards Organisation (ISO).

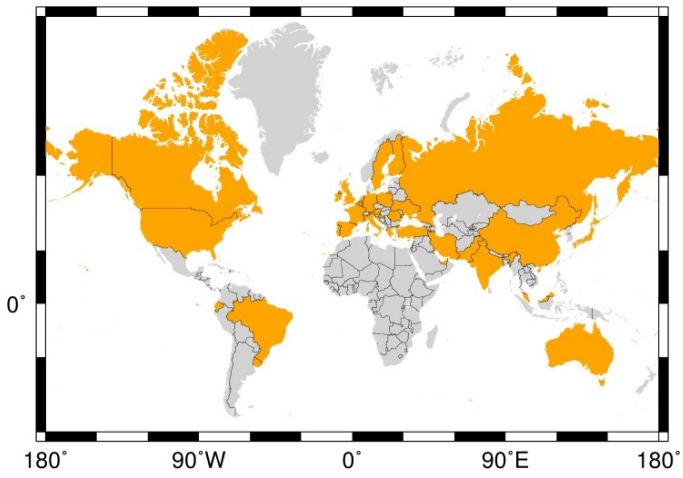

Figure 9. Visualisation of the result of country code based knowledge mapping: ISO referenced state association (Mercator projection).

The computing task can be parallelised for objects and entities. For demanding application scenarios, e.g., dynamical implementations, this implementation widely benefits from parallelisation. The parallelisation will be an individual task of implementing a parallelisation concept optimal for the resources, on precondition that the computational resources and architectures are known in detail and available.

C. Visualisation

The spatial visualisation for the presented implementations is done according to the implementation architecture (Figure 1).

Table VI lists the alternative modules implemented for visualisation of both methods implemented for affiliation based knowledge mapping and country code based knowledge mapping.

TABLE VI. SPATIAL VISUALISATION: ALTERNATIVE PROCEDURES FOR AFFILIATIONS AND COUNTRY CODES.

Alternative Procedures	*Module*
Spatial Visualisation Affiliation Configuration	`spatial_vis_pol`
Spatial Visualisation CC Configuration	`spatial_vis_poly_cc`

The module `spatial_vis_pol` is responsible for visualisation of affiliation based computational sequences. The module `spatial_vis_poly_cc` is responsible for visualisation of country code based computational computational sequences.

The functional code for the modules is generated for the respective type of visualisation. In this case, there is no principle impediment for a combined application of both codes if required.

The essential attribute characteristics for affiliation based knowledge mapping spatial visualisation are illustrated by the listing in Figure 10.

```
1 ...
2 gmt pscoast -JM4.5i -R-180/180/-60/84 -F<CountryCodes>+glightgray -Glightgray
   -Baf -BWSne -P -K > <PSFile>
3 ...
4 gmt psxy <DataFile> -J -O -R -Sc0.15c -G255/0/0 -W0.05p,black >> <PSFile>
5 ...
```

Figure 10. Spatial affiliation based knowledge mapping visualisation characteristics for GMT (excerpt).

The essential attribute characteristics for country code knowledge mapping based spatial visualisation are illustrated by the listing in Figure 11.

```
1 ...
2 gmt pscoast -JM4.5i -R-180/180/-60/84 -F<CountryCodes>+glightgray -Glightgray
   -Baf -BWSne -P -K > <PSFile>
3 ...
4 gmt pscoast -J -R -N1/0.15p,black -F<CountryCodes>+gorange -O >> <PSFile>
5 ...
```

Figure 11. Country code based knowledge mapping spatial visualisation characteristics for GMT (excerpt).

Individual attributes can be a matter of module configuration or visualisation attributes in a certain context can be a matter of training procedures.

V. DISCUSSION

Implementations can range from generic to specialised, as granted by the methodology, all the components and the illustrated architecture. A reason for illustrating the methodology with a well defined implementation is that from many experiences made from working with methodologies, specialised implementations tend to be better comprehensible by the majority of researchers in various disciplines.

The methodology of knowledge mapping, as illustrated via implementation of two methods discussed here, allows a versatile number of methods to be created for a purpose, based the same knowledge and data.

A. Comparison and discussion of results

The two sequences show different characteristics

- in content and context, as well as
- in architecture and computational requirements.

Country code based and affiliation based solutions result in visualisation of different distribution patterns. While an affiliation based solution can have a higher granularity it can be more precise in detail. In that context, a country code based solution is associated with more dependencies in the results – border lines, different country context, especially for handling and visualising long-term intervals. For example, considering the same data, on the one hand geo-references of a place do not really change much over time, on the other hand border lines of states change much faster on a global scale.

For a visual comparison, the results from both the affiliation based and country code based sequences were placed on the same spatial map (Figure 12).

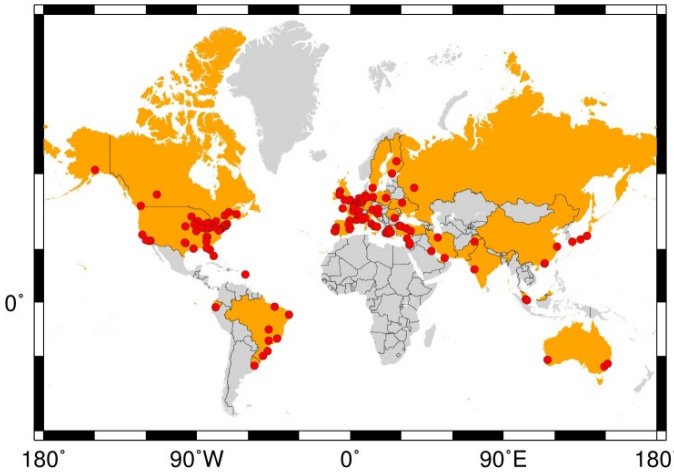

Figure 12. Comparison of both affiliation and country code based knowledge mapping: Geo-referenced place and ISO referenced state results.

There are more differences in detail, which can influence decisions on applicability and implementation. In general, there are arbitrary ways of implementing a knowledge mapping target based on the same Knowledge Resources. An implementation will in most cases be triggered by a combination of items, e.g., purpose, implementation efficiency, and computational performance. The characteristics and resolvability achieved via different knowledge mapping may be different.

The number of countries is much more limited and the identification can be much more standardised than for geo-referenced places. The distribution of affiliation associated places can create a different impression than a visualisation based on country data. The sizes of mapped country areas can create a different impression than a visualisation based on country data. Associations based on both results can be significantly different, leading to further different knowledge context.

A further significant difference of the two case study implementations is the fact that the computational requirements are much more complex for affiliation mapping than for country code mapping. Depending on the objects and entities and the selected knowledge resources the factor of complexity can go up by millions. This is foremost relevant for the computation of comparative modules and analysis and visualisation of results.

B. Knowledge and its computational footprint

Based on the case studies, the characteristics of both solutions result in different computational requirements. Table VII compares the solutions regarding the numbers of computational checks required, done for the same object and entities.

TABLE VII. CORE PROCEDURES AND OBJECTS: COMPARISON OF COUNTRY CODE AND AFFILIATION BASED MAPPING.

Procedure	*Country Code*	*Affiliation*
Comparative Mapping		
pre-filter Checks	5,500	72,000
Knowledge Mapping Checks	40,000	570,000
post-filter Checks	7,000	75,000
Conceptual Mapping		
Checks UDC	300	5,000,000
Checks, other references	300	500,000
Spatial Mapping		
Results	$>$ 50 Polygons	$>$50 Points
Context, object level	$>$ 120 Polygons	0 Polygons
Context, basic	1 Basemap	1 Basemap

Different implementations involve different knowledge. As can be reasoned from the comparison, the case of affiliation based knowledge mapping might be a challenge for certain architectures, e.g., a distributed service implementation.

On the opposite, country code mapping can mean higher requirements for supportive data and higher load on spatial mapping application components, e.g., polygons provided by additional data, requests, application bound features, and visualisation. The supportive data can easily get into the range of millions of entities and Giga Bytes of data size per single request. If considering that country shapes will differ for a certain year or era, then multiple supportive data sets might be needed. Therefore, load distribution is very much different for the implementations due to the nature of the different methodologies. The core sequences required for the knowledge mapping result in significant computational loads, especially at two steps: Comparisons and visualisation. These result in both comparative mapping load and supportive application load. Configuration of resources and modules can help to scale the computational load, nevertheless, any different configurations will have additional impact on the associated knowledge involved, which can be a significant reason for decision: For most component implementations and investments it does make a difference if a computational step takes two seconds or two days and if the required knowledge and data are involved or not. In addition to different knowledge being associated during the sequences, there is another difference: Most of the procedures are not bidirectional. If the affiliation based knowledge mapping is used in order to compute a consecutive country code based knowledge mapping and even if the result would be identical to the plain country code mapping this does not indicate that the country code mapping could also provide a consecutive affiliation mapping in the same manner.

C. Re-use, continuous creation, and improvement

Access and interface modules, especially for accessing structures, dealing with formatting, and handling of sorting and filtering can easily be reused or cloned with modifications. Visualisation modules can also be easily reused and adopted for different methods of knowledge mapping.

The modules characteristic for a respective knowledge mapping method make up the core for a case. Different algorithms should be implemented in modular ways, e.g., allowing standalone of algorithms as well as an integrated use of algorithms. Nevertheless, on premise of sufficient complexity of the knowledge resources, even all the knowledge required with different knowledge mapping methods can overall be delivered by the knowledge resources. The delivered knowledge can comprise the knowledge complements, e.g., including supportive knowledge for methods, references, algorithms, implementations of algorithms, and visualisation components.

With natural language target data or comparable sources a lot of processing may have to be done before getting into the knowledge mapping itself. For example, codepages have to be resolved and codepages have to be recoded, languages may have to be recognised by document, sentence, and even word and different ways of writing the same object may have to be resolved. Incomplete object references may be associated with full entries and so on. Creation and improvement of resources and knowledge content are continuous processes. The optimisation, e.g., regarding the resources and modules for improving resulting outputs is intrinsically supported by the application of the modules itself. This is based on the fact that intermediate results from any application or run can be used for training of procedures and Knowledge Resources.

VI. CONCLUSION

This paper presented the research results from an extended case study and implementation for the identification and spatial mapping of arbitrary non-georeferenced input data entities.

The methodology of knowledge mapping was used for creating methods and implementing components for different tasks, e.g., for advanced knowledge as successfully demonstrated with the case studies. The methodology allowed an efficient implementation and realisation of methods for the creation of new context for objects and entities.

It was successfully demonstrated that the goal of the studies and implementations to create different automatable methods for knowledge mapping in a spatial context can be efficiently achieved in very flexible, modular, and reusable ways.

The more, due to the high quality of the knowledge resources in addition with the long-term training, the completeness of the resulting mapping in this case proved to be ultimatively complete and sufficiently precise for the target objects without additional intervention, for both methods.

The multi-disciplinary and multi-lingual Knowledge Resources and the Knowledge Mapping based implementations can benefit from being continuously assisted by training procedures, which can contribute to the complementary knowledge content. In addition, the results from any of these realisations can be used to further valorise new knowledge and continuously improve the long-term knowledge resources, which again extends the quality and quantity of available resources.

With this research the implementations targeted on knowledge based, automatable computational cases of spatial visualisation. This goal was achieved while preserving facilities for any form of non automated or semi-automated use without principle constraints.

In addition, the Knowledge Resources could be extended and improved in quality and quantity by applying the implementations to various target objects, due to the successfully mined results achieved from the implemented cases, which become part of the knowledge resources themselves.

In consequence, the result of this research is a functional architecture, which proved to provide most flexible facilities for creating knowledge mapping and different and very scalable computational solutions. In consequence, the further development of resources and methods allows to consider different constraints when implementing solutions for a certain task. It was shown that the architecture allows to efficiently create implementations with significantly different characteristics.

The knowledge resources and the knowledge based solutions provide comprise universal knowledge and are not limited to a certain discipline or task. Nevertheless, examples limited to a defined task had to be taken for demonstration. The presented case studies illustrated how the knowledge mapping is applied for different solutions, namely country code based knowledge mapping and affiliation based knowledge mapping. The knowledge objects involved for these solutions however were not limited to a single discipline and task and are truly multi-disciplinary and multi-lingual as are all the components and referenced knowledge involved in the scenarios. Both solutions are very much visualisations of object entities. Regardless of that fact, both workflows are significantly different in steps, methods, algorithms, details of involved knowledge, and computational characteristics.

The facts, which become visible when the case study examples are discussed as an example of general abstraction, while still accessing the same resources: The large range of flexibility from knowledge, algorithmic, and computational perspectives. The complements of possibly required solutions share the complementary knowledge. Here, results comparable to the country code solution can be created with geo-referenced place data. In contrast, from the data involved with the country code solution it is not possible to create a geo-referenced view based on the associated data.

From the educational view on insight it may be interesting being able to generate different views of knowledge and information in different ways and with different media based on this methodological approach. The achieved results can become part of what is known in addition of what is remembered [26] and can preserve contextual details not learned otherwise.

Therefore, besides the individual context and results delivered by different implementations, it holds “The journey is the reward”. The methodology of knowledge mapping as described can be used for any knowledge and context. The conducted case study is using terms in arbitrary text on the one hand, which can be associated with geo-referencing on the other hand. A different application scenario can be regional floras and faunas being mapped to an biological context, in which case even no geo-referencing or cartographic visualisation needs to be involved. Instead, the results can show the level of complexity for certain cases.

In conclusion, one can choose solutions under different constraints of application scenarios, e.g., knowledge involved, flexibility of sequences, and computational requirements. That way, it is possible to create scalable solutions considering the implementation of required procedures and methodologies, as well as the implementation of required infrastructures. Further future research will be spent on extending the dimensional extent of knowledge resources and on the creation of advanced methodologies for creating method for advanced knowledge mining, further increasing quality and quantity of multi-disciplinary and multi-lingual content, knowledge mapping, and integration.

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Fuzzy Outlier Detection by Applying the ECF-Means Algorithm

A clustering ensemble approach for mining large datasets

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***Abstract*—This paper focuses on how to mine large datasets by applying the ECF-means algorithm, in order to detect potential outliers. ECF-means is a clustering algorithm, which combines different clustering results in ensemble, achieved by different runs of a chosen algorithm, into a single final clustering configuration. Furthermore, ECF is also a manner to "fuzzify" a clustering algorithm, assigning a membership degree to each point for each obtained cluster. A new kind of outlier, called o-rank fuzzy outlier, is also introduced; this element does not strongly belong to any cluster, which needs to be observed more closely; moreover, a novel validation index, called $o.FOUI$, is defined too, based on this new kind of fuzzy outliers. The proposed method for fuzzification is applied to the k-means clustering algorithm by using its Weka implementation and an ad-hoc developed software application. Through the three exposed case studies, the experimental outcomes on real world datasets, and the comparison with the results of other outlier detection methods, the proposed algorithm seems to provide other types of deeper detections; the first case study concerns the famous Wine dataset from the UCI Machine Learning Repository; the second one involves the analysis and exploration of data in meteorological domain, where various results are explained; finally, the third case study explores the well-known Iris dataset which, traditionally, has no outliers, while new information is discovered by the ECF-means algorithm and exposed here with many results.**

Keywords-ECF-means; Fuzzy Outlier Detection; Data Mining; Ensemble Clustering; k-means; Weka.

I. INTRODUCTION

The Ensemble Clustering Fuzzification (ECF) means [1] is an algorithm aimed at combining multiple clustering models to produce a better result than that of the individual clustering components. The proposed ensemble approach is carried on using the well-known k-means algorithm, its Weka implementation, and an ad-hoc developed software application. Compared to the version described in [1], we made some updates obtaining a new version of the algorithm. First of all, the most important variation to the algorithm consists in removing any equal partitions determined by two different runs of k-means algorithm. Therefore, all the ensemble results and the evaluation indexes are calculated on the number of different obtained partitions and not on the total number of performed iterations. Moreover, we also define a new validation index, called o-rank fuzzy outlier index ($o.FOUI$) by calculating the percentage of o-rank fuzzy outliers discovered by ECF.

The clusters achieved by the algorithm can be read in a "soft" way, in order to better explore and understand the results, and discover potential outliers in the dataset.

An outlier, or an anomaly, is an observation that is numerically distant from the rest of the data. What "distant" means depends on the context and on the domain, on the type of data and on the objective of analysis that must be achieved. Additionally, outlier detection is the process, or a technique, to find patterns in data that do not conform to estimated behavior. It plays a primary role in both statistical and data mining tasks, so much that identifying, understanding, and predicting anomalies from data is one of the key pillars of modern and advanced data analysis.

Nowadays methods and algorithms for data analysis increasingly involve huge amounts of data which are certainly rich in valuable information and useful knowledge, but also full of noise and impurities. The main challenges of outlier detection with this increasing complexity, variety, and volume of datasets, are how to discover similar outliers in one fell swoop, as a group [2]. Thus, an advantageous activity of data analysis must strictly have a data preparation step that includes data cleaning and anomalies removal activities.

Several outlier detection techniques have been proposed in literature [3]. Roughly, the approaches to outlier detection can be divided into two main categories: statistical and non-statistical methods. Within the non-statistical methods, the Machine Learning techniques for Data Mining are very popular, studied, and even among the most applied. Statistical methods are typically model-driven while Data Mining methods are typically data-driven. Mainly the Data Mining approaches for anomaly detection are divided into Proximity-based, Density-based, and Clustering-based techniques. This paper focuses on clustering-based outlier detection algorithms that look for outliers by applying one of the clustering algorithms and retrieve the anomalies subset. Moreover, this paper presents our idea on how apply the ECF-means algorithm for outlier detection task, and therefore, we explore datasets by applying this clustering-based technique.

Whilst usually it is hard to attach an outlier score to objects by using most of the clustering algorithms [4], the ECF-means algorithm defines a new class of outliers, consisting of elements that in [1] are named o-rank fuzzy outliers.

Therefore, ECF-means is able to assign a score to each element of the dataset depending on the vector constituted by its memberships to every obtained clusters. An element whose score is lower than a fixed threshold level is an outlier, because it belongs to two or more different clusters, without a clear and unambiguous membership. In this way, it is possible to have different kinds of outliers by fixing different thresholds: an element with level 1 is not a true outlier, whilst an element of level 0 is a full anomaly. These elements can be analyzed separately in order to understand if they are records that have undergone measurement errors and need to be deleted, or elements that are, from some point of view, special elements, confirming the idea that outliers are sometimes more interesting than the majority of the data.

Finally, the detected outliers are something new compared to those discovered by the crisp or traditional techniques for outlier analysis, and the two ways rarely discover the same anomalies.

In this paper, we present some applications of ECF-means algorithm, including datasets explorations, clustering results, outliers detection and classification. For the sake of clarity, this algorithm has many purposes and this paper focuses on an its application aimed at detecting outliers in various real-world benchmark datasets, testing its results and comparing the discovered anomalies with those detected by classical statistical methods. Our examples will demonstrate the efficiency of the ECF-means approach, comparing our results with those retrieved by other methods.

A. Structure of the paper

In Section II, we present some outlier detection generalities, including different approaches to discover anomalies in large datasets, and application fields. Particular attention is given to the clustering-based algorithms for anomaly detection and to properties of the algorithms for outliers detection.

In Section III, we provide cluster analysis general outlines, including main definitions, its scope and its role in Data Mining. Furthermore, some concepts regarding Ensemble Clustering, soft and hard clustering are mentioned.

In Section IV, the original k -means algorithm is synthesized, exposing its pros and cons.

In Section V, the ECF-means is presented, including some main definitions; in particular, we introduce the o-rank fuzzy outlier definition.

In Section VI, we present some validation measures for cluster analysis and for fuzzy clustering, including Silhouette, Partition Entropy Coefficient, the Threshold Index, and a novel index called o -rank fuzzy outlier index.

In Section VII, the ECF-means SW application is explained, underlining the updates of the new version.

In Sections VIII, IX, and X we show how the new version of the implemented software tool has been used in three different applications, underlining how it helped us to explore datasets, to discover new knowledge, to detect potential outliers, and to group objects in order to train custom models.

Finally, in Section XI, we show our general considerations in order to motivate future works and researches.

II. Outlier Detection

In outlier detection, the main goal is to discover objects that are different than the most other objects in the dataset. In many applications outliers contain important information and their correct identification is crucial.

A. Different Approaches and Application Fields

Outlier detection, or interchangeably anomaly detection, is the process of finding data objects with behaviors that are very different from expectation. Precisely, such objects are called outliers, anomalies, abnormalities, discordants or deviants. Outlier detection is generally considered a problem of machine learning or data mining, in the same way as classification and clustering.

A very common definition of an outlier is provided in [5] and it states:

"An Outlier is an observation which deviates so much from the other observations as to arouse suspicions that it was generated by a different mechanism."

In Data Mining and Statistics, outliers are particularly important aspects of the data. It may be difficult to evaluate the amount of noise in the data set or the number of outliers. More than that, what is noise or an outlier to one person may be interesting to another person. So, a unique mechanism that can identify outliers in datasets is impossible to define. Furthermore, the resolution of potential conflicts in detection is often possible thanks only to domain knowledge, which cannot always come to the aid of data analysts, especially when they are dealing with big data.

Table I shows several examples with categories of anomalies and it confirms why an uniform definition of anomaly is very hard to achieve. It is also evident that there is no clear separation between these types of outliers.

TABLE I. Examples of Outliers

	Example	Category
1	Outlier with respect to rest of the data points	Point Outlier, Contextual Outliers
2	Outlier with respect to local neighborhood	Point Outlier, Contextual Outliers
3	Outlier with respect to the data distribution	Point Outlier, Contextual Outliers
4	Outlier with respect to local dense regions	Point Outlier, Collective Outliers
5	Outlier tight cluster in a sparse region	Point Outlier, Collective Outliers
6	Outlier sparse cluster in a dense region	Collective Outliers

Outliers can be classified into three main categories that intersect with the examples in Table I:

1. point outliers, where a single instance of data is anomalous if it is too far off from the rest;
2. contextual outliers, if its value significantly deviates from the rest the data points in the same context; note that this means same value may not be considered an outlier if it occurred in a different context; these outliers are common in time-series data;
3. collective outliers, where a set of data instances collectively helps in detecting anomalies.

The technique chosen for anomaly detection can be based on the type of data you are dealing with. Many of these approaches have been exactly developed for certain application domains, while others are more generic and reusable. One of the main criteria used to select the outlier detection technique is based on the nature of the outlier to discover.

Approaches for outlier detection are reported in Table II [6] [7] [8].

TABLE II. METHODS FOR OUTLIER DETECTION

Method	Description
Nearest neighbor-based	lazily analyze the nearest neighborhood of a test point to assign it an outlier score relative to their neighborhood; in particular, these methods are based on the idea that normal instances lie in dense neighborhoods whilst anomalous points lie in sparse neighborhoods
Clustering-based	the anomaly score assigned to a test point is based on its relationship with its nearest cluster; by using these algorithms, outliers do not belong to a cluster or are far away from the nearest cluster representative
Classification-based	operate under the hypothesis that a classifier can be trained from a given feature space that can discriminate between normal and outlier classes
Statistical	are based on building a probability distribution model and considering how likely objects are under that model; outliers appear in the low probability regions of the distribution and have high anomaly score
Spectral decomposition-based	are unsupervised learning techniques that find an approximation of the data using a combination of attributes that reveal low dimensional structure in dimensional data; points that are different from others in the lower approximation are detected as outliers
Information theoretic	by which an anomalous point is an instance that has irregularities in the information content by using different information theoretic measures such as entropy or complexity

Other authors report [4] that the Machine Learning methods for outlier detection can be classified as proximity-based techniques, mainly founded on Nearest Neighbor concept, density-based techniques, where outliers are objects that are in regions of low density, and clustering-based techniques, where outliers can form small groupings or where an outlier is an object does not strongly belong to any cluster.

TABLE III. APPLICATIONS FIELDS OF OUTLIER DETECTION

	Field	Goal
1	Medical Informatics	Healthcare analysis, diagnostics, in a wide variety of medical specializations
2	Intrusion Detection	Break-ins, penetrations, and other form of computer abuse detection
3	Fraud Detection	Credit card, mobile phone
4	Fault / Damage Detection	Industry damage, multi-failures in Avionics systems, and others
5	Crime Investigation / Counter Terror Op. Planning	Fake news, misinformation, security, surveillance, social network monitoring
6	Other Domains	Speech Recognition, Traffic Monitoring, Detecting Faults in Web Applications, Detectiong Outliers in Astronomical Data, in CRM, in Census Data, in Biological Data, Novelty Detection in Robot Behaviour, Click Through Protection, and others

The well-known DBSCAN clustering algorithm [9] can be considered, for example, both in the density-based category and in the clustering-based one, because DBSCAN assumes that regions or points with density lower than a global threshold are noise or outliers.

It is very important to underline that outlier detection can represent both the objective of the analysis and a data cleaning method in the Data Preparation step of the CRISP-DM [10].

Outlier detection is central for a wide variety of applications and activities [11] [12] such as reported in Table III.

B. Clustering-based Outlier Detection

Outlier detection finds objects that are not strongly related to other objects, while on the contrary cluster analysis finds groups of strongly related objects in the dataset. One implication is that clustering can be successfully used for outlier analysis.

This approach is based on the idea that anomalous points do not belong to a cluster or to a single cluster without ambiguity. Another possibility occurs when the anomalous point is far away from the nearest normal cluster representative (such as the centroid, the medoide, etc.). The use of an unsupervised outlier detection approach based on a clustering algorithm also has the advantage of avoiding the bias introduced by training an algorithm with anomalous instances, labeled wrongly as normal data, producing many and unmanageable misclassifications.

Applying a clustering method to detect anomalies can discover, such as all the kinds of outlier detection approaches, single, spare, and rare elements, or also clusters of outliers, forming a collection, which is why in this case anomalies are called “collective outliers”. For the sake of clarity, many times the collective outliers aggregate far from the rest of the elements of the dataset, and then they could be modeled by a rule, forming a real new cluster and not an actual set of anomalies. So, an almost always applicable rule by which we can understand if a potential anomaly is a real anomaly, is to recognize if the anomaly belongs to a pattern. As already mentioned, the subset of the detected anomalous points may also not form a cluster, for example, because they are not cohesive with each other or they are not well separated from the rest of the clusters.

The main idea to detect anomalies by using a clustering approach is based on the property that “normal” data belong to large and dense clusters, whereas outliers belong to small or sparse clusters, or they are singletons, not belonging to any cluster. Consequently, all clusters smaller than a minimum size can be discarded, reassessed, or reported.

The clustering approach to anomaly detection can be used with any clustering algorithm, but requires thresholds for the minimum cluster size and the distance between a small cluster and other clusters. The idea of a clustering-based algorithm for outlier detection is captured by the definition [4]:

“An object is a cluster-based outlier if the object does not strongly belong to any cluster.”

In this context, “strongly” also means “clearly” and “without ambiguity”, and in the next sections the meaning of these words will be more explicit.

The binding of a point to its cluster can be measured by a score. A simple way of defining this score is to first cluster the whole dataset and then use the distance of the point to its closest cluster centroid. The points that have the highest scores are potential outliers.

After objects of a set are clustered and outliers are discovered and removed, the set with the rest of objects can be clustered again, analyzing if outliers affect the clustering. This is a very thorny problem, especially if k-means is chosen as the clustering algorithm, the results of which depend on the choice of the initial centroids and on the number k of clusters to be determined.

Another problem to be highlighted concerns the size of the clusters. If a cluster has very few points, these are potential outliers only if the other clusters have much larger sizes, otherwise nothing can be said. In a nutshell, outlier detection is strongly conditioned by the selected threshold.

Furthermore, many clustering techniques, such as k-means, do not automatically determine the number of clusters. This is a problem when using clustering in outlier detection, since whether an object is considered an outlier or not may depend on the number of obtained clusters.

All these aspects make us understand how the problem of outlier detection is strictly dependent on the set of data, the chosen method, the parameters of the algorithm, and the analysis goals. As consequence we have that we are not always sure that a discovered point is really anomalous.

The cluster-based outlier definition inherently contains a fuzzy reinterpretation of cluster analysis and outlier detection. For this reason, the ECF-means algorithm is a good candidate to detect potential outliers and to explore the dataset and clustering results.

C. Fuzzy Clustering-based Approach to Outlier Detection

In order to detect anomalies, fuzzy clustering is an alternative approach to classical clustering-based methods that are centered on the concept of crisp membership. Recently fuzzy clustering-based methods are applied in many fields, analyzing various types of data, and also getting very good results [13] [14] [15] [16]. In most of these works, however, authors use the fuzzy c-means clustering (FCM) algorithm, or a variant of it, for detecting outliers. Moreover, many crisp clustering techniques have difficulties in handling extreme outliers but fuzzy clustering algorithms tend to give them very small membership degree in surrounding clusters.

A systematic approach is to first cluster all objects and then assess the degree to which an object belongs to any cluster. Generally, the rules of assignment of the degree of membership characterizes the fuzzy clustering results. For example, the distance of an object to its cluster center can be used to measure the degree to which the object belongs to a specific cluster. If the elimination of an object results in a substantial improvement in the objective, then we would classify the object as an outlier. In a nutshell, clustering creates a model of the data and anomalies distort that model.

Another way to state if an object is an anomalous point is to calculate a level of "undecidability" of the point; for example, if the point belongs to two clusters with the same degree, then it has a high possibility of being an outlier.

D. Ensemble Outlier Detection

Mainly, an ensemble classical approach to outlier detection combines the outputs of individual outlier detection components by a weighted majority voting rule in a complete unsupervised context. The construction of ensembles is proposed as a solution to increase the individual capacity of each algorithm component and to improve the "anomalousness" of a potential outlier. However, no gain will be obtained by using components whose results are equal. So the discovered outliers sets must have some different anomalous points.

Whilst unsupervised outlier detection algorithms often suffer from high false positive detection rates, an ensemble approaches can be used to reduce these rates and many applications have shown good results to achieve more accurate and reliable anomalies [17].

The ensemble components can be built by applying each approach in Table II. However, the classification-based methods are more common than clustering-based ones [18].

The approach presented here is not a classical clustering-based method, it is a rather unique approach between ensemble methods for anomaly detection, due to its hybrid nature. In fact, on the one hand, it is the consequence of an aggregation clustering method, on the other hand, it exploits its fuzzy implication to assign scores to all points of the dataset, and on the basis of these scores it attributes a level of "outlierness" to the points.

E. Properties of the Algorithms for Outlier Detection

An anomaly detection method can enjoy some properties.

The idea presented here is to apply an algorithm for anomaly detection to a dataset, to remove the discovered anomalous points, and then to apply to the remaining data the same algorithm again.

Let S be a set of points, F an outlier detection method, and A the set of outliers of S discovered by F. In this case we can write $F(S) = A$. If $F(S - A) = \emptyset$, then F is an ***invariant*** algorithm for S (or S is invariant respect to F). In this case, F finds all the outliers of S in one fell swoop. If F is invariant for each set, simply F is invariant.

The mentioned DBSCAN algorithm [4] [9] can be considered as a clustering-based outlier detection method; in a nutshell, the clustering results depend on the radius ε of the epsilon-range-queries (which are hyperspheres) and on m parameter that is the minimum number of data objects required in an epsilon-range-query. For DBSCAN the outliers are noise, i.e., those points belonging to those clusters that have less than m elements, and therefore, they are not reached by any epsilon-range-query. Fixing ε and m, DBSCAN is invariant for each set.

The ECF-means algorithm is invariant for some datasets and not for others, as will be shown in the case studies in the next sections.

For the sake of clarity, the invariance property is not a property of the anomaly detection method, but of the set analyzed by the method.

If F enjoys the invariance property for each set, then on one hand, F is a very "robust" method for outliers detection,

but on the other hand, the method is a very strong property, or it can be very hard to prove it. It can be relaxed by a more general property explained in Figure 1.

Invariance Property of Order n

$S = A_0$ set of points
F outlier detection method
A_1 the set of outliers of S discovered by F:
$A_1 = F(S) = F(A_0)$
A_2 the set of outliers of $A_0 - A_1$:
$A_2 = F\big(S - F(S)\big) = F(A_0 - A_1)$
A_3 the set of outliers of $A_0 - (A_1 \cup A_2)$:
$A_3 = F\left(S - \left(F(S) \cup F\big(S - F(S)\big)\right)\right) = F(A_0 - (A_1 \cup A_2))$
… …
$A_n = F(A_0 - (A_1 \cup A_2 \cup \ldots \cup A_{n-1}))$
$A_{n+1} = F(A_0 - (A_1 \cup A_2 \cup \ldots \cup A_n))$

F is n-invariant for S if and only if $A_{n+1} = \emptyset$ and $A_n \neq \emptyset$

Figure 1. Generic Invariance Property of F.

In the generic invariance property of F, $A_{n+1} \cap A_n = \emptyset$ $(n > 0)$.

III. CLUSTER ANALYSIS

In order to detect potential outliers and to explore the dataset, cluster analysis is widely used in data mining. In this section, some general clustering considerations are shown.

A. Introduction

Clustering, or cluster analysis, belongs to intersection of Statistics, Machine Learning, and Pattern Recognition. It is a very useful unsupervised method for discovery pattern in large amount of data. It is a technique to group a set of objects into subsets or clusters. It is widely used [19] for Data Mining tasks, because it can be easily applied to understand, explore, prepare, and model data. It plays an outstanding role in many applications, such as scientific data exploration, information retrieval and text mining, web analysis, bioinformatics, and many others.

It can be applied at various steps of the Knowledge Discovery in Database (KDD) process. KDD can be carried out according to the Cross Industry Standard Process for Data Mining (CRISP-DM) [10]. Table IV shows the six steps of CRISP and where the cluster analysis can be applied. Some cluster analysis tasks are also reported.

TABLE IV. CRISP-DM STEPS AND CLUSTER ANALYSIS

	CRISP-DM Step Name	Cluster Analysis Tasks
I	Business Understanding	--------
II	Data Understanding	Data Exploration and Description
III	Data Preparation	Data Selection, Cleaning and Reduction, Features Selection, Gain and Raising
IV	Modeling	Generate Test Design, Data Modeling (Segmentation, Associative Rules, …), Model Customization
V	Evaluation	--------
VI	Deployment	--------

In the literature, there are many categories of algorithms for clustering: Heuristic-based, Model-based, and Density-based [20]. Their common goal is to create clusters so that objects in the same cluster should be as similar as possible, whereas objects in one cluster should be as dissimilar as possible from objects in the other clusters. Usually, it is not easy to choose the most useful algorithmic approach, the most satisfying result, and therefore, the most usable configuration. In fact, the different models for clustering may produce configurations that are very different from one another. Anyone applying a clustering algorithm immediately realizes how difficult it is to choose the final cluster configuration. We may have different results because we choose different algorithms, or different parameters of the fixed algorithm. Furthermore, the numerous available evaluation metrics often do not facilitate this choice because they lead to very discordant results.

In spite of the availability of a large number of validation criteria, the ability to truly test the quality of a final configuration remains vague and hard to achieve. Specific domain knowledge is not an aid because it is often hard to translate it into operating rules, neither the domain expert has a real target class for evaluating and comparing the results. So, why do not consider all the obtained configurations? That is, why do not find a method that summarizes all the results of clusterings? Meta-learning ensemble methods may be an answer. The idea is that no single model or criterion truly captures the optimal clustering, but a cooperation of models could provide a more robust solution. Cluster Ensemble, or Aggregation Clustering, or Multiview Clustering, aims to find a single clustering from multi-source basic clusterings on the same group of data objects [21]. However, these ensemble methods, such as voting-based clustering [22], consensus clustering [23], or clustering aggregation [24] do not assign a level of membership to every point in clusters.

In order to overcome the limits mentioned above, the ECF-means algorithm can be included within ensemble procedures. It is also an *a posteriori* criterion for optimization of the obtained groupings. This procedure takes in input any partitioning clustering algorithm for which it is possible to initially choose the k number of clusters to be determined and a seed for the random choice of the initial k centroids.

The k-means algorithm is one of the clustering algorithms that checks all the conditions listed. So, it is considered as the reference clustering algorithm. In Weka implementation of k-means [25] [26], the name of the algorithm is *SimpleKMeans*; in this version the seed parameter is s, which is the initialization value for the random number generator. Using the same seed value will always result in the same initial centroids then. Exploiting this seed parameter, many different configurations are evaluated and compared, and also used in our meta-algorithm for ensemble final configuration.

ECF-means can lead also to a "soft" interpretation of the clusters, in order to better explore and understand the results, and to find possible outliers in the dataset.

B. Definitions and Scope

A Clustering algorithm produces a partition on an unlabeled data set, such that no cluster is empty, no two

clusters intersect, and the union of all clusters is the data set itself.

The goal is to create clusters that are coherent internally, but substantially different from each other. In a nutshell, objects in the same cluster should be as similar as possible, whereas objects in one cluster should be as dissimilar as possible from objects in the other clusters.

Similarity between objects that belong to a cluster is usually measured by a metrics d. Two objects x and y are similar if the value of $d(x, y)$ is small; what "small" means depends on the context of the problem. d is defined by some distance measure. Typically, the Euclidean Distance (or simply the squared Euclidean Distance) is widely used in many applications (it is also used in the ECF-means) for the computation of similarities:

$$ED^2(x, y) = \sum_{i=1}^{n} (x_i - y_i)^2$$

It is important to underline that, also depending on the type of data, other many metrics are possible.

Numerous clustering algorithms are available in the literature and there are several points of view for examining clustering techniques; a very good landscape of Clustering algorithms can be retrieved in [20], and an in-depth and complete study of clustering techniques, algorithms and applications can be retrieved in [27].

C. Ensemble Clustering

Different clustering approaches or different views of the data can lead to different solutions to the clustering problem. Indeed, also initial settings of a fixed algorithm may produce clusters that are very different from one another. This evidence is closely related to the theory of Ensemble Clustering (or Multiview Clustering), which studies this issue from a broader perspective [21] [28].

Therefore, instead of running the risk of picking an unsuitable clustering algorithm, a cluster ensemble can be used in order to get a "better" clustering configuration. The idea is that no single model or criterion truly captures the optimal clustering, but a collective of models will provide a more robust final solution.

Most ensemble models use the following three steps to discover the final clusters configuration:

1. Generate N different clusterings, by using different approaches, or different data selection, different settings of the same algorithm, or different clusterings provided by different runs of the same algorithm. These represent the ensemble components.
2. Combine the results into a single and more robust clustering, by using a meta-rule or a set of rules.
3. Evaluate the ensemble clustering result and compare it with the results of the N components.

As already mentioned, the ensemble components can be selected in a wide variety of ways.

Some strategies for building clustering ensemble components follow:

1. By using different subsets of features. Each clustering configuration is found by means of overlapping or disjoint subsets of the original features set.
2. By selecting different subsets of the data, via random sampling.
3. The different components can be selected combining a variety of models and algorithms such as partitioning, hierarchical or density-based methods, random or deterministic algorithms, and so on.
4. The different components can correspond to different settings of the same algorithm.
5. The different components could be obtained from a single algorithm, randomizing the initial choice of the clusters centroids. Of course, an example is k-means; thus, the ensemble can be formed as the result of N different runs of the algorithm.

After the individual components have been obtained, it is often a challenge to find a meta-rule able to combine the results from these different solutions in order to create a unified ensemble clustering.

D. Hard and Soft Clustering

Clustering algorithms can also be classified into hard and soft algorithms. A hard clustering algorithm leads to a partition of crisp sets. In a crisp set, an element is either a member of the set or not. On the other hand, a soft clustering algorithm leads to fuzzy clusters. Fuzzy sets allow elements to be partially in a set. Each element is given a degree of membership in a set.

One of the most famous fuzzy clustering algorithms is fuzzy c-means [29] (FC-means), which allows an object to belong to two or more clusters with a membership degree between zero (not an element of the set) and one (a member of the set). It has been widely used in many real-world application domains where well-separated clusters are typically not available.

The ECF-means algorithm leads to a fuzzy partitioning of the dataset, by repeatedly applying the results of the k-means algorithm, as reported in next sections.

IV. THE k-MEANS ALGORITHM

k-means is a simple clustering algorithm whose main goal is to find k non-overlapping clusters. Each final cluster is represented by its centroid that is typically the mean of the points in that cluster.

A. Introduction, scope and procedure

k-means is one of the oldest and still widely used algorithms for cluster analysis. Without any doubt, it represents the archetype of the clustering partitioning algorithms. Because of its mathematical simplicity, it is also the most studied unsupervised learning technique [30], and over the years, many of its variations and extensions have been implemented (for High-Dimensional Data, for Data Streams, Time Series, for Data with noise, and so on).

k-means is also a simple prototype-based clustering algorithm that uses the centroid of the objects in a cluster as the prototype of the cluster.

Its basic algorithmic structure is shown in Figure 2.

k-means Clustering Algorithm

Input: S set of instances; k number of clusters
Output: set of k clusters with k centroids

1. Randomly initialize k cluster centers (centroids)
2. **While** termination condition is not satisfied {
3. Assign instances to the closest cluster center
4. Update cluster centers using the instances assignment
5. }

Figure 2. k-means Algorithm.

The condition of termination of the process is satisfied when no point changes clusters.

B. Pros and Cons

The algorithm has been very successful thanks to its simplicity and also for its linear time complexity $O(knl)$, where n is the number of objects to be clustered and l is the number of iterations that the algorithm is performing.

Like most partitioning clustering algorithms, k-means has some disadvantages:

1. It is very sensitive to outliers and noise.
2. The number of clusters need to be specified by the user and often it is not simple to choose it.
3. It is not able to discover concave-shaped clusters.
4. Since the initial choice of k centroids is random, different selections can also lead to very different final partitions, especially for large datasets with many features.

The k-means algorithm always terminates, but it does not necessarily find the "best" set of clusters.

C. Fuzzy c-means

The fuzzy c-means (FCM) algorithm has got many versions. The code of Figure 3 does not use incremental updates of cluster centroids.

Basic Fuzzy c-means Algorithm

1. Select an initial fuzzy pseudo-partition, i.e. assign values to all the w_{ij}
2. **repeat**
3. Compute the centroid of each cluster using the fuzzy pseudo-partition
4. Recompute the fuzzy pseudo-partition. i.e., the w_{ij}
5. **until** The centroids do not change.
(Alternative stopping conditions are "if the change in the error is below a specified threshold" or "if the absolute change in any w_{ij} is below a given threshold."

Figure 3. Basic Fuzzy c-means Algorithm.

k-means can be regarded as a special case of fuzzy c-means [4] and the behavior of the two algorithms is quite similar.

V. Ensemble Clustering Fuzzification Means

The initial selection of centroids can significantly affect the result of the k-means algorithm. To overcome this, the algorithm can be run several times for a fixed value of k, each time with a different choice of the initial k centroids.

In many software implementations of k-means, for example, in its Weka version, it is possible to choose a seed parameter (s), useful for the random selection of the first initial centroids (s is the random number seed to be used). Using this parameter, it is possible to realize, as will be described in the following sections, a procedure able to optimize and reinforce the obtained partition.

A. Introduction and Definitions

Let $S \subseteq \mathbb{R}^m$ be a set of points. Let k be the desired number of clusters to be determined. Changing the seed (s) from 0 to $N-1$, N partitions of S can be generated by applying the k-means algorithm. Some of these partitions are exactly the same, considering or not the order of groupings. Others, however, differ for very few records, and others for many.

In the following $N \times k$ matrix, called Clustering Matrix C of S, each row is a partition of k clusters of S.

$$C = \begin{pmatrix} C_{1,1} & C_{1,2} & \dots & C_{1,k} \\ C_{2,1} & C_{2,2} & \dots & C_{2,k} \\ \dots & \dots & C_{i,j} & \dots \\ C_{N,1} & C_{N,2} & \dots & C_{N,k} \end{pmatrix}$$

$C_{i,j}$ is the j-th cluster obtained at the i-th iteration of the clustering algorithm, with $i = 1, \dots, N$ and $j = 1, \dots, k$.

It is possible to associate a new $N \times k$ matrix to C, called MU matrix, which is the matrix of the centroids of the clusters:

$$C \to \begin{pmatrix} \mu(C_{1,1}) & \mu(C_{1,2}) & \dots & \mu(C_{1,k}) \\ \mu(C_{2,1}) & \mu(C_{2,2}) & \dots & \mu(C_{2,k}) \\ \dots & \dots & \mu(C_{i,j}) & \dots \\ \mu(C_{N,1}) & \mu(C_{N,2}) & \dots & \mu(C_{N,k}) \end{pmatrix} = MU$$

$\mu(C_{i,j})$ is the arithmetic mean of the j-th cluster of the i-th iteration of the algorithm, with $i = 1, \dots, N$ and $j = 1, \dots, k$.

B. Clusters Sort Algorithm

The algorithm in Figure 4 is useful for sorting the clusters partitions of C matrix. This step is essential because k-means can produce different orders of clusters in different runs, even if the partitioning results can be the same.

Please note it is possible that the average of some elements of the second row C_2 in Algorithm 1 has a minimum distance from two or more averages of elements of the first row C_1. In this case, the minimum value of the minimum values is chosen.

C. The ECF-means Algorithm

Let C be a Clustering Matrix of S, sorted by using the Algorithm 1.

We define $\underline{C_j}$ as ***floor of*** $\boldsymbol{C_j}$: $\underline{C_j} = \bigcap_{i=1}^{N} C_{i,j}$, with $j = 1, \dots, k$. It is possible that $\underline{C_j} = \emptyset$ ($j = 1, \dots, k$). Moreover, $\underline{\boldsymbol{S}} = \bigcup_{j=1}^{k} \underline{C_j}$ is defined as the ***floor of*** $\boldsymbol{S}$.

Algorithm 1: Clusters Sort Algorithm

Input: two different rows of C:
$C_1 = (C_{1,1}, C_{1,2}, \dots, C_{1,k})$ and $C_2 = (C_{2,1}, C_{2,2}, \dots, C_{2,k})$
Output: a new order of the second row:
$(C'_{2,1}, C'_{2,2}, \dots, C'_{2,k}) = C'_2$

C_1 represents the reference row of the current sorting procedure (e.g., obtained by fixing $s = 0$ in the Weka k-means algorithm).

1. Calculate the $2 \times k$ matrix of clusters centroids:
$$MU = \begin{pmatrix} \mu(C_{1,1}), \mu(C_{1,2}), \dots, \mu(C_{1,k}) \\ \mu(C_{2,1}), \mu(C_{2,2}), \dots, \mu(C_{2,k}) \end{pmatrix}$$
2. Compute the Euclidean Distances (ED) in MU. The following $k \times k$ matrix is the Δ matrix of the EDs:
$$\Delta = \begin{pmatrix} d_{1,1} & d_{1,2} & \dots & d_{1,k} \\ d_{2,1} & d_{2,2} & \dots & d_{2,k} \\ \dots & \dots & \dots & \dots \\ d_{k,1} & d_{k,2} & \dots & d_{k,k} \end{pmatrix}$$
Where:
$d_{i,j} = ED\left(\mu(C_{1,i}), \mu(C_{2,j})\right)$, with $i, j = 1, \dots, k$.
3. Calculate the minimum value of each row of Δ.
$\min\{d_{1,1}, d_{1,2}, \dots, d_{1,k}\} = d_{1,\overline{j_1}} = min_1$
$\min\{d_{2,1}, d_{2,2}, \dots, d_{2,k}\} = d_{2,\overline{j_2}} = min_2$
… … … … … …
$\min\{d_{k,1}, d_{k,2}, \dots, d_{k,k}\} = d_{k,\overline{j_k}} = min_k$
4. The second row C'_2 is:
$(C'_{2,1}, C'_{2,2}, \dots, C'_{2,k}) = (C_{2,\overline{j_1}}, C_{2,\overline{j_2}}, \dots, C_{2,\overline{j_k}})$
Where:
$C'_{2,1} = C_{2,\overline{j_1}}$ is the cluster (in C_2) that has the centroid with the minimum distance from the centroid of the first element of C_1.
… … …
$C'_{2,k} = C_{2,\overline{j_k}}$ is the cluster (in C_2) that has the centroid with the minimum distance from the centroid of the k-th element of C_1.

Figure 4. Clusters Sort Algorithm.

Let x be an element of S; we can count the number of clusters of the first column of C where x is, the number of clusters of the second column of C where x is, and so on. In this way, we can associate a new numerical vector to x, called ***attitude of x*** ($att(x)$):

$$att(x) = \left(att_1(x), att_2(x), \dots, att_k(x)\right),$$

where $att_j(x)$ is the number of clusters in the j-th column of C where x is located. $att_j(x) = N \Leftrightarrow x \in \underline{C_j}$ and $\sum_{j=1}^{k} att_j(x) = N$. In this manner, we are defining a function att_j ($j = 1, \dots, k$ and $I = \{1,2, \dots, N\}$):

$$att_j : x \in \bigcup_I C_{i,j} \rightarrow att_j(x) = \left|\{i \in I : x \in C_{i,j}\}\right|$$

where, as usual, $|A|$ is the number of the elements of the set A.

Finally, we can define the ***probability vector of x***, as:

$$p(x) = \left(\frac{att_1(x)}{N}, \frac{att_2(x)}{N}, \dots, \frac{att_k(x)}{N}\right)$$

Thanks to the simple mathematical notions of the current section, we are able to "soften" the "hard" k-means algorithm and we can have a new Fuzzy Clustering Algorithm. According to this approach, each element of the dataset belongs to each cluster with a different degree of membership, and the sum of these probabilities is equal to one.

Furthermore, the method can also be interpreted in a different way. Indeed, this "fuzzification" procedure can be used not only with k-means algorithm, but also for others partitional clustering algorithms for which it is possible to choose the number of clusters to be determined. In this way, the algorithm is part of the Ensemble algorithms. For these reasons, ECF-means is also a meta-algorithm because we reach a fuzzy partition of the dataset by using a multiple clustering algorithm schema.

The Algorithm 2 of Figure 5 is able to assign a probability membership to each point of the dataset and to "slice" the data in clusters.

Algorithm 2: ECF-means (Fuzzification of k-means)

Input: $S \subseteq \mathbb{R}^m$; number k of clusters to be determined; membership threshold t ($0 \leq t \leq 1$); number N of k-means iterations
Output: set of k clusters of level t; probability vector of each element x of S

1. **Apply** the k-means algorithm to S, fixing the random seed $s = 0$, obtaining the clusters $C_{0,1}, \dots, C_{0,k}$ ($C(0)$-configuration)
2. **foreach** $s = 1, \dots, N-1$
3. **Apply** the k-means algorithm to S, obtaining the clusters $C'_{s,1}, \dots, C'_{s,k}$ ($C'(s)$-configuration)
4. **Apply** the Clusters Sort Algorithm to $C'(s)$, considering $C(0)$ as reference, obtaining the clusters $C_{s,1}, \dots, C_{s,k}$ ($C(s)$-configuration)
5. **end**
6. **foreach** $j = 1, \dots, k$
7. **foreach** $x \in S$
8. **Calculate** $p_j(x) = att_j(x)/N$
9. **Fix** the cluster $C_j^t = \{x \in S |\, p_j(x) \geq t\}$
10. **end**
11. **end**

Figure 5. ECF-means Algorithm.

The membership threshold t in the Algorithm 2 is fixed by the user and it is very useful to change the "level" to clusters final configuration. If $t = 1$, then $C_j^1 = \{x \in S | p_j(x) = 1\} = \underline{C_j}$. Additionally, $\underline{S} = \bigcup_{j=1}^{k} C_j^1$. If $t = 0$, then $C_j^0 = \{x \in S | p_j(x) \geq 0\}$ and $\bigcup_{j=1}^{k} C_j^0 = C_j^0 = S$.

Let $p(x)$ be the probability vector of x and let $M = \max att(x) = \max\{att_1(x), att_2(x), \dots, att_k(x)\}$ be the maximum of $att(x)$, if this exists. We can define the position of M in $att(x)$ as $PMA(x)$, if this exists.

D. o-rank Fuzzy Outlier

As has been defined, to each point of the dataset it is possible to associate a probability vector, which is as matter of fact a vector of degrees of memberships. What happens if we cannot unambiguously identify the cluster to which the point belongs? What happens if the two highest components

of the vector are equal (or almost equal)? In this case, two interpretations are possible; the "ambiguity":

1. depends on the clustering procedure, for example, on the choice of k or on the selection of the number N of iterations,
2. is intrinsic to the point because the point is an anomaly.

The first interpretation leads to the definition of a novelty validation measure called Threshold Index TI, which is reported in the next section. Thanks to the second interpretation it is possible to define a new particular type of outlier, called o-rank fuzzy outlier.

An element $x \in S$ is an ***o*-rank fuzzy outlier of S** if $p_j(x) - p_l(x) \leq o$ $(0 \leq o \leq 1)$, where $p_j(x)$ and $p_l(x)$ are the first two highest value components of $p(x)$. The o parameter is also named "outlier threshold".

The definition of o-rank fuzzy outlier helps us to treat these points as special points, which need to be observed more closely, because they belong at least to two different clusters, with a degree of "ambiguity".

The o parameter allows to create a hierarchy of outliers; that is, o represents a score to be assigned to each point of the dataset. For example, if $k = 3$ and $p(x_1) = (1, 0, 0)$, $p(x_2) = (0.1, 0.45, 0.45)$, $p(x_3) = (0.75, 0.05, 0.2)$, and $p(x_4) = (0.5, 0.4, 0.1)$, then:

- x_1, x_2, x_3, x_4 are 1-rank outliers
- x_2, x_3, x_4 are 0.55-rank outliers
- x_2, x_4 are 0.1-rank outliers
- x_2 is a 0-rank outlier

The set of 1-rank fuzzy outliers of S is S; the set of 1-rank fuzzy outliers of S that aren't o-rank fuzzy outlier, with $o < 1$, is the floor of S. From the "o-rank fuzzy outlier" perspective, each point in the dataset is an outlier.

The o-rank fuzzy outliers, where o is close to 0, are the most interesting points of the dataset, which need to be analyzed separately from the rest of the other points. Their fuzzy nature pushes us to a deepening, also to understand if they are "polluting" elements of the dataset, or they are wrongly selected by the algorithm and, therefore, they are ambiguous points for the algorithm but not anomalous in the dataset, or they constitute the main objective of detection.

If ECF is considered a method for outliers detection, and if o.FOU is the set of o-rank fuzzy outliers of S, it could be very interesting to find the highest o for which ECF-means is invariant for S, naturally if a such o exists:

$$\max\{o: ECF(S - o.FOU) = \emptyset\}$$

For this selected o, the set of o-rank fuzzy outliers of S that make ECF-means an invariant method for outliers detection is a special subset that has to be detailed.

E. Updates to the New Version of the Algorithm

As pointed in the previous sections, changing the seed (s) from 0 to $N - 1$, N partitions of S can be generated by applying the k-means algorithm. Some of these partitions are exactly the same, considering or not the order of groupings. In this new version of the algorithm, after applying the clusters sorting algorithm, all the identical configurations are deleted, leaving only all the different partitions. Obviously, two partitions are different if they have at least one element that belongs to two different clusters of the two partitions.

This change effects on the whole designed method. As consequence of this choice, all the ensemble results and the evaluation indexes are calculated on the number of different obtained partitions and not on the total number of performed iterations.

Two different seeds could lead to the same partition because through them the same initial centroids are selected, or because of some topological reason, which is for the geometric distributions of the elements in the dataset. It might be interesting to find out some rules by which different selections of the initial centroids lead to the same final configuration and to discover if a pattern exists for these elements. This change was made above all to avoid that the Weka algorithm based on the seed (s) too often chooses the same initial centroids and, therefore, that the corresponding partitions are too privileged and impact on the final result.

Even the case studies presented have clearer results thanks to the changes that have been made, and the new validation index facilitates the interpretation of the achieved results.

Note that, especially for small datasets, the possible different final configurations can be very few; in this case, an ensemble approach can be superfluous or even useless.

VI. Cluster Validity Assessment

Clustering validation has long been recognized as one of the critical issues essential to success of clustering applications [27].

A. Introduction

One of the most important issues in clusters analysis is the evaluation of the clustering results. In order to compare the outputs of different clustering algorithms, or the different partitions retrieved by the same clustering algorithm by using different parameters, it is necessary to develop some validity criteria. Moreover, if the number of clusters is not given by the clustering algorithm, many cluster validity methods have been developed in the literature; indeed, to find the optimal number of clusters in the data set is a very central task in data analysis. These methods lead to many different indices, specialized for the various categories and approaches of clustering algorithms; moreover, the methods are usually divided in supervized and un-supervized methods, or in internal and external validation criteria [27].

Most validation indices take into account the concepts of cohesion and separation [31]; therefore, the index is a measure that "optimizes":

- Cohesion, also called compactness or tightness: patterns in one cluster should be as similar to each other as possible. The fitness variance of the patterns in a cluster is an indication of the cluster's cohesion.
- Separation: clusters should be well separated. Distance among the representatives of the clusters provides an indication of cluster separation.

B. Silhouette Index

One of the most widespread and useful indices is the Silhouette [32] [33]. The Silhouette method is an unsupervized method (it does not need a class attribute to calculate it) for evaluation of clusterings. It is a measure of how similar an object is to its own cluster (cohesion) compared to other clusters (separation).

The Silhouette index is calculated strarting from the definition of the silhouette of each point of the dataset. The silhouette $s(i)$ of a point i is calculated by the following formula:

$$s(i) = \frac{b(i) - a(i)}{\max\{a(i), b(i)\}}$$

Where:

- $s(i)$ is the silhouette of i
- i is a generic point in the dataset;
- $a(i)$ is the average distance between i and all other data within the same cluster.
- $b(i)$ is the smallest average distance of i to all points in any other cluster, of which i is not a member.

From the above definition it is clear that $-1 \leq s(i) \leq 1$.

The Silhouette index is the aritmetic mean of the silhouettes of each point in the dataset.

A value of the Silhouette index far from zero expresses a good result of the clustering algorithm.

C. Validation Measures for Fuzzy Clustering

Let $U = (u_{li})\ (1 \leq l \leq k, 1 \leq i \leq n)$ be the membership's matrix of a fuzzy partition of a dataset S with n records, and k is the number of clusters.

The first validity index for fuzzy clustering is the Partition Coefficient Index (PC) [34]. PC is based on U and it is defined as:

$$PC = \frac{1}{n}\sum_{l=1}^{k}\sum_{i=1}^{n} u_{li}^2$$

$PC \in [1/k, 1]$. Furthermore, a PC value close to $1/k$ indicates that clustering is "very fuzzy"; the value $1/k$ is obtained when $u_{li} = 1/k$, for each l, i.

Another index is the Partition Entropy Coefficient (PE):

$$PE = -\frac{1}{n}\sum_{l=1}^{k}\sum_{i=1}^{n} u_{li} log_a(u_{li})$$

$PE \in [0, log_a k]$. Furthermore, a low PE value indicates that clustering is "not very fuzzy". PE values close to the upper limit indicate an absence of any clustering structure within the dataset or the inability of the algorithm to extract it.

The main disadvantage of PC and PE is their monotonic evolution tendency with respect to k. To avoid this, a modification of the PC index can reduce the monotonic tendency and was defined by:

$$MPC = 1 - \frac{k}{k\ -\ 1}\ (1\ -\ PC)$$

where $0 \leq MPC \leq 1$.

Finally, let we define a novel validity index, which we call the ***Threshold Index TI***, by the following formula:

$$TI = \frac{|\underline{S}|}{|S|}$$

TI provides a measure of the quantity of elements in the dataset that are fixed in every partition (they belong to the floor set) with respect to the size of the whole dataset.

Finally, if o.FOU is the set of o-rank fuzzy outliers, then let we define the ***o-rank fuzzy outlier index*** (***o.FOUI***), by the following formula:

$$o.FOUI = \frac{|o.FOU|}{|S|}$$

$o.FOUI$ tells how many elements in the dataset are o-rank fuzzy outliers with respect to the size of the whole dataset.

Thanks to these validation measures, it is possible to have a rough idea of the fuzzy nature of the whole dataset and, thanks to $o.FOUI$, if too many points are outliers, then it is necessary to modify the parameters of the algorithm, such as k or N. For this reason, they are useful to better select these parameters.

VII. ECF-MEANS TOOL V2.0

With the purpose of testing the ECF-means algorithm, a software application has been designed and developed. It has been carried on using a Client/Server architectural pattern, where the Server part consists of the algorithm and other support utilities, while the Client part is made by a browser-based application, responsible of the ECF-means result visualization.

The algorithm had an important update and it leads to a new version of the software tool, and that is why we have renamed the tool updating it to the version 2.0. However, the tool presents an option to choose whether to keep the old version of the algorithm, leaving even the same configurations, or go to version 2.0, deleting the same partitions.

A. Software Implementation

The ECF-means web application is built up of two main modules: the first one wraps the ECF-means Algorithm that has been implemented in Java programming language, and it makes use of the Weka k-means algorithm (*SimpleKMeans*) [25] [35] as clustering algorithm implementation.

The second module consists of the web application client part, which has been implemented by using JavaScript libraries, such as D3.js, as visualization library, and jQuery for Ajax asynchronous data communication and Document Object Model (DOM) manipulation tasks.

B. GUI & Data Visualization

The implemented tool provides a user-friendly GUI, by which it is very easy to load datasets, fix the ECF-means parameters, and understand the algorithm results visually.

The GUI can be divided into three functional blocks, as highlighted by red numbered circle in Figure 6.

Through the first functional block, user can upload a dataset from a local file system, in csv or arff formats; after that he/she can specify the number of clusters k (default is set to two), the initial seed number (default 0), and the number of iterations N to perform (default 100).

The o Value spin box controls the o-rank fuzzy outlier value and hence the $o.FOUI$ index. Furthermore, its value changes cluster points shape and color: if a point has a difference between the two highest values of its probability membership vector less than this value, the point is displayed as a grey square.

Two checkboxes control computation of, respectively:

1. Silhouette Indexes.
2. Only different cluster configuration, as stated in Section V.E.

Lastly, a set of buttons allow the following operations:

1. Run: runs the ECF-means algorithm and displays the results (clustering graphical visualization and validation measures output).
2. Save Results: saves results to an output csv file.
3. Stop: ends the current computation.

The second block is where clustering visualization takes shape under scatter plot form: dataset points are displayed as circle with the color of the belonging cluster (resulting from the highest value of the probability membership vector) and with an opacity due to the degree of membership to the same cluster (stronger opacity means higher membership).

If the attributes of the dataset are two, Voronoi lines (computed considering initial seed, default $s = 0$) are also displayed.

In the top of the block, some input controls are used to affect data visualization. In particular, two combo boxes are used to allow the choosing of dataset's attributes that has to be displayed. Below this, a slider allows to set the degrees of membership above which a point is displayed (Membership Threshold t).

Instead, rightmost input fields, in order from top to bottom, control the visualization of:

1. The Initial Seed Centroid points (each with a "cross" symbol).
2. The Mean Seed Centroid points (each with a "plus" symbol).

Figure 6. Software GUI and clustering visualization.

The last third block is divided into three box panels: in the first one the validation measures are displayed, as described in Section VI.C, such as PC, PE, MPC, TI, and $o.FOUI$. In addition, Sum of Squared Errors (SSE) and Silhouette (S) measures have also been included; they are calculated considering Initial Seed (IS) and Mean Seed (MS), where MS is the mean value of the measure over all the N iterations, which lead to the definition of IS-SSE, MS-SSE, IS-S, and MS-S. Below this box, a second box displays the number of different retrieved partitions.

Lastly, in the bottom part of the block, a popup panel is displayed when a user clicks on a cluster point, where information about this clicked point are reported, such as point features, cluster memberships vector, best cluster assignment, etc.

C. Output Results

The ECF application exports results in csv format, where each row of the output file represents a point x of the dataset. The application appends ECF-means algorithm results as additional columns to the attributes columns of the point x.

TABLE V. COLUMN NAMES MEANING

Column Names	Description
ISCDistance$_i$, with $i = 1, \dots, k$	Vector of Euclidean Distances between point x and Initial Seed Centroids
ISCMembership	Cluster membership derived from the position of the smallest value in ISCDistance vector
MSCDistance$_i$, with $i = 1, \dots, k$	Vector of Euclidean Distances between point x and Mean Seed Centroids
MSCMembership	Cluster membership derived from the position of the smallest value in MSCDistance vector
Membership$_i$, with $i = 1, \dots, k$	Probability vector of point x, $p(x)$
ECFMembership	Cluster membership derived from the $PMA(x)$
o-rank fuzzy outlier	Y, if the point x is an *o*-rank fuzzy outlier, where o is fixed through the o Value input box by the user N, otherwise

Table V shows these additional column names meaning, where Mean Seed Centroid (MSC) is the arithmetic mean value of all computed centroids in N iterations.

VIII. CASE STUDY 1: THE WINE DATASET

The Wine dataset from the UCI Machine Learning Repository [36] is widely mined both by applying classification algorithms and clustering techniques. Chemical indicators are used in order to analyze the wine dataset. This case study is useful to underline the differences between classical methods for outlier detection and ECF-means.

A. Dataset Exploration

The Wine dataset has got 178 instances described by 13 attributes, with no missing values, and divided into three classes {0, 1, 2}, with the distribution [59, 71, 48]. These data are the results of a chemical analysis of wines grown in the same region in Italy but derived from three different cultivars. The analysis determined the quantities of 13 constituents found in each of the three types of wines.

TABLE VI. LIST OF WINE DATASET VARIABLES (FEATURES)

#	Name	#	Name
1	Alcohol	8	Nonflavanoid phenols
2	Malic acid	9	Proanthocyanins
3	Ash	10	Color intensity
4	Alcalinity of ash	11	Hue
5	Magnesium	12	OD280/OD315 of diluted wines
6	Total phenols	13	Proline
7	Flavanoids		

The attributes (variables) are listed in Table VI.

B. Outliers Detection with RapidMiner Tool

The RapidMiner tool [37] provides a series of case studies for data analysis by using machine learning techniques, and one of these concerns outlier detection in Wine dataset. The goal of these case study is to select anomalies in data resulting from a chemical analysis of wines by finding the data clusters and, then, identifying the anomalies based on local outlier factors. The clusters are achieved by applying the X-means algorithm [38] which determines the correct number of centroids based on a heuristic. Briefly, X -means is an extended version of k-means. It begins with a minimum set of centroids and then iteratively exploits if using more centroids makes sense according to the data. If a cluster is split into two sub-clusters is determined by the Bayesian Information Criteria (BIC), balancing the trade-off between precision and model complexity.

TABLE VII. X-MEANS RESULTS

Cluster	Number of Items
cluster_0	51
cluster_1	62
cluster_2	29
cluster_3	36
Tot	178

TABLE VIII. LIST OF OUTLIERS

#	Id	Cluster	Thershold
1	26	cluster_1	1.605
2	60	cluster_0	1.744
3	70	cluster_0	1.867
4	72	cluster_0	1.538
5	74	cluster_1	1.963
6	79	cluster_0	1.611
7	96	cluster_1	1.880
8	97	cluster_0	1.534
9	111	cluster_0	1.655
10	122	cluster_1	1.943
11	159	cluster_3	1.684

The outliers are detected by find the "outlier scoring" using the LOF (local outlier factor) mechanism [39]. The examples are filtered to get one data set with the outliers and another with the rest (non-anomalous points), using "outlier=1.5" as a threshold. Then, the outputs of the

RapidMiner analysis flow are the clustered data and two example sets with the outliers/non-outliers records.

The X-means algorithm provides 4 clusters, as reported in Table VII.

The outliers set, which we call OUT, provided by the RapidMiner flow, consists of 11 anomalies reported in Table VIII.

The set OUT of anomalies will be compared with the set of outliers obtained by the ECF-means algorithm, in order to discover if there is an o-rank threshold such that the two sets have some elements in common ($OUT \cap o.FOU \neq \emptyset$).

C. DBSCAN Algorithm Application

The mentioned DBSCAN algorithm can be applied in order to detect noise in the Wine dataset. Fixing $\varepsilon = 0.6$ and $m = 5$ in the Weka algorithm version, DBSCAN retrieves one cluster and provides 11 unclustered instances (noises), which are listed in Table IX, and they form the set NOI.

TABLE IX. LIST OF NOISES

#	Id	OS
1	60	YES
2	70	YES
3	74	YES
4	79	YES
5	96	YES
6	97	YES
7	111	YES
8	116	NO
9	122	YES
10	125	NO
11	159	YES

In the third column of Table IX, the "YES" value says if the unclustered instance is also in OUT set.

D. ECF-means Application

The ECF-means tool provides some different results. First of all, by changing k from 2 to 5, the best clustering outcomes are obtained by selecting $k = 3$. In Table X the validation measures are listed and they are calculated by fixing I = 500, which is the total number of performed iterations. #DP indicates the number of different partitions obtained during the 500 performed iterations.

TABLE X. VALIDATION MEASURES (I=500)

k	MPC	MS-S	TI	#DP
2	0.21	0.4	0.01	8
3	0.89	0.48	0.62	21
4	0.65	0.42	0.27	246
5	0.57	0.41	0	466

In spite of the fuzzy nature of the analyzed dataset (MPC=0.89), setting $k = 3$ the values of the Silhouette (MS-S = 0.48) and of the Threshold Index (TI = 0.62) are the highest of the list.

The floor $\underline{S}$ of Wine dataset has got 110 instances; these elements do not have a fuzzy nature (or a degree of "ambiguity"), and the first cluster has got only one element, the second one has got 58 elements, and the third one has got 51 elements. Set $S - \underline{S}$ contains potential outliers, and by changing the o parameter, different levels of o-rank fuzzy outliers are obtained, as Table XI shows.

TABLE XI. LIST OF o-RANK FUZZY OUTLIERS

o	o-$FOUI$	Id of o-rank fuzzy outliers
0.05	0.01	69
0.1	0.01	69
0.15	0.01	69, 74
0.25	0.02	69, 72, 74
0.35	0.03	61, 69, 71, 72, 74, 75

$p(69) = (0.5238, 0, 0.4762)$ is the probability vector of the element with Id = 69, whilst the probability vector of 74 is $p(74) = (0.4286, 0.5714, 0)$. The element 72, which is a 0.25-rank fuzzy outlier is not a real outlier because it is not an ambiguous element, considering its probability vector $p(72) = (0.619, 0.381, 0)$.

The detected 0.15-rank fuzzy outliers, discovered by the ECF-means algorithm, listed in Table XI, form the 0.15-$FOU = \{69, 74\}$ set.

The intersection set $OUT \cap NOI \cap 0.15.FOU$ is $\{74\}$ and this point does not represent anything new.

However, the new detected point, marked with id = 69, is really halfway between the first cluster and the third one and its discovery makes us understand how the proposed ECF-means method is able to enrich our knowledge on the analyzed dataset. Moreover, this point is found also by the RapidMiner outlier detection process, using "outlier=1.3" as threshold of the selecting filter, instead of 1.5.

IX. CASE STUDY 2 IN METEOROLOGICAL DOMAIN

The application of the ECF-means algorithm to the meteorological dataset [40] has been extensively presented in [1], where numerous results have been described. To deepen the nature of the dataset and to have an example of data analysis, you can consult [41].

This case study is useful for explaining how the algorithm is able to explore even datasets with numerous records, how the number of discovered outliers increases with the increase of the o parameter, and how the "ambiguous" points also belong to overlapping geographical areas.

A. Summary of the Previous Results

Briefly, in this section a summary of the results of the ECF-means application is presented.

An historical dataset made up of 9200 meteorological observations has been collected. Data have been retrieved from ECMWF MARS Archive containing the surface Synoptic observations (SYNOP) provided by 4 geographical sites: Charles De Gaulle (CDG) airport in Paris and Grazzanise, Milan, and Pantelleria airports in Italy.

SYNOP observations are recorded every hour and the list of the meteorological variables [41] used for applying the ECF-means algorithm is reported in Table XII. Each airport site has got 2300 records and the SITE attribute has 4 values.

Considering the Silhouette measure, the best clustering partition is obtained by selecting $k = 3$ for k -means

algorithm (Silhouette=0.49). Fixing $k = 3$ and considering SITE attribute as Class attribute, CDG and Milan are inserted into the same cluster (Cluster 0) by the algorithm (4 sites in 3 clusters): it seems that the two sites have a lot in common! Thus, we try to merge these two sets, obtaining a new set called CDG+MIL.

TABLE XII. LIST OF METEOROLOGICAL VARIABLES (FEATURES)

#	Name	#	Name
1	Pressure	6	cloud cover
2	three-hour pressure change	7	height of base of cloud
3	wind direction	8	Dewpoint Temperature
4	wind speed	9	Drybulb Temperature
5	Visibility	10	SITE

The incorrectly clustered instances are 3710 and represent 40.32% of the original dataset. k-means does not provide homogeneous clusters with respect to SITE attribute. From an intuitive point of view, the 3 sites (Grazzanise, Pantelleria and CDG+MIL) have an ambiguous meteorological nature and the 3710 unclustered instances are on the border between two or more sites. In other words, the datasets have overlapping areas, with "similar" meteorological conditions, and perhaps the sites are not so different, and they are not well-separated from each other.

The ECF-means algorithm tries to overcome the problem in which the k-means algorithm falls in this meteorological case study, and in part it succeeds, if only because it provides much more information on datasets, clusters, and on clustering results, thanks to which the data analyst can make more informed and useful choices.

By fixing $k = 3$, thanks to the ECF-means application, we are able to select the floor $\underline{S}$ of whole dataset. It has got 5363 records. The incorrectly clustered instances are 704 and represent 13.12% of $\underline{S}$.

The elements belonging to $\underline{S}$ never fluctuate from one cluster to another (considering the 350 iterations) and constitute approximately 58.3% of the initial dataset.

The obtained results lead to a clear improvement of the clustering: the clusters seem much more separate, if the contingency matrices are calculated starting from the floor set. ECF-means manages to break down the percentage of instances that are incorrectly clustered from 40.32% to 13.12%.

B. Outlier Detection by Applyng the InterquartileRange

The Weka tool provides a filter for detecting outliers and extreme values based on interquartile ranges. It can be found among the filters in the preprocess tab. The filter complies with the following schema:

A point x is an outlier ⇔

$$\begin{cases} Q_3 + OF * IQR < x < Q_3 + EVF * IQR \\ or \\ Q_1 - EVF * IQR \leq x < Q_1 - OF * IQR \end{cases}$$

A point x is an extreme value ⇔

$$\begin{cases} x > Q_3 + EVF * IQR \\ or \\ x < Q_1 - EVF * IQR \end{cases}$$

Where:

- $Q_1 = 25\%$ quartile,
- $Q_3 = 75\%$ quartile,
- IQR = Interquartile Range, difference between Q_1 and Q_3,
- OF = Outlier Factor,
- EVF = Extreme Value Factor.

The filter adds two new columns to the dataset: *Outlier* and *ExtremeValue*, which assume the values "yes" or "no", depending on the previous filter schema.

The dataset is divided by the three sites: Grazzanise, Pantelleria and CDG+MIL, and then, fixing $OF = 3.0$ and $EVF = 6.0$, the filter is applied to the three geographical sites separately.

Table XIII shows the number and the percentages of the outliers and of the extreme values discovered by the Weka filter.

TABLE XIII. SYNOP OUTLIERS AND EXTREME VALUES

	Grazzanise	Pantelleria	CDG+MIL
Outlier	144 (6.3%)	267 (11.6%)	319 (6.9%)
Extreme Values	65 (2.8%)	141 (6.1%)	157 (3.4%)

These values are statistical outliers and they depend on the distributions of all the meteorological variables.

By removing these points, putting together the three subsets, the residual dataset has got 8365 instances (some elements are both outliers and extreme values), and the three sites have the distribution [2145, 2012, 4208].

C. Outlier Detection by Applyng ECF-means

It is very useful to make a classification of the o-rank fuzzy outliers of the SYNOP dataset. As we already said, from the "o-rank fuzzy outlier" perspective, each point in the dataset is an outlier. The elements that belong to the $\underline{S}$, for example, are 1-rank fuzzy outliers but aren't o-rank fuzzy outlier, with $o < 1$.

First of all, the intersection between the set OUT of 835 detected outliers by applying the InterquartileRange filter and the set of instances that are in S and not in $\underline{S}$ has got 748 elements:

$$\left|OUT \cap (S - \underline{S})\right| = 748$$

This makes us realize how the anomalies discovered by the ECF method have much in common with the statistical outliers that are in the OUT set.

The elements belong to $o.FOU$ are o-rank fuzzy outliers and they have a fuzzy nature. However, o-rank fuzzy outliers with small o ($o < 1.5$) are the most interesting ones, and we will compare them with the OUT elements in more detail. So, also in this case study we will determine the set $OUT \cap o.FOU$ ($|OUT \cap o.FOU| \leq 748$, for small values of o).

By changing the o parameter (and fixing $k = 3$), we have the results of Table XIV, where the fuzzy outliers are divided with respect to the SITE attribute.

TABLE XIV. SYNOP o-RANK FUZZY OUTLIERS

o	Grazzanise	Pantelleria	CDG+MIL	Tot
0.05	7	22	25	54 (0.6%)
0.1	41	27	63	131 (1.4%)
0.15	145	204	248	597 (6.5%)
0.2	328	454	587	1369 (14.9%)

We found that 597 points (about 6.5% of the initial dataset) have an Outlier Threshold (difference between the two highest values of the probability membership vector), less than 0.15. These ambiguous instances belong also to OUT set:

$$|OUT \cap 0.15.FOU| = 597$$

The remaining $748 - 597 = 151$ points, which are in OUT but do not belong to $0.15.FOU$ set, are all 0.2-rank fuzzy outliers.

D. Invariance Property

Is the ECF-means method for outlier detection invariant for the SYNOP dataset? Or better, is there an o value for which the set of o -rank fuzzy outliers of $(SYNOP - o.FOU) = \emptyset$?

The tests we performed, by changing the o parameter, showed us that ECF-means is not an invariant algorithm for SYNOP set. But fixing $o = 0.15$, the set of the 0.15-rank fuzzy outliers of $(SYNOP - 0.15.FOU)$ is very small. Indeed, this set has got only 59 instances, which are new points but, deepening this set, we have discovered that these elements belong to the $0.2.FOU$ set.

For the sake of study, we repeated the procedure by setting $o = 0.2$, and then discovering the 0.2-rank fuzzy outliers of $(SYNOP - 0.2.FOU)$. Also, in this case, the resulting set is very small and it has got 40 instances.

On the other hand, if we calculate the o-rank fuzzy outliers of the floor $\underline{S}$ of the SYNOP set (we are applying the ECF-means algorithm to $\underline{S}$ that has got 5363 records) we find out that $0.15.FOU$ is empty and $0.1.FOU$ has got only 11 elements, whilst $0.05.FOU$ has got 27 records (0.5% of $\underline{S}$), and this result is really amazing.

E. Experimental Results

The results obtained in this case study encourage us to reflect a lot. Unlike the previous case study, here we do not find any new points compared to those discovered by the traditional method based on statistics. But surely the most interesting result is the ability that the proposed method has to assign a score to each set of outliers.

Moreover, this case study gave us the opportunity to investigate the invariance property of the ECF-means method and to research the connection between the floor set of SYNOP and the o-rank fuzzy outliers. Although we did not find a precise analytical relationship between floor of SYNOP and o (and we do not believe it exists because of the many algorithm parameters involved), we discovered a method to reduce the number of o-rank fuzzy outliers and to determine a "stable" subset of the original dataset.

SYNOP is a very difficult set to analyze, not only because it has many statistical outliers (about 9.1% of the original dataset), but also because, as repeatedly pointed out by the meteorologist and as also discovered in [1] and in [41], there are no net separations between airport areas, from a weather point of view. For example, the elements in $0.15.FOU$ are very fuzzy points and they belong to more than one cluster, and probably to more than one airport site (to overlapping areas).

In [41] the dataset is mined in order to find short-range temporal models for fog prediction; a next step would be to find out if prediction errors belong to $o.FOU$, for some o; or, if the generic forecast error decreases by removing the detected outliers from the dataset, or analyzing only the floor $\underline{S}$ of SYNOP dataset.

X. CASE STUDY 3: THE IRIS DATASET

The famous Iris dataset is a multivariate dataset that contains 3 classes of 50 instances each, where each class refers to a species of iris plant (Iris-setosa, Iris-virginica, and Iris-versicolor). Four features were measured from each sample: the length and the width of the sepals and petals, in centimeters.

The use of this dataset is very common in classification and clustering tasks, where numerous results have been obtained. Moreover, historically this dataset has been one the driving force of many theoretical studies, above all to discover and to deepen many non-linear classification methods.

From a statistical point of view, the Iris dataset has neither outliers nor extreme values; this makes the dataset a good example for exploration by the ECF-means algorithm, in order to discover new kind of outliers.

A. Summary of k-means Results

The data set only contains two clusters with rather obvious separation: one of the clusters contains Iris-setosa, while the other cluster contains both Iris-virginica and Iris-versicolor.

Fixing $k = 3$, the incorrectly clustered instances are 18, as reported in the contingency matrix of Table XV, and represent 12% of the original Iris dataset, by applying the simple k-means algorithm (or by applying the ECF-means algorithm, fixing $s = 0$ and $I = 1$).

TABLE XV. CLASSES TO CLUSTERS ($s = 0$ AND $I = 1$)

0	1	2	Assigned to cluster
0	0	50	Iris-setosa → Cluster 2
40	10	0	Iris-versicolor → Cluster 0
8	42	0	Iris-virginica → Cluster 1
32%	35%	33%	

All the records of the Iris dataset belonging to the Iris setosa class come together in a single and homogeneous cluster. No point in this cluster shows an ambiguous or fuzzy nature, so none of these points is an outlier. The fuzzy outliers of the dataset are, therefore, to be searched among the records labeled by versicolor tag or virginica one.

B. ECF-means Algorithm Application

Fixing $k = 3$ and choosing the number of iterations $I = 7500$, the performed iterations generate the validity indexes and the statistics of Table XVI, where the o parameter is set to 0.1.

TABLE XVI. VALIDITY INDEXES (7500 ITERATIONS)

Index	Value	Descriptive note
MPC	0.73	If the Normalized Partition Coefficient Index is 1, then the clustering is not fuzzy
Silhouette Index	0.57	An everage Silhouette greater than 0.5 indicates reasonable partitioning of data
TI	0.5	50% of the instances belong to the floor of the Iris dataset; then, the other 50% of the instances have a fuzzy nature
No. of $0.1.FOU$	13	13 elements have $o \leq 0.1$ and they are 0.1-rank fuzzy outliers. From the results of the next tables $o \leq 0.057$
$0.1.FOUI$	0.0867	13/150=0.0867
No. of different partitions	6	The 7500 performed Iterations generate 6 different partitions. The first seeds (s) generating these partitions are: 0, 1, 31, 98, 1794, 5894

EFC-means provides the results in the contingency matrix of Table XVII, where the incorrectly clustered instances are 17 and represent 11.33% of the original Iris dataset.

TABLE XVII. CLASSES TO CLUSTERS ($k = 3,\ I = 7500$)

0	1	2	Assigned to cluster
0	0	50	Iris-setosa→ Cluster 2
47	3	0	Iris-versicolor → Cluster 0
14	36	0	Iris-virginica → Cluster 1
41%	26%	33%	

Thanks to the ECF-means application, we are able to select the floor $\underline{S}$ of whole Iris dataset S. $\underline{S}$ has got 75 elements (TI = 0.5) that have the distributions in Table XVIII.

TABLE XVIII. CLASSES TO CLUSTERS ($\underline{S}$)

0	1	2	Assigned to cluster
0	0	32	Iris-setosa→ Cluster 2
4	3	0	Iris-versicolor → Cluster 0
0	36	0	Iris-virginica → Cluster 1
5.33%	52%	42.67%	

$\underline{S}$ has got 3 incorrected clustered instances that represent 4% of $\underline{S}$.

In conclusion, if $t = 1$, then $|C_0^1| = 4$, $|C_1^1| = 39$, and $|C_2^1| = 32$.

C. Outlier Detection by Applyng ECF-means

The 50 elements in Table XVII tagged by Iris-setosa class are divided in 4 subsets, depending on their probability vectors, which are in Table XIX. The last column of the table contains the difference between the two highest probabilities of the vector (the o parameter).

The 32 elements in the A1 subset belong to the floor of Cluster_2 (Table XVIII) and, therefore, to the $\underline{S}$ set. Although the elements in B1, C1, and D1 do not belong to $\underline{S}$, their probability of belonging to the Cluster_2 is very high (around 79.6%).

TABLE XIX. IRIS-SETOSA PROBABILITY VECTORS (7500 ITERATIONS)

	N. of elements	Clus_0	Clus_1	Clus_2	o
A1	32	0	0	1	1
B1	13	0.204	0	0.796	0.592
C1	4	0.2035	0	0.7965	0.593
D1	1	0.2037	0	0.7963	0.5926

In conclusion, the elements tagged by Iris-setosa class label form the Cluster_2. This result, as we know, does not surprise us, and confirms the goodness of the ECF-means algorithm.

The results obtained by analyzing the other floral classes seem to be much more interesting.

The 50 Iris-versicolor elements have the probability vectors of Table XX. These elements fluctuate between the Cluster_0 and the Cluster_1, and no element is in Cluster_2.

TABLE XX. IRIS-VERSICOLOR PROBABILITY VECTORS (7500 ITERATIONS)

	N. of elements	Clus_0	Clus_1	Clus_2	o
A2	34	0.796	0.204	0	0.592
B2	6	0.5231	0.4769	0	0.0462
C2	4	1	0	0	1
D2	3	0	1	0	1
E2	2	0.7965	0.2035	0	0.593
F2	1	0.5285	0.4715	0	0.057

The elements of A2, C2, and E2 belongs to Cluster_0, without any doubt. In particular, the 4 elements of C2 are in the floor of Cluster_0.

Surely, by analyzing the table, the instances marked by the Iris-versicolor class label are mainly found in Cluster_0, and the floor of this cluster has got only 4 elements, and then they belong to the $\underline{S}$ set.

The 3 elements in D2 are put in the floor of the Cluster_1, but they have the Iris-versicolor label class, and then they are unclustered instances.

The 7 elements belonging to B2∪F2 are 0.057-rank fuzzy outliers, even if their probabilities of belonging to Cluster_0 are greater than the probabilities of belonging to Cluster_1.

The 50 Iris-virginica elements have the probability vectors of Table XXI. Also, these elements fluctuate between the Cluster_0 and the Cluster_1.

In this case, the floor of the Cluster_1 has got 36 instances (to which are added the 3 instances tagged by Iris-versicolor label, retrieved in the Iris-versicolor case, Table XX).

TABLE XXI. IRIS-VIRGINICA PROBABILITY VECTORS (7500 ITERATIONS)

	N. of elements	Clus_0	Clus_1	Clus_2	o
A3	36	0	1	0	1
B3	8	0.796	0.204	0	0.592
C3	6	0.5231	0.4769	0	0.0462

The 8 points of B3 seem to belong to Cluster_0 and then they are unclustered instances.

The 6 elements in C3 are, without any doubt, 0.0462-rank fuzzy outliers.

TABLE XXII. 0.057-RANK FUZZY OUTLIERS OF IRIS DATASET

	El. Num.	Sepal length	Sepal width	Petal length	Petal width
1	52	6.4	3.2	4.5	1.5
2	57	6.3	3.3	4.7	1.6
3	66	6.7	3.1	4.4	1.4
4	71	5.9	3.2	4.8	1.8
5	77	6.8	2.8	4.8	1.4
6	86	6	3.4	4.5	1.6
7	87	6.7	3.1	4.7	1.5
8	124	6.3	2.7	4.9	1.8
9	127	6.2	2.8	4.8	1.8
10	128	6.1	3	4.9	1.8
11	139	6	3	4.8	1.8
12	147	6.3	2.5	5	1.9
13	150	5.9	3	5.1	1.8

Choosing the maximum o in the previous Table IX, Table X, and Table XI, for which the elements are fuzzy outliers, the Iris dataset has got 13 elements that are 0.057-rank fuzzy outliers (B2∪F2∪C3), and they are presented in Table XXII.

D. Invariance Property

Also for Iris dataset we study the property of invariance. First of all, in summary, from the previous application of ECF-means algorithm, we have:

- $|0.057.FOU| = 13$,
- $|Iris - 0.057.FOU| = 137$,
- $|\underline{Iris}| = 75$.

The ECF-means method is invariant for the Iris dataset. That is to say, the set of 0.057-rank fuzzy outliers of $(Iris - 0.057.FOU) = \emptyset$. Not only that, the smallest o value for which we have o-rank fuzzy outliers is $o = 0.552$.

Furthermore, if we consider $\underline{Iris}$, the set of o-rank fuzzy outliers of $\underline{Iris}$ is empty for any value of o such that $o \leq 0.246$. Then, for this case study, $\underline{\underline{Iris}} \neq \underline{Iris}$, but $|\underline{\underline{Cluster\_0}}| = 2$, $\underline{\underline{Cluster\_1}} = \emptyset$, and $\underline{\underline{Cluster\_2}} = \underline{Cluster\_2}$, which confirms the elements labeled by the Iris-setosa class are still preserved by the algorithm.

E. Experimental Results

The 13 0.057-rank fuzzy outliers are labeled by the Iris-versicolor class or by the Iris-virginica one, and not by Iris-setosa class, as reported in the scatter plot chart of sepalwidth, petalwidth space in Figure 7 (left part), where they are marked by boxes in grey color. In particular, 7 fuzzy outliers have the Iris-versicolor class and 6 the Iris-virginica class. They belong to $S - \underline{S}$ and can be analyzed separately in order to understand their fuzzy nature.

Moreover, there are 11 unclustered instances (D2∪C3), but the elements in D2 belong to the floor of the Cluster_1. Finally, the floor of Iris dataset has got 75 points (A1∪C2∪D2∪A3), as reported in Figure 7 (right part); the floor of a set can be easily achieved by scrolling the "Membership Threshold" slider up to 100% in the graphical user interface of the tool, because the floor has got only the elements with the probability vectors equal to $(1, 0, 0)$, or to $(0, 1, 0)$, or to $(0, 0, 1)$.

The charts also show the centroids of the three clusters. The "cross" symbol indicates the Initial Seed Centroid points, whilst the "plus" symbol are the Mean Seed Centroid points. In each cluster, the farther away are the "cross" and the "plus" symbols, the more points are fuzzy (and, therefore, fewer points belong to the floor of the considered cluster).

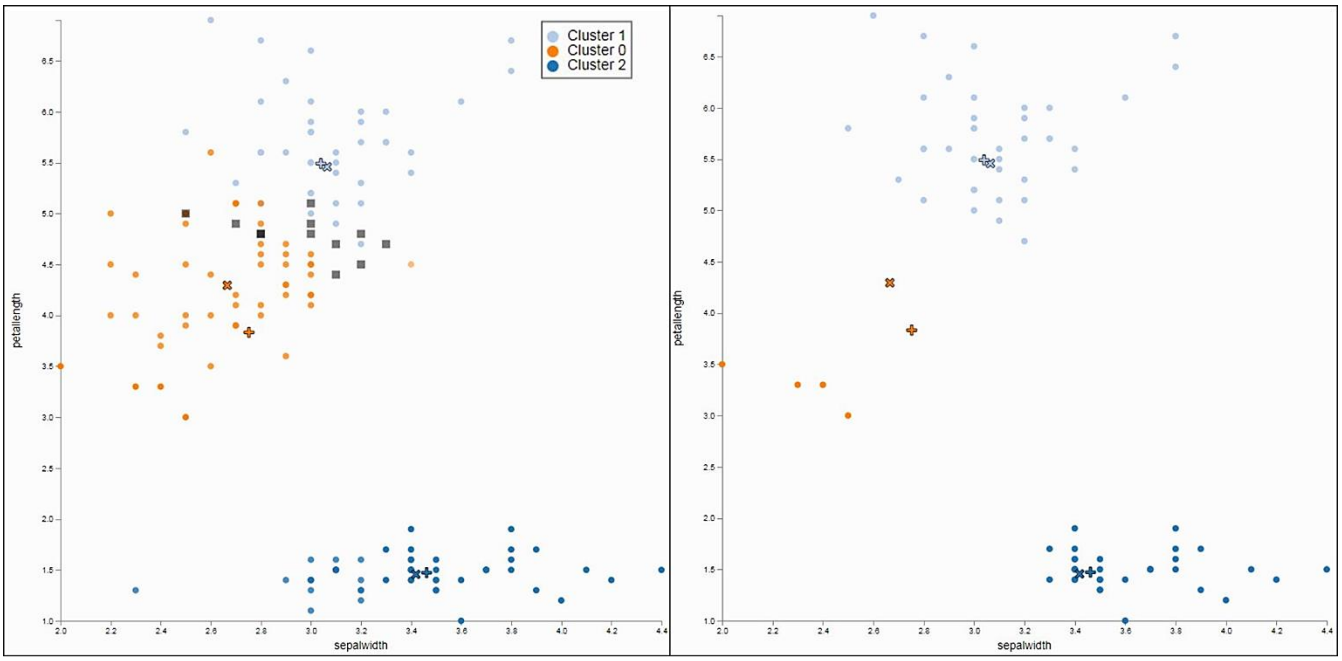

Figure 7. Scatter plot chart of S with 0.057-rank fuzzy outliers in grey (on the left) and $\underline{S}$ scatter plot chart (on the right).

Thanks to the obtained results, we can easily understand how the algorithm is able to optimize the partitioning of the data space with respect to the class that expresses the floral typology. The algorithm is able to find this partitioning in one fell swoop. By applying the simple k-means we may not be able to get the same partition. However, the most interesting result is that the algorithm is able to preserve the cluster with Iris-setosa label and to find the floating elements that are at the limits of the floral types.

These "disturbing" elements can be analyzed separately in order to understand if they are, from some point of view, outliers or records that have undergone measurement errors.

The arithmetic mean of the 13 discovered fuzzy outliers is, for example, $\mu_{13} = (6.277, 3.008, 4.761, 1.67)$ and the arithmetic mean of the distances of the 13 points from μ_{13} is 0.441. Moreover, if you subdivide the 13 points into two subsets, taking into account the two values of the target class, the 7 records with Iris-versicolor value have $\mu_7 = (6.4, 3.157, 4.628, 1.543)$ and the arithmetic mean of the distances of the 7 points from μ_7 is 0.389; the 6 records with Iris-virginica value have $\mu_6 = (6.133, 2.833, 4.917, 1.817)$ and the arithmetic mean of the distances of these 6 points from μ_6 is 0.25.

These measures give us an idea of how the outliers are close to each other, and how they have a low dispersion around the average.

XI. Conclusion and Future Works

In this work we have presented a procedure for detecting outliers or anomalies in large datasets, using the ECF-means algorithm, which is an ensemble method useful for optimizing and "fuzzifing" cluster analysis results. After describing the various types of outliers and the main approaches of data mining for their discovery, in this paper we defined a new category of outliers, called o-rank fuzzy outliers, based on the different degrees of membership of the point to the various obtained clusters.

By using an ad hoc implemented software application and the Weka version of the well-known k-means algorithm, three case studies have been proposed, aimed at showing the strengths of the ECF-means ensemble approach.

In particular, with the tool it is possible:

1. optimize the choice of algorithm parameters, such as the number k of the clusters to be determined, by calculating validation metrics such as the Silhouette, the partition entropy coefficient, and two new metrics that are the threshold index (TI) and the o-rank fuzzy outlier index (o.FOUI), which have been defined for the first time in this work. These new indexes give us a rough estimate of the amount of outliers of the dataset;
2. calculate a degree of membership of each point to each cluster;
3. select the o-rank fuzzy outliers of the dataset as those points that have a fixed level of ambiguity, and also choose the level;
4. view the obtained results using a simple and interactive graphical interface.

The presented case studies showed that the ECF-means algorithm is able to detect more and different anomalies than those discovered by the usual outlier detection methods: these new points are elements that have a high level of ambiguity and which must be subjected to a more in-depth analysis. Being able to assign a level or score of ambiguity to each point is certainly one of the strengths of the proposed method, which is a method for exploring data.

However, we had that all the most exciting results can be obtained by the active interaction with the software tool interface, thanks to which, by scrolling the sliders, changing parameters, and visualizing groupings, numerous properties of the dataset can be discovered.

In future works, we are going to evaluate our method on other several datasets, for example, on others from UCI ML Repository.

Future investigations about the algorithm:

1. to find the relationship between the clusters centroids calculated considering the initial seed ($s = 0$) (the "cross" symbols in the GUI) and those obtained considering the means of the centroids computed over all the N iterations (the "plus" symbols in the GUI), as it was stated in the case study of the Iris dataset;
2. to understand the relationship between the distance among the cross and the plus centroids and the floor of each cluster;
3. to discover a criterion for the o parameter optimization in relation to the other parameters, such as k and N.

Additionally, in order to understand the final configuration, the floor of the analyzed dataset, and the discovered fuzzy outliers, why not train a model by using a machine learning technique, able to predict the probability vector of a point in a test set? The model could be a multivariate and regressive classifier with $k - 1$ output variables, useful to know the level of "ambiguity" of a new and not yet clustered observation.

For the current study, we have chosen the simple k-means as the reference clustering algorithm. Furthermore, we can consider other algorithms in substitution or in addition to it, and this will surely be one of the next improvement of the tool.

Another information that can be very useful to the data analyst is the frequencies of the partitions that are obtained by varying the seed s. This feature, and other statistical computations, will also be added to the next tool update.

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Current Progress in Cross-Platform Application Development

Evaluation of Frameworks for Mobile Application Development

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Abstract — **Cross-platform development is increasingly driven by web frameworks. Modern frameworks typically support application deployment for different platforms as well as the creation of progressive web apps. This approach is also driven by the increasing number of different device types and platforms. Development efforts can be significantly reduced by utilization of modern frameworks. Hence, several modern frameworks that have proven to be suitable for cross-platform development will be compared in this article. This article will extend our previous research on cross-platform development by several dimensions: at first, research on literature and technology developments regarding cross-platform development is extended. Secondly, we added further frameworks into our analysis. Thirdly, the evaluation approach is systematically extended to discuss each framework on an individual basis. This is driven by a reference architecture and implementation. To create a sound and objective framework comparison, the reference architecture is utilized to implement applications by means of each framework. Subsequently tests for different mobile devices and platforms are defined. All frameworks are compared according several key metrics. Finally, we describe current strengths and weaknesses of all approaches before giving an outlook on future steps of research.**

Keywords — cross-platform development; web component; web application framework; progressive web app.

I. INTRODUCTION

This article is an extended version of a former conference publication, see [1] for further details. Mobile devices have become an important platform for today's software applications. Especially, the utilization of smartphones increased rapidly within the last couple of years [2][3]. Since smartphones are often utilized to consume or orchestrate services, this process includes a vast range of applications. Smartphones also connect to other domains such as the Internet of Things (IoT) and often utilize smart cloud-based services [4].

The introduction of smartphones rapidly increased the need and development of mobile software. The development of mobile software applications is a special case of software engineering. Mobile applications are often also referred to as apps, which implies that the application is intended to be used on a smartphone or wearable device [5]. Thus, development must cope with specific aspects such as: short application lifecycles, limited device capabilities, mobility of users and devices, availability of network infrastructure as well as security and privacy issues [6]. The difference in devices also generates a variety of different resolutions and display sizes.

While developers are enacted to create and distribute applications in a large scale, they also have to deal with these inherent differences and limitations of mobile devices (i.e., battery life or small displays). Furthermore, it is necessary to address different operating systems (especially for smartphones, and, to a limited extent, for feature phones as well). Since the market for smartphones has consolidated recently, some operating systems (i.e., Windows Phone, BlackberryOS and other OS hold a market share of 3.2%) vanished again. Still, to address the smartphone market, applications for both, Android (market share: 72.4%) and iOS (market share: 24.4%) need to be provided [7]. In addition, Android is split into different versions, manufacturers and various system customizations. Despite vendor customization and just considering the Android version, current most widely used is Oreo (8.0 and 8.1 with 28.3%), followed by Nougat (7.0 and 7.1 with 19.2%) and finally, the latest version Pie (9; with 10.4%) [8].

In order to reach as many users as possible, applications need to support all major device platforms and versions of operating systems [6][9]. This introduces the need to either develop platform specific or platform agnostic applications. Platform specific implementations (native apps) literally require almost as many application implementations as platforms that are intended to be addressed. Therefore, this approach generates correspondingly high development expenditures. On the other hand, with a more generic approach, a single application or some core components could serve as the basis for multiple platforms. Besides reduced developments efforts, a generic approach also strengthens reuse of code and components.

Currently, generic approaches can be further subdivided into Web and hybrid applications (see Figure 1). Web applications can be used virtually under any platform, as a Web browser is preinstalled on almost all devices. The most salient advantage is application portability, which basically comes at no cost. Web apps are typically optimized by means of Hyper Text Markup Language (HTML5), Cascading Style Sheet (CSS) and JavaScript [10]. Numerous frameworks (such as Angular, Bootstrap, React or Vue) provide additional functionality on top of Web standard technologies and help to speed up development of Web apps.

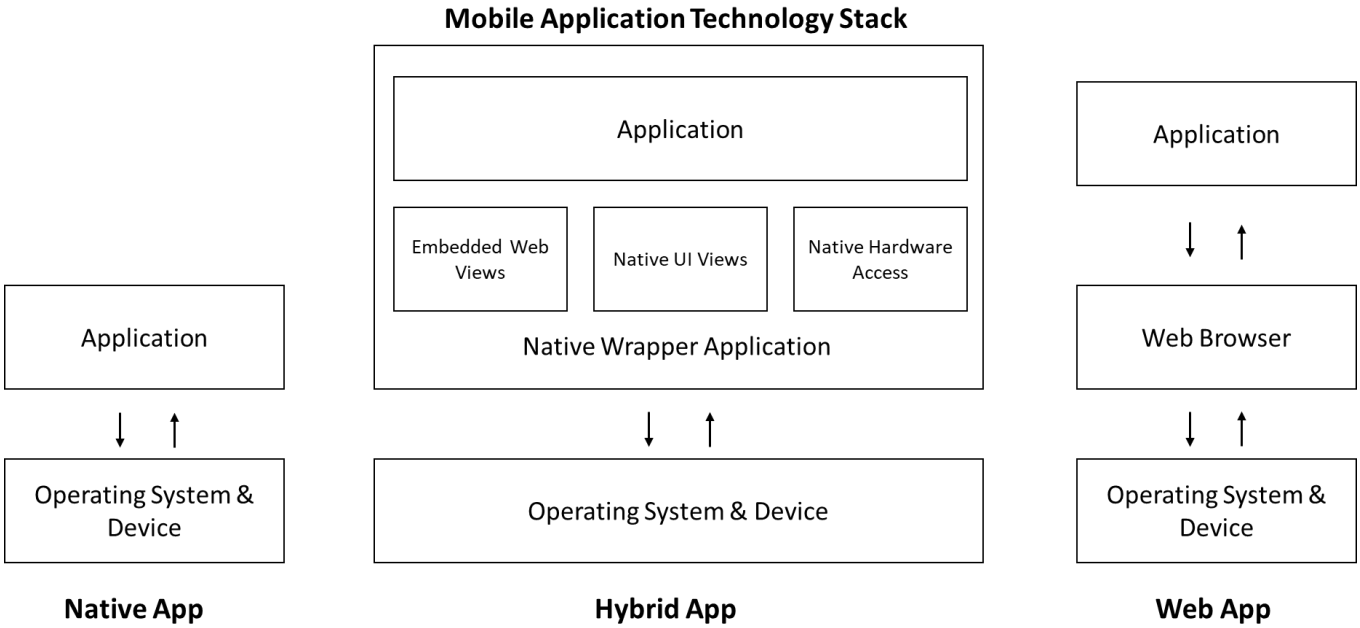

Figure 1: Mobile App Technology Stack.

Major disadvantages of Web applications are that they do not possess platform specific look and feel and often are restricted in functionality – especially access to system functions and device sensors. Furthermore, they must be interpreted and suffer performance losses compared to native applications [11].

Hybrid applications are built on frameworks such as Apache Cordova or Adobe PhoneGap. Often they rely on Web technologies also, and enact access to native device functions and sensors [6]. Hybrid apps utilize a specialized browser to present the user interface (UI). This results in a presentation layer, which is identical or very near to widgets used in native apps. Today's hybrid framework technologies are mainly extensions of Cordova and PhoneGap, as they extend and simplify the development of cross-platform applications. Therefore, the frameworks Cordova and PhoneGap are not included in the evaluation. While hybrid apps overcome some issues of Web apps (such as access to system functions and sensors), they still experience a loss of performance compared to native applications. However, it is notable that performance of hybrid apps has improved a lot with latest developments [6][10]. Comparing the short development lifecycles of devices and operating systems on the one hand to that of hybrid app frameworks on the other, it is noticeable that the latest developments are implemented with delays by the frameworks. As a result, access to new functionalities can be gained earlier when development is based on native apps.

Issues of supported functionality, performance and the generic question of maintenance of cross-platform applications lead us to the evaluation of multiple cross-platform frameworks. With this paper we want to record the current state of the art in the development of cross-platform apps. In addition, we want to uncover innovations and differences that arise with the deployment of new frameworks and versions. We achieve this with our reference app. The remaining parts of this article are structured as follows: First, Section II introduces the literature research method. This work can be seen as a starting point for further work on the article. Section III provides an overview of current mobile app development. In Section IV, a reference architecture is presented and five framework-based implementations of this architecture are discussed. The reference implementations are being evaluated in Section V. Finally, Section VI outlines the conclusion and outlook for further research.

II. LITERATURE RESEARCH

A comprehensive literature research was initiated to identify significant literature on the topic of cross-platform development and cross-platform frameworks. In addition, important scientific articles from the same field of research should be identified, which will form the basis for the later main part of the article. For this purpose, the proven literature research of Brocke et al. [12] was used. A five-phase model is defined by Brocke et al., which enables a systematic literature search. In the process, they combine approaches from Cooper [13] and Webster & Watson [14] . The method, the five-phase process is shown in Figure 2.

A. Definition of review scope

Phase I defines the different characteristic values of literature research. We apply the taxonomy of Cooper [13] in this phase as a basis. The applied taxonomy according to Cooper is explained below and also shown in TABLE I. The focus of

this article is on research outcomes in the area of cross platform technologies. In addition, the practical application of these technologies plays an important part in our research. If the technologies in focus are not applied in a broad common sense, they might lack in one or more aspects (e.g., they are just not well-known, they are error prone, they do not offer simplified multi-platform deployment, they do not support well supported programming languages or constructs or they are simply not applicable to specific project requirements).

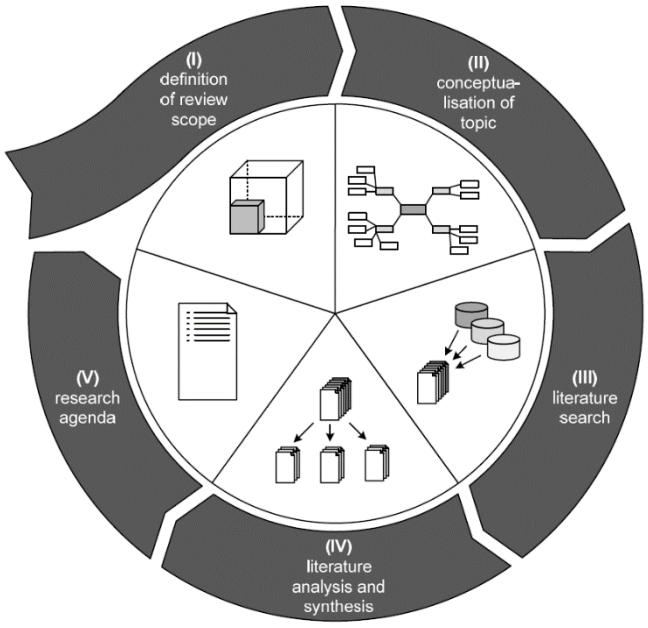

Figure 2: Literature review framework used for literature research according to Brocke et al. [12].

The goal of our work is to answer central questions on cross-platform development. We intend to do so by analysing different cross-platform frameworks and comparing them with each other. In a broader sense, the organisation of the work is to be characterised as conceptual. The different frameworks are described individually and compared step by step. The perspective of the authors is classified as neutral. The authors intend to provide the reader with a no-obligation perspective and to perform the subsequent tests from a neutral perspective. The article is aimed at general scholars who are interested in the cross-platform concept and also want to acquire knowledge about the existing frameworks and their distinctions. In addition, practitioners dealing with cross-platform development will be addressed. The underlying literature research does not claim to be exhaustive, because of its topicality in this thematic area. Therefore, a short overview of the current state of research is given, with the aim of a central literature search, which focuses on the above defined topics.

TABLE I: APPLIED TAXONOMY OF COOPER [13].

Characteristic	**Categories**			
(1) Focus	Research outcomes	Research methods	Theories	Applications
(2) Goal	Integration	Criticism		Central issues
(3) Organisation	Historical	Conceptual		Methodological
(4) Perspective	Neutral representation		Espousal of position	
(5) Audience	Specialised scholars	General scholars	Practitioners / politicians	General public
(6) Coverage	Exhaustive	Exhaustive and selective	Representative	Central/ pivotal

B. Conceptualisation of the topic

In Phase II, the conceptualization of the cross-platform development topic field is carried out. In the current work, this is done on the one hand by brainstorming and on the other hand by systematic mapping of topics on a canvas, which supported the research team in developing a common standpoint on the topic analysed. In addition, initial concepts were identified, which will then be searched for within the scope of the third phase.

C. Literature search

Phase III describes the procedure for literature search. In this section, the reader has the opportunity to gain insights into the authors' systematic approach.

The framework conditions are set at the beginning. Therefore, the key terms are defined as follows. The literary search uses two keyword strings. The first keyword string is "cross-platform development", the second search string equals "cross-platform frameworks". The string was searched in English language.

Furthermore, the media types are defined on the basis of Brocke et al. [12]. The sources of the current research consist of the latest journal and conference articles as well as web documents. The aim of this selection is to identify the main findings on the state of scientific research. Different databases are selected for the two source types. Peer-review articles in journals or conferences are found in current databases such as ScienceDirect, Emerald Insight and especially through the Google Scholar search engine. Web documents have been investigated by the search engine Google.

The next step is to perform the electrical search. In addition to the keyword-string entered, the search settings in the database for articles are set to journals and conferences and the web search is focused on documents. In addition, the last three years are taken into account. The first 20 hits of all types of researched publications are considered, which are sorted in advance according to relevance.

According to later findings, the search was extended to the five specific frameworks Ionic, Xamarin, React Native, Oracle Jet and Flutter. The same search process was used for these five concepts.

D. Literature analysis and synthesis

Phase IV comprises the literature analysis and synthesis of the collected works. This is done through a multi-level filtering approach to obtain the final list of documents relevant to the following activities. These steps apply to the two media types from the previous section.

The first type of filter refers to the title that has been published. The presence document must refer to the keyword string. If this requirement is fulfilled, the literature will continue to be considered. Secondly, abstraction is examined. There, the existing literature must contain elements of the keyword string. If this requirement is also met, the literature will be considered further. The full text is then filtered. If the document contains or refers to the contents of the keyword string, it is included in the final selection. The final step is the redundancy analysis, which eliminates redundant entries from journals and Internet documents.

Afterwards, the relevant literature is then transferred to a spreadsheet in, which the results are first classified according to the following criteria: author, title, publication type, year of publication, language, publisher/journal and found database/search engine. In the next step, the works were examined for their relevance in terms of content. The spreadsheet is converted into a so-called concept matrix according to Webster & Watson [14]. The identified focal points and concepts for cross-platform development and cross-platform frameworks are added to the spreadsheet. The concepts are assigned to the individual documents in the form of crosses. As a result of this step, the concept matrix can be used.

E. Research Agenda

Finally, Phase V aims to identify topics within the so-called Research Agenda. These topics are under-represented in the identified literature. This allows a recommendation; which concepts should be part of future research. Further fields of research are addressed in section VI Conclusion and Outlook. Based on the identified documents, the main focus will mainly be on the cross-platform frameworks. In other words, which of the identified frameworks are particularly useful for the suitability of mobile applications? As a result of Section II, the identified works will be presented in an additional step. This will be addressed as status quo of cross-platform development hereafter in Section III Related Work.

III. Related Work

This section covers different solutions and technologies which enable fast and efficient cross-platform-development of applications.

A. Cross-Platform Development

As stated above, there are several approaches for cross-platform development. This type of development is subject to typical challenges of ubiquitous computing. In addition, further challenges are typical to cross-platform development [6], [15], the most important issue being associated with:

1. User Interface (UI)
2. Limited Resources
3. Device Management
4. Application Maintenance

The design of UI is associated with questions of simplicity and intuitiveness. For mobile cross-platform development, this is extended by design guidelines defined by the different operating systems. It is further restricted because of different device capabilities (e.g., screen sizes and resolution) [16]. Limited resources is a typical issue in mobile software engineering; for cross-platform development the application size and resource consumption (especially power and memory management) is a typical issue [6][17]. Since cross-platform development addresses a vast variety of devices, their management in terms of appropriate usage of hardware and sensors (i.e., CPU, memory, Bluetooth, or camera) becomes another typical challenge. Furthermore, different operating systems must be handled as well. Finally the application has to be maintained by following short lifecycles of devices, operating systems and frameworks [6][16].

A lot of different methods that address cross-platform development can be observed in science and industry. Some are based on model-driven software engineering [18]. The advantage of model-driven methods is that developers and users, which are less familiar with specific programming paradigms are enabled to efficiently implement applications. As Object Management Group (OMG) standard, the Interaction Flow Modeling Language (IFML) offers model-based and platform-independent development of applications for different types of devices. Following the Model-Driven Architecture (MDA) it is based on a meta-model and it is built upon Web Modeling Language (WebML). A Web-based and an eclipse-based modelling environment is provided for IFML. Furthermore, extensions for Apache Cordova and PhoneGap are provided [18][19]. An open challenge is to keep the extensions up-to-date. Other solutions, such as WebView, utilize native code and combine it with Web technologies. Native components are used as containers to render Web pages that contain application logic and presentation layer definitions. Native components serve to access device-specific functions (i.e., push notifications or sensor data). Although WebView is a native application, it can internally use Web technologies without switching to a standard browser. WebView also supports CSS and JavaScript for custom interface development [11]. However, WebView does have two main drawbacks: 1) custom styling is necessary to gain a native look and 2) its performance is below average [20]. In summary, we observe three general approaches to cross-platform development:

1. Native application
2. Transformation- or generator-based application
3. Interpreted application (parser-based)

With native development, an application is developed for each specific device (and operating system). Benefits include the native look and feel, the ability to use all platform-specific features and a comparatively high performance of the app. The most prevalent disadvantage is high efforts for development and maintenance.

TABLE II: COMPARISON OF FRAMEWORK POPULARITY [21].

Source	Unit	Ionic	Xamarin	React Native	Oracle Jet	Flutter
StackShare	Stacks	2.360	461	3.880	N/A	105
	Fans	2.310	549	3.740	N/A	156
	Jobs	98	47	726	N/A	5
	Votes	1.660	646	821	N/A	49
Hacker News	Posts	669	995	917	8	N/A
Reddit	Posts	989	1.080	N/A	55	1.080
Stack Overflow Stats	Posts	4.430	35.000	45.100	280	9.890
GitHub Stats	Stars	36.700	N/A	73.200	295	51.400
	Forks	12.800	N/A	16.200	81	5.360

The latter is a result of redundancy in code and support because each platform has to be served by a separate application [11][15].

The use of generators employs a meta-implementation, which is then transformed to specific platforms (e.g., as used in Cordova or Ionic). Similarly, model-driven development approaches (such as IFML) may use transformations to produce platform specific code. An advantage is that the application logic is platform agnostic [18]. Applications, which are interpreted rely on some kind of parser. The parser interprets application code during runtime in order to create platform specific instructions. Fabrik19 utilizes an interpreted approach in its Mobility Suite (MOS) framework.

B. Cross-Platform Frameworks

As discussed above, there are a lot of cross-platform frameworks like IFML, Cordova, Corona Software Development Kit (SDK), Appcelerator Titanium, TheAppBuilder, PhoneGap, Native Script, SenchaTouch, Framework7, Apache Weex, Flutter, Oracle Jet, Jasonette or Manifold – also see [9]. All of them utilize one or a combination of the three methods to create platform specific applications. In our evaluation we also regard the popularity of the different frameworks. We consider communities like StackShare, Hacker News, Reddit, Stack Overflow Stats as well as GitHub Stats. In our comparison, we strive to evaluate the most frequently used and most progressively developed frameworks as illustrated in TABLE II.

Ionic offers a generator-based approach [22]. The framework is free to use and available as open source. Additionally, several services are available via pay on demand. The generator utilizes a Web application as input. Thus, development of cross-platform applications is based on Web technologies (JavaScript/TypeScript, HTML5 and CSS; see Figure 3). Ionic also relies on Angular [22] in order to foster component based development and reuse of templates. Ionic officially supports Android, iOS and Universal Windows Platform (UWP) [23]. Since Ionic is based on Web applications that are generated into platform specific applications through Apache Cordova, these source applications may also be executed in any Web browser. Native operating system functions and access to sensors is only available after generation of platform specific code. The utilization device specific functionalities often also rely on plugins that have to be declared as dependency [19].

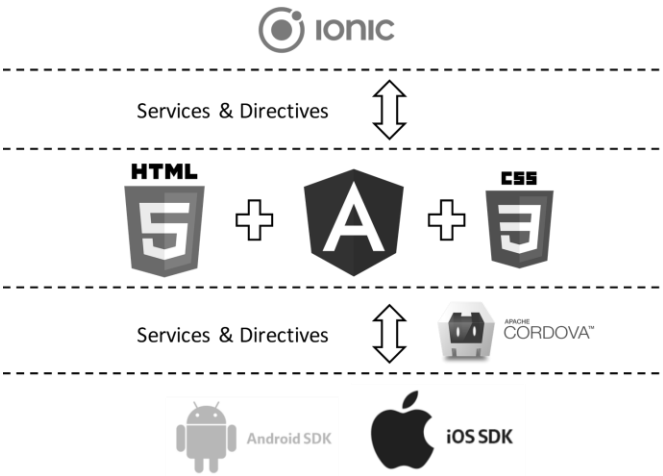

Figure 3: Ionic Architecture [23].

Xamarin is another framework to develop cross-platform apps for Android, iOS and UWB [24]. Other platforms such as Linux are not supported and macOS support was recently added with the launch of Xamarin.Mac.

Xamarin is based on .Net and utilizes C# as programming language. Xamarin is divided into two major parts: 1) Xamarin platform and 2) Xamarin.Forms. The Xamarin platform (Xamarin.Android, Xamarin.iOS) provides APIs to share code for application logic between all platforms. The UI is written individually for each platform. Xamarin.Forms allows to create additional platform-independent UI, which are mapped into native UI in a second step (see Figure. 4). The

development environment is based on Visual Studio (or Xamarin Studio for macOS) [24].

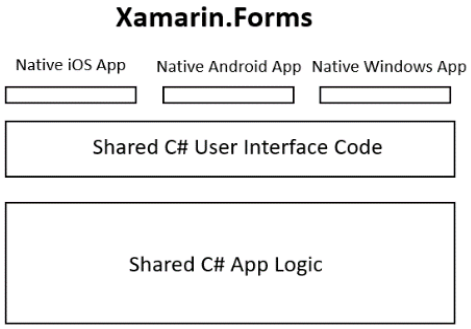

Figure 4: Xamarin Architecture [24], [25].

React Native is a parser based open-source framework for building cross-platform applications [26]. It is based on React. Both frameworks are being developed by Facebook. React Native currently supports Android and iOS and uses a NativeScript Runtime environment to execute the application code (see Figure 5). However, with a little more effort, it is also possible to deploy to UWP. Since React is built on JavaScript, this holds true for React Native as well. React Native invokes Objective-C APIs to render to iOS components and Java Application Programming Interface (APIs) to render to Android components. This means that no code generation is utilized in React Native. Facebook promises that the performance of apps would be almost as good as that of native applications. Components for React Native may either be built as functional components or class components [26].

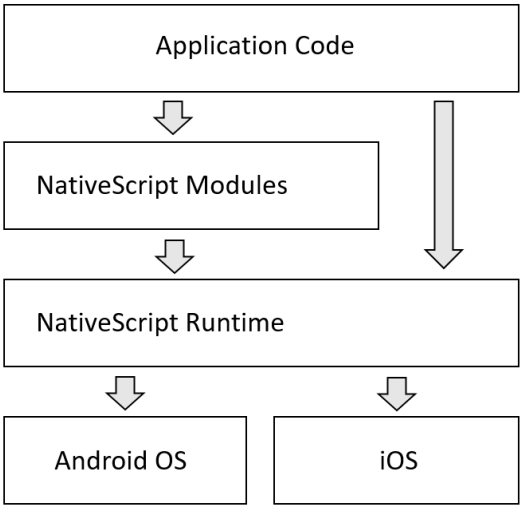

Figure 5: React Native Architecture.

Oracle Jet follows a similar philosophy as Ionic and was developed in the software house Oracle. The framework and its tools are freely available as open source. Oracle Jet also uses the generator-based approach. Web technologies (JavaScript, Knockout, jQuery, HTML5 and CSS, etc. see Figure 6) are used for the development. Platform-specific versions can be derived from the web application. Apps for Android, iOS and UWP can be officially released. Also, an execution in the browser is possible without further ado, particularly since the application is converted by means of Web technologies. For the use of platform-specific sensors, Cordova plug-ins must be used [27][28].

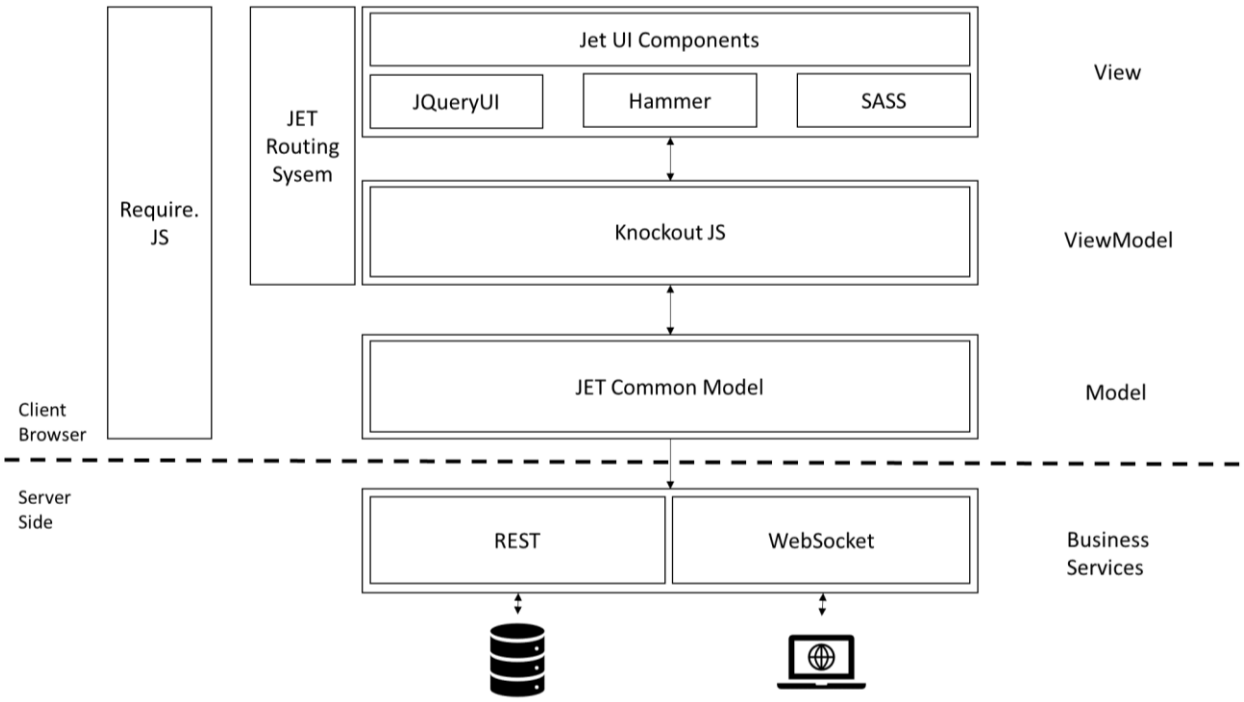

Figure 6: Oracle Jet Component Architecture [29].

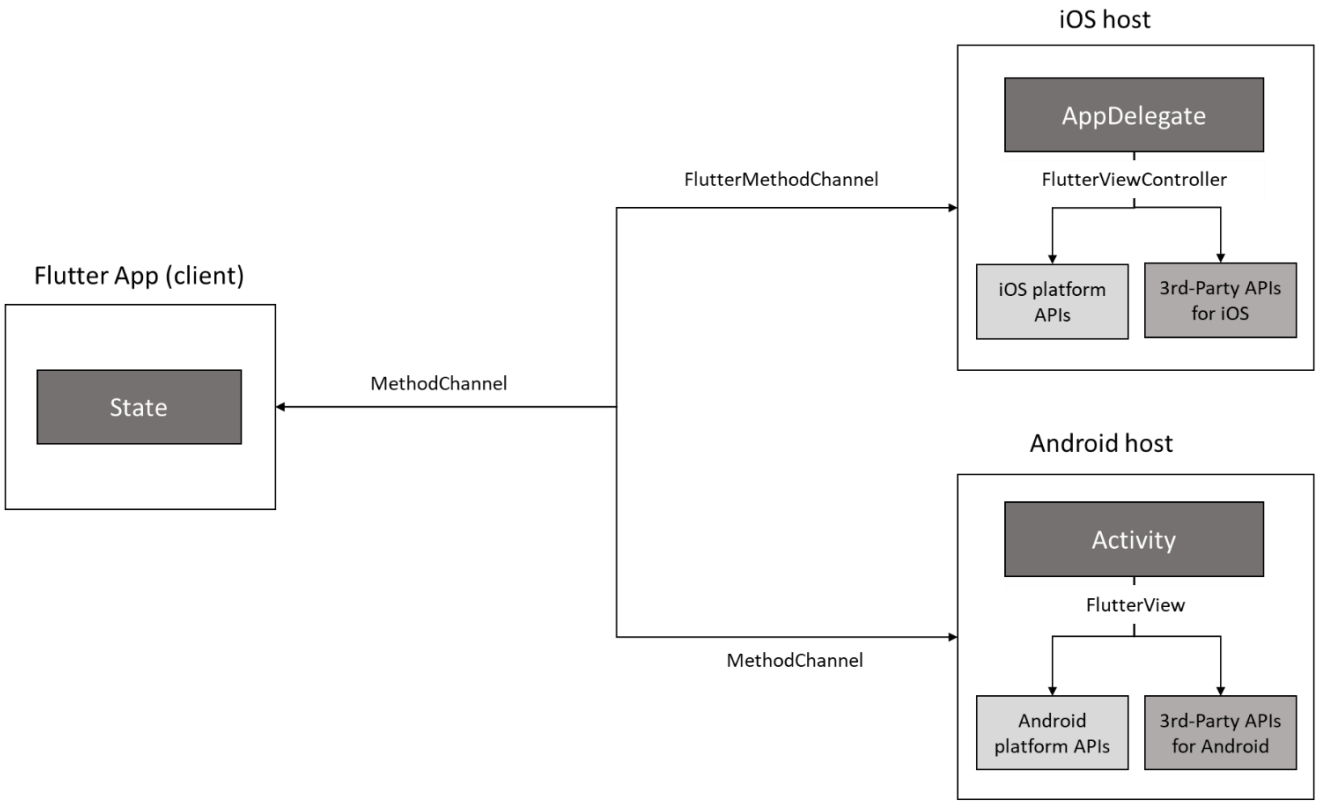

Figure 7: Flutter Architecture.

Flutter is a parser based, open source SDK, which offers an easy way to develop high-fidelity and high-performance mobile apps for android and iOS. Flutter uses a rich set of Cupertino (iOS) and Material Design behaviours and widgets. Furthermore, Flutter implements platform-specific code like navigational patterns, fonts and more. Flutter apps are written in Dart. Its syntax looks a lot like Java, JavaScript, C# or swift. Dart uses the standard Android and iOS toolchains to compile your code [30]. Flutter does not separate views, controllers, layouts and other properties like other frameworks. It uses one consistent, unified object model, so called widgets. Widgets can define structural elements (like buttons or menus), stylistic elements (like fonts or colour schemes, aspects of layouts (like margins) and so on [31]. Messages between the client (UI) and the host (platform) are passed using platform channels as illustrated in Figure 7. These messages and their responses are passed asynchronously. This way the user interface will remain responsive.

IV. Reference Architecture and Implementation

This article follows the constructivist paradigm of design science [32]. Thus, insights will be retrieved by creating and evaluating artefacts in the form of models, reference architectures and, in our case, specific implementation variants and efforts spent on their creation. Contrary to empirical research, the goal is not necessarily to evaluate the validity of research results with respect to their truth, but to the usefulness and feasibility of the different approaches in order to solve a common problem – here, to deploy with ease to different mobile platforms. Following this line of thought, requirements will be imposed by the definition of a reference application architecture. The reference architecture is derived using common hypotheses, practitioner interviews and literature review. The reference architecture serves as requirements model for the implementation of different alternatives and tests in a real environment.

Thus, the reference application architecture is defined to compare most utilized frameworks against each other and to identify strengths and weaknesses. To enact a comprehensive comparison [9][33], the application should access native system functionalities and provide a platform specific UI. In short, the frameworks should generate applications, which are close to native applications. Thus, we also evaluated against platform specific UI guidelines for Android and iOS [34]. We defined the following functional reference criteria:

1. Layout: Grid
2. Layout: Tab
3. Operating System Function: Access current time
4. Sensor Function: Access current position (GPS)
5. Sensor Function: Access the phone camera

In addition to functional criteria, it is also important to measure quality aspects, such as development efforts and application performance. Therefore, we analysed two different types of layouts mentioned in the list above, which are often used in today's apps – Mock-ups are depicted in Figure 8,

which serve as system templates for the reference app. Three tabs can be used to test the system time, GPS and camera functions.

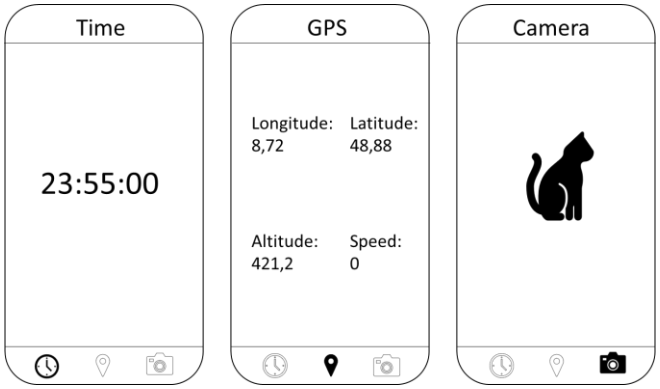

Figure 8: Wireframes.

A. Ionic

Layout – Grid: Ionic provides a typical Grid-View with the `<ion-grid>` component [23]. Furthermore, styling of the GridView can be set individually. **Layout – Tab**: Using Tabs in Ionic is easy as wall, it may be just derived by use of the starter template (which provides this from scratch). Precise instructions may also be found in the documentation [23].

Access system time: This is derived by simple and built-in JavaScript function calls (e.g., date().getHours() is used to get the current hour). **Access current position (GPS)**: To determine the position, the Cordova plug-in Geolocation has to be installed via npm. Then, it can be integrated in the project [23]. As shown in Listing 1 the position can be retrieved, if the necessary sensors are available and permissions are given. **Access to the camera**: To use the camera, the Cordova plugin Camera is required and has to be integrated into the project [23].

Listing 1

```
getThePosition(){
   this.geolocation.getCurrentPosition().
      then((resp) =>{
         this.longitude = resp.coords.longitude;
         this.latitude = resp.coords. latitude;
         this.altitude = resp.coords. altitude;
         this.speed = resp.coords. speed;
   }).catch((error) => {
      console.log("Error getting location",
error);
   });
}
```

Debugging & testing: Ionic offers several methods to debug and test apps. If the application is not utilizing sensor information, a clean Web test can be driven (by `ionic serve`). Web tests may be carried out as known for Web applications in general – such as debugging by means of the browser's developer console (`F12` shortcut) or employing Web driver test scripts. If sensor information is utilized the application has to be deployed to a platform specific device or an emulator. With Ionic this can be done by calling `ionic cordova build android|ios` to build the app and `ionic cordova emulate android|ios` to execute the app on an emulator. If a test device is being utilized instead of emulation (by calling `ionic cordova run android|ios`) the application may again be tested in a browser, e.g., using Google Chrome (`chrome://inspect/#devices` has to be called and the specific device has to be selected). In order to automate unit testing typical tooling as known for other JavaScript-based frameworks can be used. To test the reference implementation, we could simply employ the well-known frameworks Karma and Jasmin. The application source code is publically available via GitHub, the repository URL is:

https://github.com/futureLABHsPforzheim/ionic_blog_prototype.git

B. Xamarin

Layout – Grid: In Xamarin the layout differs, depending on the chosen platform. For Android `GridView` and for iOS `uicollectionview` has to be used [24]. **Layout – Tab**: In Xamarin tabs have to be set up manually. There is no standard template available to support this layout. Typically, a tabbed page will be used to reference other content integrated as tabs.

Access system time: To retrieve the system time, a `ViewModel` is created, and a `DateTime` attribute tracks the current time. For updates a `PropertyChanged` event is fired. The reference is made possible by the data binding. **Access current position (GPS)**: The current position is determined by the plugin `Xam.Plugin.Geolocator` [24] (installed via NuGet). Adjustments are needed to support Android. In addition, necessary privileges for querying the position must be granted. After configuration, the logic can be implemented. Attributes for longitude and latitude have to be mapped to determine the location (see Listing 2). **Access to the camera**: Camera access is realized with the plugin Xam.Plugin.Media [24]. It has to be configured by means of xml. In important step is the definition of a resources folder to determine where to store captured pictures and videos. The camera itself can be called asynchronously (`getTakePhotoAsyncCommand`).

Listing 2

```
public async System.Threading.Tasks.Task
   getLocationAsync()
   {
     var locator = CrossGeolocator.Current;
     locator.DesiredAccuracy = 50;
      if (locator.IsGeolocationAvailable &&
             locator.IsGeolocationEnabled) {
               var position = await
                 locator.GetPositionAsync();
               this.Longitude="Longitude" +
                  position.Longitude.ToString();
               this.Latitude="Latitude" +
                 position.Latitude.ToString();
      }
   }
```

Debugging & testing: Xamarin enables unit testing and debugging with Visual Studio. For Xamarin, Visual Studio basically offers the same mechanisms as known for any other component, which is developed within Visual Studio (such as break points and live debugging). Visual also offers support for asynchronous testing and mock object creation, e.g., if the Model View Viewmodel (MVVM) pattern is applied and view models invoke service operations asynchronously.
Visual Studio also provides a well sophisticated profiler, which provides monitoring of memory utilization and object allocation. Finally, Xamarin also offers also a test cloud for UI-Tests – where automated testing for native and hybrid applications is done by employing the App-Center. The source code of the Xamarin-Reference-App is publically available via GitHub, the repository URL is:

https://github.com/futureLABHsPforzheim/xamarin_blog_prototype.git

C. React Native

Layout – Grid: React Native does not provide a grid layout immediately. To resemble a grid-layout within the reference implementation, a ScrollView component was used and individual views had been adapted by means of CSS. Alternatively, third-party grid components could be utilized as well to resemble a grid layout. React Native Easy Grid and React Native Layout Grid are just two examples of these components, which may be installed via npm. **Layout – Tab**: React-Native Expo IDE can create a starter app, which directly operates with tabs. Manual creation is not as easy as in Ionic but efforts are still considerably low.

Access system time: Is achieved by simple JavaScript calls. `this.state` [26] is needed for the databinding and `new Date().getHours()` retrieves the current hour. **Access current position (GPS)**: The determination of the current position is already integrated in the React Native API [26]. The position is retrieved by calling `navigator.geolocation.getCurrentPosition`, further details can be seen in Listing 3. **Access to the camera**: Camera and access rights have to be configured and `hasCameraPermission` has to be set to zero. The `componentWillMount` method the permissions are checked and we the status is updated. The asynchronous method `takePicture` is utilized tJano check if the camera is available and if it was possible to take a picture.

Listing 3

```
Navigator.geolocation.getCurrentPosition(
   (position) => {
      this.setState({
         latitude: position.coords.latitude,
         longitude: position.coords.longitude,
         error: null,
      });
},
(error) => this.setState({ error: error.message }),
{ enableHighAccuracy: true, timeout: 20000,
maximumAge: 1000},
);
```

Debugging & testing: React Native similarly offers multiple ways to debug and test apps. Debugging mode can be activated from a developer menu. This can be called by keyboard shortcuts or, if running on a test device, by shaking the smartphone. To debug the JavaScript code in Chrome, a remote debugging session can by created when select `Debug JS Remotely` is selected from the developer menu. This will open `http://localhost:8081/debugger-ui` in a new browser tab. Other debugger implementations may be used as well and a recommendation then would be to use the standalone version of React developer tools. These can be installed via `npm install -g react-devtools` and may be called via `react-devtools`. To set up unit testing for React Native it is recommended to utilize Jest and execute tests via node. For integration testing, several different options exist. Integration testing always relies on platform specific environments; thus, those have to be set up first. The application source code is publicly available, the repository URL is:

https://github.com/futureLABHsPforzheim/react_blog_prototype

D. Oracle Jet

Layout – Grid: Oracle Jet offers several components for displaying data. With the tag `<oj-data-grid>` data can also be displayed in a GridView. **Layout – Tab**: Oracle Jet offers ready-made templates for tabs that can be reused. An independent implementation can be done by using the tag `<oj-tab-bar>` in combination with a `<ul>` [27].

Access system time: Oracle Jet also uses JavaScript technologies, so the time query is similar to Ionic (`date().getHours()`. **Access current position (GPS):** Oracle supports the use of Cordova plug-ins. After installing the Cordova plugin Geolocation, it can be integrated into the project. As can be seen in Listing 4, the values are stored in variables latitude and longitude after a successful determination of the location. **Access to the camera:** In Oracle Jet, the Cordova Camera Plugin can be used to provide camera functionality. In order to use the camera in Oracle Jet, an appropriate authorization must be granted.

Listing 4

```
self.getMapLocation = function (info) {

    navigator.geolocation.getCurrentPosition
        (onMapSuccess, onMapError, {
            enableHighAccuracy: true });
        };
        var onMapSuccess = function (position) {

        self.latitude(position.coords.latitude);
        self.longitude(position.coords.longitude);
    };
```

Debugging & testing: Oracle Jet applications can be examined with any browser. In our development environment we used Chrome for debugging. As soon as the application was started with `ojet serve ios|android|windows -browser`, debugging in the local browser is possible. Debugging on an emulator or a physical device is also possible. The commands `ojet serve ios|android|windows -emulator` and `ojet serve ios|android|windows -device` are used

for this purpose. As soon as the app is started, it can be examined in the browser. Chrome offers a selection of available devices via `chrome://inspect/#devices`. Thus, console outputs, network communication, memory utilization etc. can be examined. To test the application and its functionality, different frameworks can be used that are JavaScript compatible. Oracle itself uses QUnit [27]. The source code is publically available via GitHub, the repository URL is:

https://github.com/K1ngdan1/JetRefApp.git

E. Flutter

Layout – Grid: To use the GridView in Flutter with Dart you define a new GridView.count(). CrossAxisCount defines the amount of children in a Row and childApsectRatio their size, both spacing options define how much space is between the grid items, which are defined by children. Here children attribute is filled with a list of widgets (see Listing 5).

Listing 5

```
return new Container(
      margin: const EdgeInsets.only(top: 200.0),
      color: Colors.white30,
      child: new GridView.count(
          crossAxisCount: 2,
          childAspectRatio: 1.0,
          padding: const EdgeInsets.all(4.0),
          mainAxisSpacing: 4.0,
          crossAxisSpacing: 4.0,
          children: widgets),
    );
```

Listing 6

```
return Scaffold(
      appBar: AppBar(
        title: Text('Colla Test App'),
        elevation: 0.7,
        bottom: new TabBar(
          controller: _tabController,
          indicatorColor: Colors.white,
          tabs: <Widget>[
            new Tab(icon: new Icon(Icons.timer)),
            new Tab(icon: new
                    Icon(Icons.location_searching)),
            new Tab(icon: new
                    Icon(Icons.camera_alt)),
          ],
        ),
      ),
      body: new TabBarView(
        controller: _tabController,
        children: <Widget>[
          new Time(),
          new Gps(),
          new Camera(widget.cameras),
        ],
      )
    );
```

Layout – Tab: Dart defines Tabs with a widget named TabBar, which creates the look of the Tab Bar. To use the TabBar a TabController is needed to pass different options e.g., the amount of tabs to the TabBar. The TabBarView creates the functionality for the GridView (see Listing 6) [35]. **Access system time:** To access the system time new DateTime.now() is called. **Access current position (GPS):** To access your location you first need to import the package location. Then define a new variable and initiate it (see Listing 7).

Listing 7

```
Location _location = new Location();
StreamSubscription<Map<String,double>>
    _locationSubscription;
```

As illustrated in Listing 8 it can then be listened to the OnLocationChanged method, which returns the current location [36].

Listing 8

```
_locationSubscription=
_location.onLocationChanged().listen((Map<String,
double> result) {
      setState(() {
        lng = result["longitude"];
        lat = result['latitude'];
        alt = result['altitude'];
        speed = result['speed'];
      });
    });
```

Access the camera: First the camera package needs to be imported and I must be verified if a camera is available (see Listing 9).

Listing 9

```
List<CameraDescription> cameras;
cameras = await availableCameras();
```

Afterwards it is mandatory to pass the found camera and the desired resolution to the controller (see Listing 10).

Listing 10

```
controller = new CameraController(widget.cameras[0],
ResolutionPreset.medium);
```

The asynchronous method takePicture then lets the user take a picture and return its file path (see Listing 11) [36].

Listing 11

```
await controller.takePicture(filePath);
return filePath;
```

The source code of the Flutter-Reference-App is publicly available via GitHub, the repository URL is:

https://github.com/futureLABHsPforzheim/flutter_blog_prototype.git

V. FRAMEWORK EVALUTION

The evaluation and comparison of all frameworks is based on the reference architecture and the implementation of the corresponding test app. We selected several evaluation criteria based on the evaluation framework developed by Heitkötter et al. [37]. The aforementioned covers different evaluation criteria, especially for infrastructure (including the lifecycle as well as the functionality and usability of the app) and app development (including testing, debugging and developing the app). We also extended and removed some criteria (e.g., scalability). Hence, we base the evaluation on the following application properties:

1. Supported platforms
2. Supported development environment
3. Access to platform-specific functions
4. Application look and feel
5. Application portability
6. Simplicity of development
7. Application performance

At first, it is important, which platforms (Android, iOS, UWP, etc.) and to which extent these are supported by each framework. The next criterion discusses all possible development platforms and environments (Windows, MacOS and Linux). With the help of our test app we intend to analyze if platform-specific functions are available. Also, an evaluation of the UI is conducted to measure platform specific look and feel. Moreover, we want to unveil if the source code is reusable and if it can be integrated into other frameworks (portability). Also, the development efforts play a major role and will be evaluated within criterion 6. In order to assess and evaluate efforts and feasibility of the frameworks, we asked five experienced developers to implement our test application according the reference architecture. The following evaluation is also based on their feedback. Finally, we conducted an assessment of the application's performance. Therefore, the test app is used to measure: start time, used memory and execution speed of internal functionalities such as GPS polling. For this purpose, three test devices (Honor 9, Sony XZ1, Samsung Galaxy S7, IPhone 8) were used. The specifications of the test devices are listed in TABLE III. In order to stabilize test results, 100 test runs were conducted for each device. The following subsections will outline our observations for each framework individually. Finally, this section is concluded by a comparison of all frameworks.

A. Ionic

Configuring a system for Ionic and creating a first app only takes a few minutes. Regarding ramp up, the majority of our developers found that Ionic is the easiest framework to start with. It has to be mentioned that it is necessary to ensure that all dependencies (to plug-ins) are installed according their declared version. This can be error prone, especially when Ionic is updated. In case of multiple app development projects, conflicts may also arise between dependencies of different projects. Hence, previously deployed Ionic projects should be removed from the test device to prevent side effects during testing. As a prerequisite to start and develop Ionic applications only knowledge in the typical Web development stack (HTML, JavaScript and CSS) is required. TypeScript as an extension of JavaScript and thus is easy to learn if JavaScript is already known. TypeScript provides additional benefits compared to JavaScript (especially type safety) – some extension have been adopted into ECMAScript-6 (such as classes, inheritance or generics) [38].

In addition, Ionic reuses Angular, which makes it easier to keep the code clean, separate concerns and speed up development of the application itself. The project structure in Ionic is logically well structured according to Web component architecture. Since Ionic relies on Web technologies, the user is free to choose the development environment [23]. The use of Cordova is another advantage, especially because it enables access to system specific functionality and device sensors. Furthermore, Cordova improves re-use of application components, since a single code base can be utilized for all platforms. However, since Ionic is based on Web-technologies and packaged into native wrapper applications, the performance is behind native applications. Former evaluations also indicated that the performance is behind Xamarin and React Native, especially for larger applications [20].

B. Xamarin

Xamarin projects can be set up in Visual Studio. With the use of C#, Xamarin is the best choice for developers, who also work conventionally with C#. Another advantage is the native UI [24]. Users will not recognize any difference to native applications. Xamarin offers to share a single code base between platforms, to develop application logic. Platform specific extensions may be integrated with a subproject feature of Xamarin. As for all cross-platform frameworks, problems may arise with third-party plugins (installed via NuGet). We recognized several issues with outdated plug-ins. In general, our experience has shown that new device and operating features of mobile devices had been adopted very fast by Xamarin. Hence, in most cases its framework-based services can be used instead of third-party plugins. Regarding testing and debugging applications, the developers stated that Xamarin would be the most convenient framework to use. This may be the case because of extended possibilities instantly provided by Visual Studio.

C. React Native

React Native is easy to set up as well. React Native is built upon React and is also based on JavaScript. Applications developed in React Native interpreted directly and the design appears near to native. Interesting features include a well-designed live debugging. With Expo, React Native offers an open source toolchain to simplify deployment on test devices.

TABLE III: TEST DEVICES

	Honor 9	Sony XZ1	Samsung Galaxy S7	IPhone 8
Processor type	HiSilicon Kirin 960 octa-core processor (four 2.4 GHz cores and four 1.8 GHz cores)	Qualcomm Snapdragon 835 MSM8998 Octa-core (quad 2.35 GHz + quad 1.9 GHz) 64-bit Kryo processor	Exynos: Octa-core (4x2.3 GHz Mongoose & 4x1.6 GHz Cortex-A53)	Apple, Hexa-Core (64 Bit) 1. CPU: A11 Bionic, 4 x 2,24 GHz 2. CPU: A11 Bionic
Memory	4 GB RAM	4 GB	4 GB	2 GB
Graphic chip	Mali-G71 MP8 GPU	Adreno 540	Adreno 530	A11 Bionic
Display size	5,15 inches (1080x1920)	5,2 inches (1080x1920)	5,5 inches (1440x2560)	4,7 inches (750x1334)
OS Version	Android 7.0 Nougat	8.0 Oreo	Android 6.0.1 Marshmallow	iOS 12.1.2

Although this may result in some benefits, we observed that the apps that are generated by the Expo are structured differently than those set up by the console. Additionally, these apps have different access to native functions. Another disadvantage compared to the other frameworks is interface development. React utilizes a lot of specific HTML-Tags, which we recognized as somewhat difficult to use and configure. This makes it more difficult to get started than with other frameworks, even if experience in Web technologies is pre-existent.

Oracle Jet

Oracle Jet also offers its own CLI commands for the creation of cross-platform projects. Web technologies such as JavaScript, HTML and CSS are used to build individual pages of the app. To simplify the retrieval and processing of information within the application, the jQuery library is used. In addition, Oracle Jet offers a variety of UI elements to provide arbitrary display options. Oracle indicates, which plugins have already been tested and verified. Other plugins can also be used in Oracle Jet projects, but incompatibilities may occur, and their functionality is not guaranteed. Oracle Jet does not offer in-house debugging features, but existing test and debug tools can be integrated into the system. In addition, Oracle Jet offers its own packaging functions for Android, iOS and Web.

D. Flutter

Flutter is easy to setup. You literally need to download a zip folder, unzip it in a directory with no security restriction (e.g., on Windows C:\). Flutter comes with its own command line tool, but you can integrate it into your system by adding it to your environmental variables. Flutter also offers hot reload and fast native like performance, which enhances the speed of development and the feeling of a native app. Flutter uses its own programming language called Dart. It is oriented on concepts known by Java and JavaScript but offers a lot of specific extensions like the handling of asynchronous calls with their new Future class. It also has its own virtual machine and comes with 2D-Rendering. In the beginning you need to get used to Dart because there are some differences in creating the UI but since their documentation is really good you will be able to adjust yourself pretty quick.

E. Comparative Evaluation

To evaluate all frameworks comparatively and in an objective manner, we implemented a test application according the reference architecture (as defined in Section IV). In a second step, we measured the criteria defined at the beginning of Section V, to reason about benefits and limitations of all frameworks. Based on upon the evaluation criteria presented and measured below, the overall results are summarized in TABLE IV. For each evaluation criterion, we applied a nominal scale that rates the observed framework behaviour in comparison to our general expectations and in relation to the other frameworks. The nominal scale contains the following ratings: “++”=very good, “+”=good, “0”=neutral, “-“=poor, and “--"=very poor.

Supported platforms: Ionic officially supports Android, iOS and since 2016 also UWP development, although the documentation is still very limited here. Xamarin offers full support for Android, iOS and UWP. Limited support is provided for MacOS. React Native supports iOS, Android and with a little extra effort also UWP applications. Oracle Jet also supports iOS UWP and Android platforms. Flutter supports Android and iOS and with the help of Hummingbird it is possible to deploy your app in a specialized browser, which means you can use it on your desktop computer as well. The UWP is not yet supported and probably never will be because the market share is just too small to benefit from it. In a developers perspective Xamarin is rated best, because its platform support is broader than all other frameworks.

Supported development environment: Ionic applications can be developed on Windows, macOS and Linux. The development platform for Xamarin is Visual Studio for Windows and Xamarin Studio for macOS. React Native supports Windows, macOS and Linux. Oracle Jet projects, on the other hand, can be developed on Windows, macOS and Linux. Flutter can be used on any kind of operating system. Literally, since the web-based frameworks depend on technologies available on all common development environments, they all share a best in class rating. The latter does not hold true for Xamarin, since it is based on .net technologies and hence restricts use of development platforms. Thus, for this criterion Xamarin is rated less than all other frameworks.

Access to platform-specific functions: Ionic provides access to iOS, Android, Microsoft and browser-based features. Platform-specific functions can be used via various Cordova

plugins. With Xamarin, all platform-specific functions can be used in a similar fashion. However, Xamarin offers different possibilities to access platform specific functions. The fastest possibility is to install corresponding NuGet packages. A second option would be the definition of interfaces with platform or device specific implementations and expose this shared code via the dependency service. Then there is also the possibility to use native libraries, for example written in pure Java for Android, via binding. While React-Native is JavaScript-based, and many native functions are not supported, it is possible to include native SDKs and libraries. However, this requires specific code for Android (in Java) and for iOS (in Swift) which results in higher development efforts. In addition, these features are currently often not mature enough. Oracle Jet projects use Cordova like Ionic to address platform-specific functions. A common code base is therefore sufficient to address all different platforms and use their device-specific functions. Flutter uses Dart to directly interact with the native API of the client as illustrated already in Figure 8. Overall, the most comprehensive support for use of platform specific functions is given with Xamarin which it is rated best in this category.

Application look and feel: Ionic offers its own widgets for the UI. Navigation elements (e.g., back button) are provided in platform-specific style, so the differences to native apps are small. As already described in Section V, the use of a GridView in Ionic is very simple. Xamarin creates completely native UI, thus the interface is familiar to the user. Xamarin also supports styling with themes and the interface is not different to native apps. Xamarin Android also supports material design. React Native uses specialized widgets. Setting up a GridView it is not as easy as in Ionic or Xamarin, CSS has to be used to achieve this layout. In general, Ionic and React Native ignore style guidelines of platforms partially and some widgets break them explicitly. For example, tabs in Android are at the top of the screen in native apps, while this is not the case in apps developed with Ionic or React Native. Xamarin, in contrast, uses tabs as expected. Oracle Jet offers native themes to display the applications adapted to the platform used. In addition, different templates can be used to adapt the styling to your own needs. Since Flutter uses its own widgets, which are accessing the native API and Widgets via Dart. That brings the look and feel of a native written app. The most native appearance of apps is given when Flutter and Xamarin are utilized. While the other frameworks also get close to a native user experience, they still fall behind.

Application portability: Since Ionic represents a hybrid approach, portability of the source code is given and further supported through Cordova. Since Ionic modules are well-structured and based on Web technologies, they can be transferred to other Web frameworks. However, as many other frameworks, Ionic uses specific HTML tags that may not be supported in other frameworks, thus there is limited transferability of this module part. Since Xamarin separates application logic and UI related code, it offers the best portability and reuse of the logic. Furthermore, Visual Studio offers tolling (portability analyser) to transfer the UI related parts as well. Of course, it has to be said that this is restricted to .Net and mono frameworks. The UI (defined by eXtended Application Markup Language, XAML), could in principle be transformed into HTML or similar languages, which, however, requires further manual efforts in a second step. Similarly, React Native offers portability to different platforms. React-Native code is relatively easy to transfer to other frameworks that use JavaScript, HTML, and CSS. Comparable to Ionic, specialized HTML tags have to be XAML handled manually. However, since as React Native Logic, UI and CSS are typically implemented in a single file, this tends to be tedious. Like Ionic, Oracle Jet uses a hybrid approach. JavaScript is used for the application logic, HTML for the page structure and CSS for the styling. This allows this code to be transferred to other hybrid approaches that use web technologies. However, the Oracle Jet specific HTML tags represent limitations. These cannot be transferred to other frameworks and must be replaced. Even though Flutter uses Dart is possible to use the code elsewhere, since there are possibilities to compile or reuse the code in web apps like Hummingbird, DartPad and dart2js [36][39][40]. Overall, we expected frameworks to be much more advanced already, nevertheless neither of them could really fulfil our expectations.

Simplicity of development: Through a lot of documentation (tutorials, community discussion, API documentation, quick start and programming templates) a quick and efficient start in development of Ionic Apps is possible. Because of the short development lifecycle, confusion may occur through different version documents and some outdated plugins. Occasionally, the framework reveals unexpected behavior (some builds end up with broken apps, while a rebuild without code change is successful). We intend to examine this further. Currently we believe that this is related to generator issues. In principle, the development with Xamarin is fast as well, since the framework also possesses a very good documentation (tutorials, sample projects and a very precise API documentation). The programming language underneath (C#) also is very sophisticated and in our opinion much better then JavaScript. In terms of simplicity, Visual Studio or NuGet may pose a certain barrier for developers not used to it in the beginning. The entry into the development with React Native is comparable to Ionic. The use of the framework-specific UI elements is different from the other frameworks but does not impose an obstacle. The ability to see and debug all changes in real-time eases troubleshooting. A larger issue is related to external libraries and modules. Since many of these modules and libraries are not officially supported, regular maintenance and support is not guaranteed. In addition, we observed that the installation of node modules consumes much more time compared to Ionic. For Oracle Jet, the vendor provides extensive documentation from application setup to testing and debugging Oracle Jet applications. A cookbook is available for existing elements (collections, controls, forms, framework, layout and patterns). Additionally, sample projects and starter templates are offered to speed up the start of development. Thus, detailed documentations are available, which simplify the development with Oracle Jet. A detailed debugging using the browser tools promotes the development and simplifies the finding and elimination of errors.

TABLE IV: EVALUATION OF CROSS-PLATFORM FRAMEWORKS

Evaluation Criteria	Ionic	Xamarin	React Native	Oracle Jet	Flutter
Supported platforms	+	++	+	+	+
Supported development platforms	++	0	++	++	++
Access to platform-specific functions	+	++	0	+	+
Application Look & Feel	+	++	+	+	++
Application Portability	0	0	0	0	0
Simplicity of development	++	+	0	+	+
Application performance	+	+	0	+	++

Flutter comes with a very good documentation that offers a cookbook for different widgets and use cases. It also has a large number of code labs/tutorials to help you getting into Flutter and Dart. In terms of debugging and testing Dart has some tools like the Dart Analyzer to check our code for errors or the Dart Observatory, which lets you define your own breakpoints in the code without using an IDE to do so. Like in every mentioned framework you can print out logs as well. Furthermore, Flutter has integrated the possibility of writing unit tests, widget tests and integration tests, which is well documented on their official page. We faced very little errors and bug while developing though the framework is still young. In this category we rated how quick and flawless a developer can initiate and develop an application. Overall, all frameworks provide developer support but Ionic currently provides the most comprehensive developer guidelines.

Application performance: In order to stabilize test results, we deployed all test applications and measured results of 100 test runs with four test devices. Hence, we could observe the following numbers: The required start time of the Ionic test app is between 2s and 2.44s, while Xamarin requires 3 to 3.3s, React Native 4 to 4.5s and Oracle Jet 1,2s. Flutter just needed 0.5s to start the app The size of the Ionic app is 10 MB, while Xamarin requires 24 MB, React Native requires 11 MB, Oracle Jet requires 19.13 MB and the Flutter app requires 34.12 MB. The time the Ionic app takes to retrieve the current location (with high signal strength of GPS) is approximately 0.1s, while Xamarin needs 3.0s, React Native 0.4s, Oracle Jet 1.2s and Flutter 0,3s.

VI. Conclusion and Outlook

In this article, we reviewed a couple of cross-platform frameworks and discovered that they can significantly reduce development efforts, especially if code shall be shared between different platforms. This of course, is not the case with native app development. Hence, in our point of view cross-platform development is superior to native app development. This especially holds true, if a cost-benefit relation is applied. In addition, there are almost no limitations in the use of native functionalities when cross platform libraries are employed.

In this article, we focused the evaluation on five different frameworks and evaluated, which of them provides the best development support for multiplatform deployment. In order to decide, which frameworks and approaches to choose for evaluation, we conducted a literature review and did some research about popularity of frameworks. Hence, we evaluated developer-oriented web portals and usage statistics of cross-platform development frameworks. While we had been able to discover several scientific approaches to multiplatform development, we recognized that current development is mainly driven by standardized web technologies. These are typically extended by generator-based technologies, which are utilized in order to transform and package applications for platform specific rollout (deployment). Further approaches where defined in literature, such as transformation-based or interpreted application (parser-based) development.

We analysed and evaluated all frameworks on the basis of the following categories: a) supported platforms, b) supported development environment, c) access to platform-specific functions, d) application look and feel, e) application portability, f) simplicity of development, and g) application performance. The results of our evaluation conclude that Flutter is the best suited framework for cross-platform development. In our case study, we examined Ionic, Xamarin, React-Native, Oracle Jet and Flutter in detail. Our results revealed several differences to other comparable articles. First, numerous articles have reported that Ionics's performance is rather poor compared to the other frameworks. However, Ionic scored surprisingly well in our tests. Together with the Flutter framework, Ionic had the best performance score. Compared to other studies [6], performance enhancements of all evaluated cross-platform frameworks could be observed in general. This applies to response and processing times as well as sensor access. The latter can be a result of framework improvements within the latest versions as well as mobile device platform improvements. From a user's point of view, there are almost no observable performance issues when compared to native applications. All evaluated frameworks offer full access to system functionalities and sensors. Although new versions of operating systems can lead to different functionalities and sometimes completely different APIs, the rate and speed of their adoption in cross-platform frameworks is quite high [41]. All cross-platform frameworks allow generic development for different operating systems, although there are still limitations. As we mentioned before, apps are sometimes not fully portable and may require platform-specific customizations. This holds true for all approaches. Furthermore, the statement that the reuse of components between

different mobile applications is not yet fully supported is not valid. Ionic has released betas, which support the use of other components written in React, Vue and Angular [23]. Nevertheless, we could not observe that components developed in one framework could be integrated in other frameworks with ease. Since the web-component standard is promising in this context, we plan to do research of cross-component integration between different frameworks in a next step.

As another important feature of a framework, long-term support is essential to reach a wide range of users and ensure support for current applications. In newer versions of the frameworks examined, it was observed that downward compatibility with APIs of earlier releases was not given. This is common in web development and is known at least since Angular 2 completely broke with the API of its predecessor AngularJS. This can be observed repeatedly for new releases, and its likelihood that this is repeated for future framework releases is high. Thus, it is important for mobile software engineering, whether standardized component development (e.g., the web component architecture) will be adopted in all frameworks. Supplementary important aspects are, if framework consolidation is promoted or whether the spread of new programming languages and techniques will further divide the market. Similar arguments apply to the downward compatibility of the API. This will give rise to further research questions on API issues.

As mentioned above, an important question will be whether it is possible to transfer code from current framework applications into new releases and preserve their functionality (even if the API changes). Therefore, we intend to define a model-driven approach to address this problem in a next step. In this context, we plan to compare parser-based methods with transformation-based cross-platform approaches and to derive API mappings. As a broader outlook, a more detailed study in the area of web components will be performed. In this context, we are planning to assess reusability of web components. Our goal is to evaluate web component programmed utilization across multiple different frameworks.

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Holistic Analysis of the Effectiveness of a Software Engineering Teaching Approach

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***Abstract*—To provide the best training in software engineering, several approaches and strategies are carried out. Some of them are more theoretical, learned through books and manuals, while others have a practical focus and often done in collaboration with companies. In this paper, we share an approach based on a balanced mix to foster the assimilation of knowledge, the approximation with what is done in software companies and student motivation. Two questionnaires were also carried out, one involving students, who had successfully completed the subject in past academic years (some had already graduated, and others are still students), and other questionnaire involving companies, in the field of software development, which employ students from our school. The analysis of the perspectives of the different stakeholders allows an overall and holistic) view, and a general understanding, of the effectiveness of the software engineering teaching approach. We analyse the results of the questionnaires and share some of the experiences and lessons learned.**

Keywords- agile methodologies; education; software engineering; teaching; teamwork.

I. INTRODUCTION

One of the biggest challenges in teaching software engineering is empowering students with the knowledge and skills they need to be well prepared to face the labour market. This includes providing students with technical skills but also providing them with the non-technical skills associated to the software engineering process. It is also known that the teaching of software engineering cannot be limited to the presentation of concepts and methodologies as a set of abstract concepts. In our previous paper, presented in ICSEA [1], we analysed how the main concepts of the software engineering subject are assimilated by the students and if they are applied in the labour market. We also learn that it is important for students to develop practical projects to complement their education. This is corroborated by other authors who point out that wherever possible, software engineering teaching should be adequately complemented with the practice of software engineering projects so that the students can assimilate and understand them successfully [2]–[4]. Additionally, it is important to consider the growing importance of human factors in the software development process [5] and consequently the role that some of them play in the software engineering process, namely: communication, coordination, collaboration, trust, expert recommendation, program comprehension, knowledge management and culture.

Several approaches and strategies have been proposed and used to improve the teaching and learning of software engineering. They all ensure the importance of giving students hands-on experience. However, the way they propose to do so differs greatly.

This paper describes an experience in teaching Software Engineering, of a Computer Engineering program, using a project-based approach. This approach is enriched with the collaboration of software houses giving the students a real-world experience of software engineering project development. In our paper [1] we tried to understand how the main concepts of the subject are assimilated by the students and if they are applied in the professional life of our past students. In this paper we extend our approach to include the point of view of the companies that employ our students. The opinion of these companies, which employ and develop activities in this area (Software development), is very valuable. It may represent significant contributions for the improvement of the teaching-learning process and for better integration of the students in the labour market. To reach this goal, we conducted a questionnaire with a group of employers. We chose 5 companies that have recruited our graduates in Portugal. This set of companies is obviously reduced compared to the universe of thousands of software development companies worldwide. However, the collected data is a starting point for analysing what is considered relevant to these partners. Although we graduate students for a larger universe of companies, the collected data are useful as indicators of aspects that we must take into account, while obviously not neglecting other methodologies and topics related to Software Engineering.

The results of this questionnaire allow us to improve the definition of the topics on which the lecture should focus and to keep the syllabus updated. Additionally, it helps us to understand the strengths and weaknesses of the employees who graduated from our school (soft skills and technical skills). This analysis of the perspectives of the different stakeholders allows an overall and holistic view and a

general understanding of the effectiveness of the software engineering teaching approach.

The remainder of this paper will be as follows: Section II presents a brief review of related work; in Section III we present an overview of our project-based approach for software engineering; Section IV provides a brief description of the questionnaires that were conducted to achieve feedback from former students and employers; in Section V we present the results and analysis of the questionnaire; Section VI presents some lessons learned and challenges faced and finally, in Section VII we present some conclusions and we outline some of the future work.

II. Related Work

To provide the best training in software engineering, several approaches and strategies have been proposed. Some of them are more theoretical, more focused on the study of theory through books and manuals, while others have a more practical focus and often done in collaboration with companies. Nowadays, it seems to be a well-accepted fact that the software engineering training should not be strictly focused on the theoretical study of concepts and methodologies. It is important to provide students with hands-on experience in a software engineering project and provide them with the non-technical skills in a software project. It is important to promote hands-on ability training and the rapprochement between teaching and practice. Additionally, the recent diffusion of agile methodologies in software development brings many difficulties and challenges to software engineering teaching. In this context, several authors refer that current approaches to teaching software engineering are outdated and lack authenticity [6], [7]. However, as referred in [6], it is not clear which should be the best approach and there are different perspectives with different proposed approaches. Some authors (e.g., Clear and Damian [6][8]) suggest that the best approach is to emulate the workplace through distributed software development projects, through cross-university or cross-course courses, others (e.g., [9]–[11]) suggest involving students in a project where they have the possibility to experience team work and understanding in the practice of the theoretical concepts dealt with in the course and others (e.g., [12]–[14]) argue for the use of simulations and games to provide students with a variety of experiences that would not be possible within the constraints of an academic environment. Next, a brief analysis of some works that have been proposed for each one of the perspectives identified before is presented.

The emulation of the workplace through distributed projects or cross-university courses was approached and experienced by some authors. The DOSE [8], a Distributed and Outsourced Software Engineering course, followed an approach to teaching distributed software engineering centred in a distributed software development project. They experienced teaching software engineering using a geographically distributed software project involving various countries with different cultures, native languages and time zones. This approach gives the students the opportunity of facing the challenges of distributed software development and helps them understand typical software engineering issues, such as the importance of software requirements for specifications, or the relevance of adequate system design. However, they also identify some time scheduling inconveniences, and difficulties in keeping teams committed to their peers. The Undergraduate Capstone Open Source Projects (UCOSP) program [15] ran for ten terms over six years providing for over 400 Canadian students from more than 30 schools. After this period, the authors identified some lessons they had learned: Students work on real distributed open-source projects as full members of software development teams; they use the same software development processes as regular team members and are provided with explicit mentorship from volunteer mentors from each project; students integrate and apply the skills they have learned in their courses in a real development setting; students develop and improve their technical communication skills in a real development setting.

A project-oriented approach is followed in several software engineering training programmes. Its purpose is to teach students the theoretical and the practical aspects of developing software systems in a team environment giving students a chance to experience a work scenario that is closer to a real-world experience. A Project-Based learning in software engineering Lab, teaching through an e-Portfolio approach is described in [10]. In this approach, the e-Portfolio allows students to carry out a software project, addressing each phase collaboratively with other students and obtaining appropriate feedback from instructors. The e-Portfolio includes a single problem statement for the development of a complete software project comprising of a set of deliverables. To support the implementation, they chose the Moodle Platform. To assess the students' e-portfolios, various rubrics were implemented by scoring and weighting the sections and categories for every deliverable to be evaluated. Another project-based learning approach for teaching software engineering concepts is described in [11]. Their goal is to teach software engineering concepts using the Scrum framework in real life projects. Projects usually have a capacity of about 1000 workhours. To make the projects more relevant real customers were incorporated. They bring in requirements from industry and present their topics during a kick-off meeting. During the project, students work together as self- organized teams (5-7 elements). They chose an appropriate project management and team coordination process and they are only asked to use some core tools that are needed to monitor the projects.

A game-based learning methodology of teaching software engineering is presented in [13]. They suggest a methodology of two-fold use of learning games for teaching software engineers. Students, experienced in programming, develop learning games, and then they use the games that are developed for teaching the next generation of students. Students developing games learn the software development life cycle phases including testing, deployment and maintenance, they contact with customers (teachers of corresponding subjects act as customers) and users (students, learning these subjects). In their approach, they find both advantages and disadvantages. As advantages, they identify the increasing students' motivation and revealing their

creativity. The main problems observed include difficulty in organizing team work especially for students of early years and lack of time for coordinating them. Schäfer [14] describes some lessons learned after two teaching periods in using Scrum with gamification to learn and train the agile principles. They found that their approach has both advantages and disadvantages. Gamification is motivating and helps to bring participants with different backgrounds together in project teams. As drawbacks, they refer to the importance of having a real external stakeholder or customer defining a project goal externally in a Scrum learning project.

There are different approaches and strategies that may be followed to provide students with the best training in software engineering. All of them agree that the theoretical study of concepts and methodologies should be complemented with hands-on experience in a software engineering project. This would allow students to be provided with a better understanding of the theoretical concepts and to equip them with the non-technical skills in software projects. However, the way different approaches propose to provide the students with the practical experience is very different. Some of them suggest emulating the workplace through distributed projects, which may involve several entities and thus provide interesting experiences in software engineering. Others suggest a project-oriented course where students can practice requirements analysis, project management, development methodologies and teamwork. Another recommendation is using simulations and games to simulate distinct scenarios in software engineering teaching and training.

However, regardless of the approach or strategy, it is necessary to understand whether students have acquired the knowledge and skills they need for the performance of their duties, and whether they apply them in their professional activity in software engineering. To understand this, it is a holistic analysis (i.e., analysis of the big picture involving several stakeholders, namely students, alumni and employers, about the teaching methodology implemented in this subject in recent years) that is important since it allows for an understanding of the vision of the different stakeholders that may be involved in the software engineering teaching process: teachers, students, graduates and employers.

III. Overview of our Approach for Software Engineering

In this case a project-based approach was adopted for teaching Software Engineering. This subject is part of the second year of a computer science course (undergraduate course). It is a subject that has 5 ECTS and where the semester load is 30 hours for theoretical classes and 45 hours for laboratory classes. The focus of the adopted approach was to combine theory and practice.

One teacher is responsible for the subject management and theoretical lectures. In these classes, the teacher presents the concepts and methodologies and promotes discussion about them. Students are also provided with an introduction to some software development methodologies namely Waterfall, Extreme Programming, Scrum, Spiral, etc. Other topics analysed include quality and metrics in software engineering, software design, implementation, testing, configuration management, among others. In the assessment, this theoretical part has a weight of 40% for the final grade; the remaining 60% is from the practical component.

Another teacher is responsible for the practical classes. In these classes, students acquire some practice of software engineering through the specification, design, implementation and validation of a software application, as a project for teams of 4-6 students. Scrum is the adopted agile software development methodology. The teacher acts as a product owner. Each team member has a specific function (e.g., Scrum Master, Designer, etc.). Each team develops a different project. However, all the projects are focused on the development of a game from a software engineering perspective. This is important to maintain the students motivated and engaged with the project. The first deliverable is revised to accommodate feedback from the product owner. Trello is used for project management and to track progress on tasks.

A. Additional Realism

One class of the subject has been taught by professionals from software house companies. In this class, software development processes like Feature Driven Development (FDD) and Behaviour Driven Development (BDD) were approached and some of their practical aspects are discussed.

Another important initiative to enable students to get in touch with practice in software engineering is a one-day visit to the premises of another software house company. This company (Outsystems) is well-known for the software development platform they hold and that is used by many software companies worldwide. Their platform is a low-code platform for rapid application development. It is especially designed for developing applications in the context of agile projects. During this journey, students were able to have closer contact with some Scrum activities (namely Daily Scrum, Sprint, Sprint Execution) and contact with some Scrum Roles (Scrum Master, Development Team). Professionals explain to the students what they are doing, and which technologies and tools are used to support their activities. Students also had a brief session about software cost estimation.

These events are very important since they provide students with the contact and interaction with real software engineering projects with real stakeholders. They help to improve the understanding and the assimilation of the concepts learned in the classes of the subject.

B. Student evaluation

The student evaluation comprises both theoretical and practical evaluation. The theoretical evaluation is a written

exam over the course material. The exam consists of 10 questions chosen from the list of 30 questions that were made available to the students at the beginning of the semester. Most questions are reflexive questions about software engineering subjects. With this approach, the intent is to avoid students wanting to memorise the matters learned along the semester (15 weeks). Also, it is desirable that students learn and acquire knowledge for a long-life period, mainly to be used after graduation on their job integration experience. In section V, some gathering data that wants to evaluate results about the achievement to this goal of our approach will be presented.

For the practical evaluation, throughout the semester, during the 15 working weeks, students´ working teams develop the product on 6 sprints (sprints here are defined as having 2 weeks each). The teacher (i.e., product owner) meets with each team at the end of the sprint to evaluate the work in progress, the achievements and the goals for the next sprint. The team works in class (3h/week) and out of class. Halfway through the semester, after sprint 4, and at the end of the semester, after sprint 7, each team has an assessment session where both teachers are present to evaluate different parameters. Some of the parameters are: clear goals, state of the art, requirements (functional and non-functional), software development process (roles, artefacts, timings, hits and misses), team member´s description (roles, skills) task scheduling (monitoring using Trello tool), modelling (user stories), implementation (code), budget (estimated based on the lesson learned during the visit to the company referred to on the previous section of this paper), conclusions (pros and cons) and future work, literature used and citation on the final report, and final presentation and discussion.

One of the achievements that students sometimes realize is learning from mistakes. For instance, if they do not communicate within the team the achieved results are poor, when compared with other more cohesive teams. On the other hand, in collaboration with the "Scrum Master" of the team, a deeper evaluation can be done to eventually assign different grades to the members of the team.

IV. UNDERSTANDING STAKEHOLDERS' PERSPECTIVE

In order to gauge the post-retention cognitive load, a questionnaire of former students was conducted in order to obtain feedback on the importance of the subject to their current professional activity (of those who finished the course and work in the area), and also to know if the knowledge transmitted in the theoretical classes remains. For this last component, the questionnaire included questions that had already been used in the theoretical evaluation of the subject. The answers were evaluated with the same evaluation criteria, graded in a scale of 0-20. The questions were selected from the same set of 30 questions referred to in Section III-B. Respondents were informed that the results were for a study. They were also informed that the goal of the study was to understand if the concepts and knowledge acquired in the Software Engineering subject remained present. The questionnaire was also used to gather insights about the usefulness of the subject for each graduate's the practical life. Thus, questions about aspects that may be used in the day to day of their professional activities in the companies where they currently work, were included in the questionnaire.

Also, in order to get feedback from employers about issues that are important to graduate students starting their professional activity, a questionnaire for employers was conducted. The questionnaire included questions about the development processes used in the company (traditional, agile, etc.); the importance of software engineering contents to the company's activity; soft skills and technical knowledge that have more importance to the company; and a question about topics or issues that, in their opinion, should be considered in software engineering subjects. The answers were analysed and will be presented in further sections. Respondents were informed that the results were for a study. The questionnaire was also used to gather insights about issues that must be included in future editions of this subject. Thus, questions about aspects that may be important in the day-to-day activities in the companies were included in the questionnaire.

A. Questionnaire of Former Students' Description

This questionnaire was designed to be directed towards our objectives and be filled in quickly and simply. Some questions were answered in free text (case of questions of theoretical knowledge) and others are multiple choice questions (e.g., used software methodologies). The questionnaire was organized in three parts: Questions about the current professional activity of the respondents; theoretical questions about software engineering; and space for feedback on the importance of topics in their current professional life (for those who had already finished the course).

As examples of questions, we asked if the graduated students were working. If yes, we asked about the actual tasks in their companies (Planning, Requirements analysis, Design, Code, Quality control, Tester, Project management, other), the used methodologies (Waterfall, Scrum, XP, Prototyping, Spiral, FDD, Lean, RUP, other, none). About the theoretical questions we asked about the fundamentals of Software Engineering, Software Quality, Verifications vs Validation, traditional vs Agile, team dimensions and roles, among other questions and feedback.

B. Questionnaire of Employers' Description

This questionnaire was also designed to be directed towards our objectives and be filled in quickly and simply. Some questions were answered in free text and others are multiple choice questions (e.g., used software methodologies). The questionnaire was organized in distinct parts: Questions to characterize the company activity; questions to characterize topics of importance to the

companies' activity and feedback with contributions for future improvements of the syllabus.

As examples of questions, we asked about the respondent's experience, position in the company, number of students graduated from our school that work/worked in the company, activity of the company (planning, requirements analysis, design, code, quality control, tests, project management, quality assurance, others), used software processes in the company (Waterfall, Scrum, XP, Prototyping, etc.), from the different company's activities what are the most important. We also asked about the soft skills and technical knowledge that are most important to the company activities. And lastly, but not least important, we requested feedback to improve and keep the syllabus updated.

V. Questionnaire Results and Analysis

This section presents the results of the questionnaires answered by the students, graduates and also the results of the questionnaire answered by the employers.

A. *Data Collection/Methodology: students and graduated students*

As a universe of respondents, questionnaires were sent to 97 students. Of these, 56 were undergraduate students (although they had passed in this subject) and 41 graduated.

The questionnaire was done online, using the *LimeSurvey* Webtool.

The response rate was of 24.4% of the graduated students and of 21.4% of the undergraduate students.

It is important to note also that some respondents did not answer all questions.

B. *Results and Analysis: students and graduated students*

Figure 1 shows the activities the respondents (Graduated students) are involved in, in their work. 84% of the respondents are involved in more than one activity. 50% of them are involved in planning, analysis and testing but they are not involved in implementation.

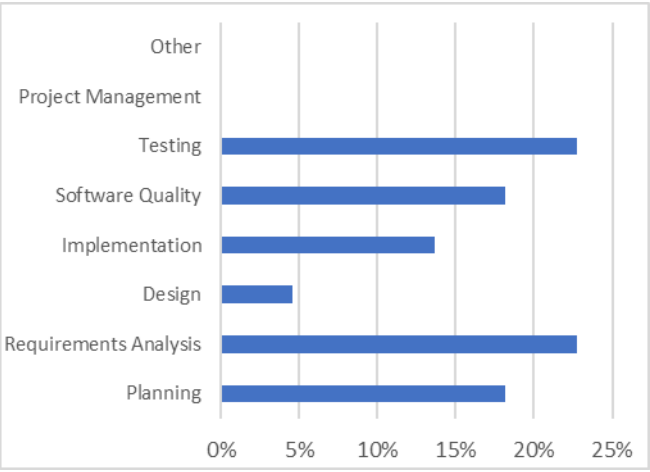

Figure 1. Activities carried out (Graduated students).

Graduated students were also asked to identify the software development methodologies they use in their activities. They were able to identify the methodologies they use considering a list of given methodologies. Results are presented in Figure 2.

More than 70% of the respondents refer that they use the Scrum methodology. This appears to be in line with the results presented in the "12th annual State of Agile report" [16] that refers that 52% of respondents stated that more than half of the teams in their organizations are using agile practices. And it is also in accordance with the results presented in another questionnaire of more than 2,000 active Scrum and Agile practitioners [17]. This study refers that 94% of agile users use the Scrum approach in their agile practice (78% use Scrum with other approaches).

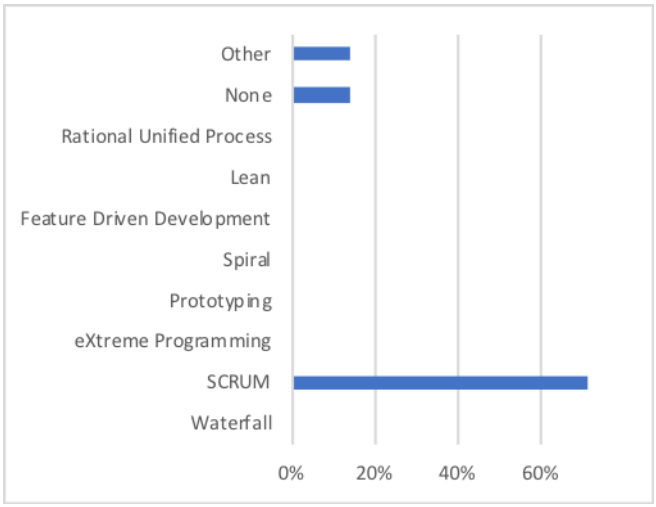

Figure 2. Software development methodologies (Graduated students).

With respect to the importance of the subjects learned, 87.5 percent, of the 8 graduated students that respond to this question, said that the content learned in the course has been considerably useful for their actual professional activity (see Figure 3).

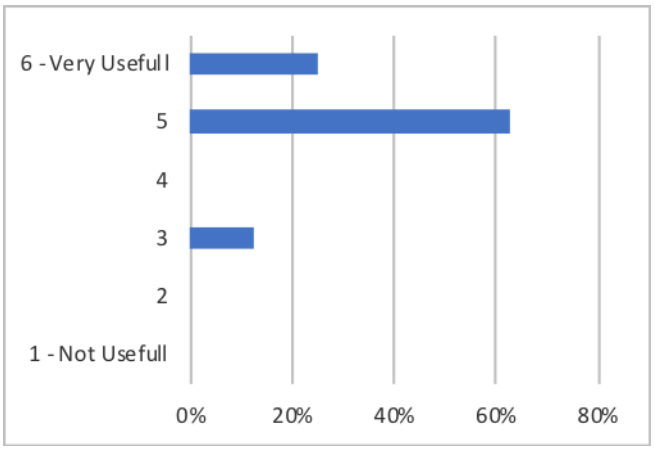

Figure 3. Course content vs professional activity (Graduated students).

The second part of the questionnaire was related to theoretical questions about software engineering. This part was evaluated in a 0-20 scale and we compare these results with the results achieved by the same individual during the course. We consider the individual "maintained" if *(grade achieved in the subject -1.5 ≤ grade achieved in the questionnaire ≤(grade achieved in the subject +1.5).*

After evaluating the answers of the non-graduated students to the questions, we conclude that there is a majority (58%) that has maintained or increased the result (41% maintained, 17% increased) (see Figure 4).

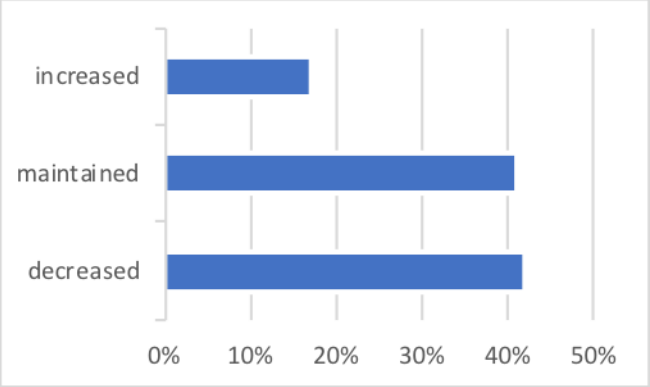

Figure 4. Grades evolution (Students).

In the case of students already graduated, the results, presented in Figure 5, are better (less cases (37.5%) of lowering grades). Despite the long period of time after they attend the course, this is probably a consequence of the practical experience they get in the field of software development.

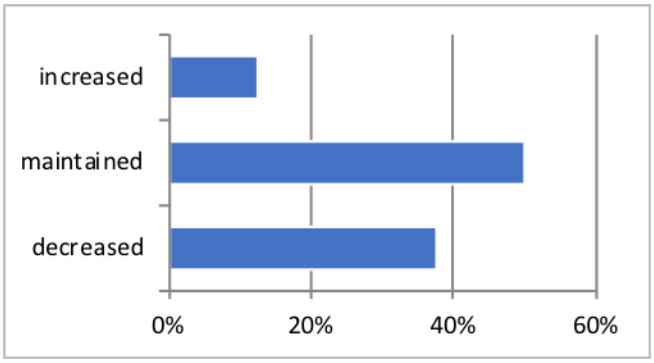

Figure 5. Grades evolution (Graduated students).

In addition, at the end of each semester, a questionnaire is usually conducted in order to obtain knowledge about the students' perception of the importance of the subject for their academic education. This questionnaire addressed four issues: acquisition of knowledge; development of skills, improvement of critical thinking; relevance for academic background. Figure 6 shows the results of the questionnaires (average values) performed in the last 2 years. Each topic was evaluated on a 6-level scale (1 nothing important – 6 very important).

In general, all issues were evaluated very positively, which shows that there is a recognition of the importance of the subject for their education.

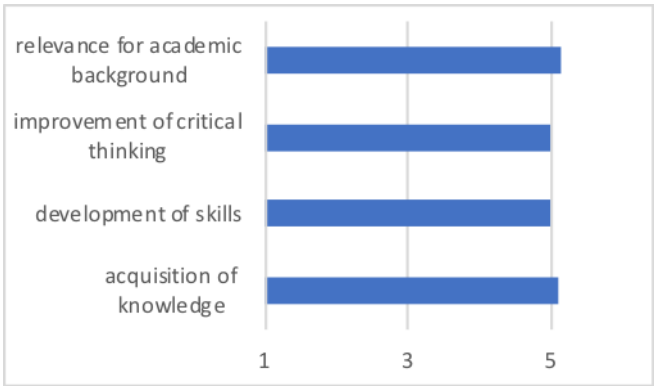

Figure 6. Students' perception of the importance of the subject for their academic education.

C. *Data Collection/Methodology: employers*

We selected 5 companies that have employed graduates of the school in recent years. The selected companies are multinationals, working in the ICT area, and each of them has at least graduates from the school as collaborators. For each company we asked a member, with an intermediate or high responsible position, to fill in a questionnaire about their activities and about the school graduates they currently employ. The questionnaires were completed by representatives of the company that hold leadership positions (Senior Manager, Executive Director, Team Manager, Business & Project Manager, Ecosystem Talent Director). The professional experience, in the ICT area, of these representatives of companies, goes from 13 years to 21 years.

The questionnaire was composed of 4 parts. The first part with general questions about the company and the respondent. The second part with 3 questions about the activity of the company. Two questions on which the respondent had to select from among the various options available, and one question where the respondent had to evaluate various options on a 1-6 scale (1 nothing important – 6 very important) on the importance of software engineering to the company's activity. The third part of the questionnaire consisted of 2 questions about the technical and soft skills of the employees who were graduated by the school. In these questions, the respondent had to evaluate several options on a 1-6 scale (1 very poor – 6 very good). Part 4 includes only one question where respondents were asked to provide feedback or additional input.

The five representatives of the companies replied to the questionnaire.

D. Results and Analysis: employers

Respondents answered that they had already worked, or are currently working, with 7, 15, 20, 30 and 38 employees who graduated from the school (each value correspond to a different company). This number of employees, graduated from the school, is higher than the number of graduates who were questioned (Sections V.A and V.B) because they represent graduates of several years. Although they do not represent the same universe, some of the graduates questioned in Sections V.A and V.B are employees in these companies. Therefore, they may be included in the group referred to herein.

Respondents were asked to fit their area of intervention by considering a list of 8 activities related to software engineering (see Figure 7). Each respondent could select several activities from a list or indicate other activities. Most companies focus on several areas of software engineering. Only areas related to quality assurance and software quality control are not ensured in all questioned companies.

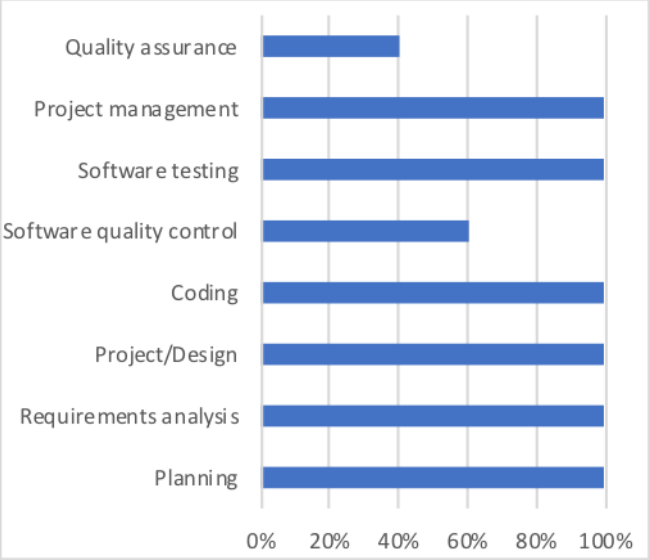

Figure 7. Company's activities.

Another important aspect, regarding the activity of companies, is related to the software development methodologies they use most in their activity. In our classes we teach some software development methodologies namely Waterfall, Extreme Programming, Scrum, Spiral, etc. However, in the practical project, Scrum is the adopted software development methodology. The goal is to provide students with knowledge and practice about the methodologies most companies follow. And it seems to be a wise decision. According to the questionnaire's responses, the Scrum methodology is the one most used by these companies. The waterfall software development methodology is also one of the most used. Figure 8 shows the software development methodologies used by the respondent companies. In this question each respondent could select, from a list, all the methodologies that they used in their projects. They could also add other methodologies.

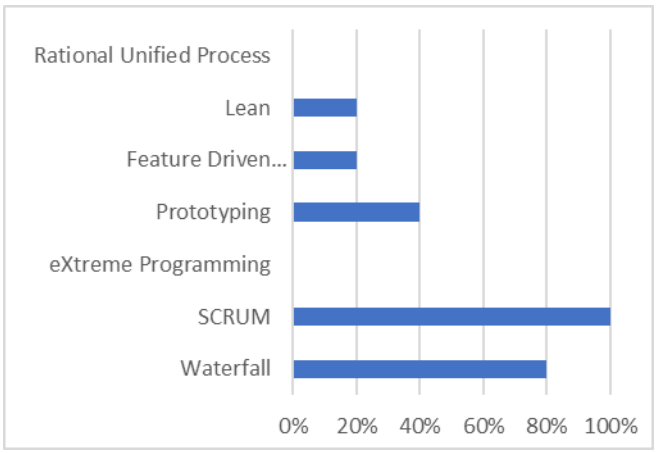

Figure 8. Software development methodologies used in the company.

Respondents were also asked to evaluate the importance of technical knowledge and skills, in 9 areas (from a predefined list) associated with software engineering. The graph, shown in Figure 9, presents the number of respondents that evaluated each area of knowledge and the average value of the importance that these respondents gave to this area of knowledge. It is important to note that some of them did not evaluate all available areas. The knowledge areas that were evaluated as most important were (in descending order of importance): coding, requirements analysis, development methodologies. Some respondents also mentioned user experience, debug and problem solving.

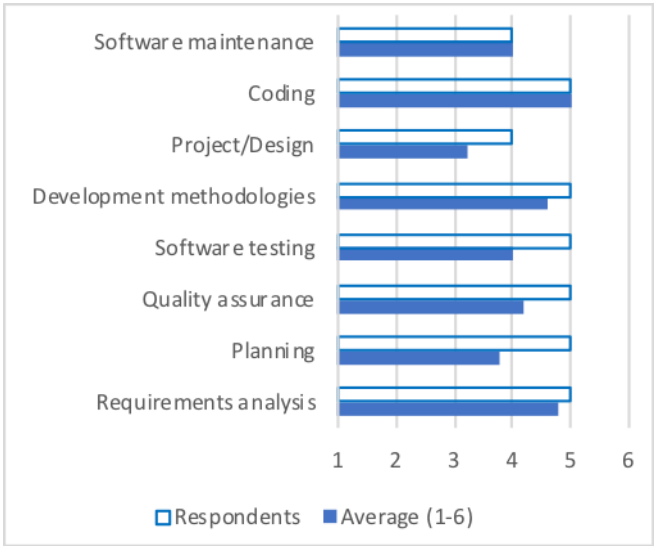

Figure 9. Importance of knowledge learned about Software Engineering for what the activity of the company is.

The next two figures represent the opinion of the representatives of the companies on graduates at school. Similarly, to the previous figure, in these issues some companies did not evaluate all the issues that are available in

the list. Graphs, shown in Figure 10 and Figure 11, show the number of companies that evaluate each skill and the average value of the evaluation that these companies gave to that skill. It is also important to note that companies were asked to make an overall assessment of employees for each competency. However, this does not have an easy answer. Employees have different competencies, work on different projects, and often relate to the respondent in different domains. This was corroborated by the respondents and, in particular, one which stated that "…it is very difficult to assign a general classification to all the employees who were recruited from school courses. Besides being many, they were also in different periods, different courses and as you know, not all are the same."

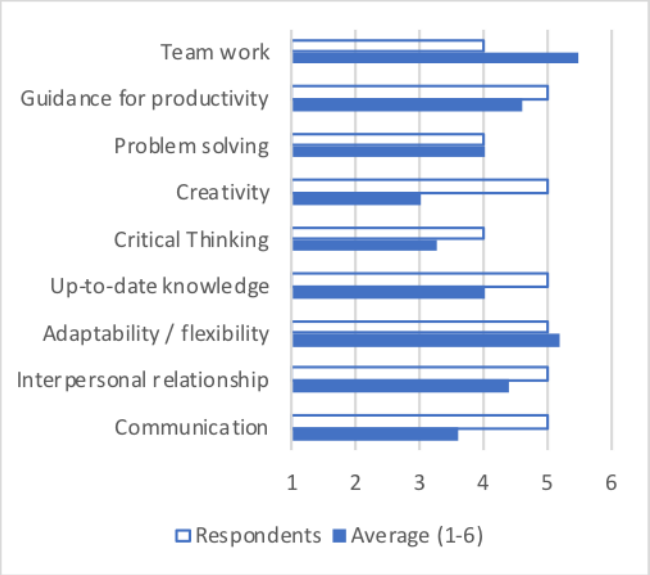

Figure 10. Strengths and weaknesses of the employees who graduated from our school (Soft skills).

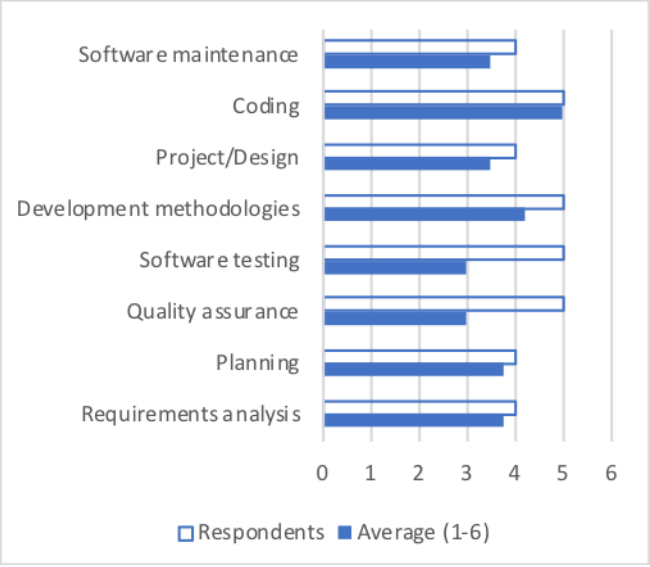

Figure 11. Strengths and weaknesses of the employees who graduated from our school (knowledge and technical skills).

Figure 10 corresponds to the feedback given by the respondents about the soft skills of their employees who graduated from school. The two skills that got higher ratings were related to teamwork and adaptability/flexibility. Both obtained very positive ratings from all respondents. With less positive evaluations arise the creativity and critical thinking.

The graph (from Figure 11) presents the feedback given by the respondents about the technical skills of their employees who graduated from school. Coding stands out for the positive. Software testing and the quality assurance had lower ratings.

The last part of the questionnaire was one open question where respondents were free to provide feedback or additional input. The answers obtained are different because they represent different perspectives and are usually conditioned by the nature of the company and the activities in which it focuses. However, these are valuable inputs as they represent the perspectives and real needs of companies. Below, some comments received:

"... any educational institution should be increasingly adapted to the major market trends, including them in the course programme ... so that the transition to the labour market is simple and contributes to meet the current needs ...".

"… strengthen the most used subjects: Methodologies/Development processes, Implementation/Coding, Maintenance and Software Testing...".

"…strengthen the areas of Software Quality (automatic software testing, AI (artificial intelligence), ... as well as Computer Security…".

However, these comments also show the different perspectives and focus of each of the companies.

VI. Lessons Learned and Challenges Faced

The contributions of this paper are in the form of the lessons learnt, which may be seen as guidance for others looking to approximate the know-how of students to the methods and techniques used by software companies. In summary, these are:

- Students should learn by doing and, wherever possible, software engineering principles should be assessed in the context of practical work, rather than by regurgitating material taught or extracted from textbooks.
- Students must have well defined and known goals. The assessment of the theoretical subjects does not need to be a surprise in the exam.
- Opening classes to external stakeholders (by promoting talks or visiting companies) during the last part of the semester helps students to reinforce knowledge and motivate them to the subjects.
- It is very important to get feedback from past students and evaluate if the transmitted concepts and knowledge are still there, and if it was improved by the work experience in the labour market.
- It is important to choose projects that are of interest to the students and that can motivate them and involve them in their development.

- It is very important to get feedback from companies that employ past students. It may contribute to a better adjustment of the syllabus with the real needs of the labour market. It also provides very important feedback on the technical and behavioural skills of former students.
- It is important to analyse the different perspectives of the various stakeholders: teachers, students, graduates and employers. This allows a holistic analysis and may help to improve the teaching methodologies.

However, during our experience, we faced challenges like:

- Difficulty in maintaining all team members equally motivated and engaged in the same way throughout the entire project development period;
- Keeping all students involved in the project. Some students may drop out, leaving the team during the semester, and affecting the workflow and scheduling of the remaining members of the team;
- Allowing students to experience various roles within the team. It is necessary to find a way to rotate the roles of each one within the team, to avoid any student being too focused on just one role. It is important that everyone experiences a diversity, as broad as possible, of different roles;
- Allowing students to experience different methodologies in real environments. More field trips and contact with companies that use different methodologies, must be promoted to foster more diversity of experiences.
- The representative of the companies that collaborated with us were very cooperative. However, some difficulties in responding to questionnaire questions were identified. This was mainly due to the fact that companies employ several graduates and therefore they try to make an average assessment.

VII. Conclusion and Future Work

Our questionnaire of former students was the starting point of a reflexion about the impact of the approach followed in previous years in the subject of Software Engineering. Based on the results, we think that allowing students to know the pool of questions in advance, fosters the students on important knowledge in the field and to understand these items, that we want students to maintain over a long period of time. The second questionnaire, of employers, give us important feedback to know the most important aspects of software engineering to companies, in the field of software production, where several of our former students are working. The feedback allows us to understand the employer's opinion about our graduated student's training and get contributions to focus our teaching goals in topics that are considered relevant to the future of our students. Using the feedback achieved from the questionnaire given to the employees of our graduated students, we want to improve and maintain updated the contents of this subject. This holistic analysis that includes different perspectives from different stakeholders: teachers, students, graduates and employers, gave us important guidelines to improve the teaching methodologies and syllabus.

Regarding the assessment of students, in future editions of the subject the pool of questions will be increased to improve the effect of randomisation for the next exams. Also, a mix of questions from the pool (~66%) and other questions (~33%), will be used to build the exams and explore the advantages of both approaches. As for the practical component, based on the results, Scrum is still used as a case study since it is one of the most used processes by companies where our graduated students work.

One final remark to reiterate that the study presented here is based on data collected from our students and alumni of the Software Engineering subject and from a group of 5 experienced representatives of multinational companies with whom we interact. This set of companies is obviously reduced compared to the universe of thousands of software development companies worldwide and the opinion of other employers may differ significantly according to their own reality and activity. In any case, the collected data is useful as indicators of aspects that we must take into account, obviously without neglecting other methodologies and topics related to Software Engineering.

We will continue to make all efforts to listen to these types of stakeholders (students, alumni and representatives of companies) and to broaden the universe of respondents, with the aim of keeping the themes and methodologies taught updated.

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Managing Technical Debt in Timed-boxed Software Processes: Quantitative Evaluations

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***Abstract*—Technical debt is currently receiving great attention from researchers, because it is believed to affect software development to a great extent. However, it is not yet clear how technical debt should be managed. This is specifically true in time-boxed development processes (e.g., in agile processes organized into development sprints of fixed duration), where it is possible to remove technical debt as soon as it is discovered, or wait until the debt reaches a given threshold, or wait until a whole sprint can be dedicated to technical debt removal, etc. We aim at investigating the effectiveness of different technical debt management strategies and the consequences of a wrong perception of the actual technical debt. We are interested in the consequences on both the amount of functionality and the quality of the delivered software. We propose a System Dynamics model that supports the simulation of various scenarios in time-boxed software development and maintenance processes. The proposed model is conceived to highlight the consequences of management decisions. The proposed model shows how productivity and product quality depend on the way technical debt is managed. Our study shows that different strategies for managing technical debt in a time-boxed development and maintenance process may yield different results—in terms of both productivity and delivered software quality—depending on a few conditions. Software project managers can use customized System Dynamics models to optimize the development and maintenance processes, by making the proper decisions on when to carry out maintenance dedicated to decreasing the technical debt, and how much effort should be devoted to such activities.**

Keywords–Technical debt; System Dynamics; Simulation; Technical debt management; Software project management.

I. INTRODUCTION

Both practitioners and researchers are dedicating a growing amount of attention to technical debt (TD). In general, TD is connected with a lack of quality in the code. The idea is that, if maintaining a piece of software of "ideal" quality has a given cost, maintaining a piece of software of "less than ideal" quality implies an extra cost.

It is also common knowledge that if no action is performed to improve code quality, a sequence of maintenance interventions will decrease quality, that is, TD increases and the cost of maintenance increases as well. Not managing TD at all could lead to code that is not maintainable.

However, it is easy to realize that too much time and effort dedicated to TD removal activities could have a negative effect on the overall speed of development, since time and effort devoted to TD management are usually subtracted to 'regular' development activities (developing new code, applying requirements changes, testing, etc.). So, a project manager should look for the optimal tradeoff between TD removal and regular development.

These considerations show that project managers need to identify the best TD management strategies and methods, and evaluate their effectiveness before putting them in practice. Quite importantly, managers need to reason in quantitative terms, in order to maximize the amount of released functionality at the best reasonable quality level.

For this purpose, we proposed a System Dynamics model that represents the development of software via a sequence of time-boxed development phases (e.g., Scrum sprints) [1]. Like any System Dynamics model, the proposed model can be simulated, thus providing quantitative indications concerning the effectiveness of development in terms of amount and quality of code delivered. The proposed model [1] was used to illustrate a few development scenarios and the consequences of TD and the adopted TD management practices. It was shown that dedicating a fixed fraction f of the available effort to TD remediation is more or less effective—with respect to both the delivered amount of functionality and the resulting software quality—depending on the value of f. In other words, to obtain good results, it is critical that the project manager guesses the value of f that optimizes the quantity and quality of delivered code at the beginning of the process. This is quite difficult, in general. On the contrary, it is easier to dedicate to TD removal a quantity of effort that is proportional to the size of the debt; it is also quite effective, with respect to both the delivered amount of functionality and the resulting software quality.

However, we can note that to implement the latter strategy, one has to know the amount of TD that is associated with the code. Generally, the amount of TD is evaluated by software managers via tools that perform static analysis of code and apply "expert" rules that detect the presence or absence of specific situations that contribute to the TD. Quite often, software managers do not have the time or the technical knowledge needed to verify the measure of TD provided by tools, hence they decide how much effort will be dedicated to TD removal based on the indications from tools.

Now, the indications from tools could overestimate (respectively, underestimate) the amount of TD. As a consequence, the project manager could dedicate more (respectively less) effort than needed to manage TD: we expect that in such cases the results—in terms of amount of delivered functionality and

quality—will worsen, with respect to the situation when the proper amount of effort is dedicated to TD management.

Accordingly, in this paper we enhance the results presented in [1] by exploring the effects of basing decisions concerning TD management on an inaccurate perception of the amount of TD in the code.

The paper is organized as follows. In Section II, we provide background concerning TD and System Dynamics. In Section III, we introduce our model of software development and maintenance, characterized by time-boxed incremental phases. In Section IV, the model is used to simulate the behavior of the process when different strategies for allocating effort to pay off the TD are used. In Section V, we discuss the outcomes of simulations, especially as far as productivity and delivered quality are concerned. In Section VI the model is enhanced to take into account errors in the perception of TD, and the results of simulations are reported. Section VII accounts for related work. Finally, in Section VIII, we draw some conclusions and outline future work.

II. Background

We here concisely recall the TD concepts proposed in the literature that we later model and illustrate via simulations (Section II-A) and the principles of System Dynamics modeling (Section II-C).

A. Technical Debt

In the last few years, TD has received great attention from researchers. For example, a recent Systematic Mapping Study on TD and TD management (TDM) covering publications from 1992 and 2013 detected 94 primary studies to obtain a comprehensive understanding on the TD concepts and an overview on the current state of research on TDM [2].

An updated Systematic Mapping Study identified elements that are considered by researchers to have an impact on TD in the industrial environment [3]. The authors classified these twelve elements in three main categories: (1) Basic decision making factors, (2) Cost estimation techniques, and (3) Practices and techniques for decision-making. They mapped these elements to the stakeholders' point of view, specifically, for business organizational management, engineering management, and software engineering areas.

Several authors proposed definitions for TD and its interests. Nugroho et al. [4] define TD as *"the cost of repairing quality issues in software systems to achieve an ideal quality level"* and the interests of the debt as *"the extra maintenance cost spent for not achieving the ideal quality level."* Other works try to empirically correlate TD with software size, software quality, customer satisfaction, and other software properties, in the context of enterprise software systems [5].

In a recent Dagstuhl Seminar [6], the following definition of TD was proposed: *"In software-intensive systems, technical debt is a collection of design or implementation constructs that are expedient in the short term, but set up a technical context that can make future changes more costly or impossible. Technical debt presents an actual or contingent liability whose impact is limited to internal system qualities, primarily maintainability and evolvability."*

The Software Quality Assessment based on Lifecycle Expectations (SQALE) method [7] addresses a set of external qualities (like Reliability, Efficiency, Maintainability, etc.). Each of these qualities is associated with a set of requirements concerning internal qualities, each provided with a *"remediation function,"* which represents the cost of changing the code so that the requirement is satisfied. Based on these functions, the cost of TD is computed for each external quality and for all qualities.

The Object Management Group has published a beta version of the specification of a measure of TD principal, defined as *"The cost of remediating must-fix problems in production code"* [8]. The measure can be computed automatically as a weighted sum of the *"violations of good architectural and coding practices,"* detected according to the occurrence of specific code patterns. The weight is computed according to the expected remediation effort required for each violation type.

B. Tools Detecting Technical Debt

Several tools are now available to detect TD automatically. Examples of tools are (alphabetically ordered): CAST [9], [10], SonarCloud [11], Squore [12], [13], TeamScale [14], [15], and many more.

The CAST Research Labs (CRL) is part of the enterprise CAST Application Intelligence Platform and is focused on the calculation of the TD for software applications by collecting metrics and structural characteristics of software. CRL also returns insights that can help developers improve the application structural quality.

SonarCloud (aka SonarQube) is an open source cloud platform where software developers can upload their software and collect a set of quality metrics, bugs, vulnerabilities, code smells, code coverage, and code duplications. Starting from all these data, SonarCloud estimates the TD of the software under analysis. Developers may study also the evolution of the TD over time by navigating interactive charts.

Squore is a commercial solution similar to SonarCloud. A set of dashboards visually report quality metrics and 4 key insights (i.e., the overall rating of the software under analysis, trend analysis, forecasts, and project portfolio comparison). Moreover, a specific section is related to TD where four indicators (efficiency, portability, maintainability, and reliability) are used to calculate the TD density and ranking (similar to the six grades used by SonarCloud). The remediation cost shows how many man-days are supposed to be needed to eliminate all TD highlighted.

TeamScale is a commercial tool based on a set of dashboards where managers can monitor the evolution of the quality of their applications. TeamScale is able to analyze the architecture conformance, code clones, missing tests, coding conventions, documentation, external and internal software metrics, and TD. Developers and managers can track the evolution of their software applications by comparing different releases and visualizing the history trend of quality metrics.

All of the mentioned tools can be used to get an overall evaluation of code quality, expressed in terms of TD.

C. System Dynamics

System Dynamics was developed by Jay Forrester [16] as a modeling methodology that uses feedback control systems principles to represent the dynamic behavior of systems. The elements of System Dynamics models are levels, constants,

auxiliary variables and rates. The dynamics of systems is determined by how levels work: given a level L, its value in time is always determined by an equation $L(t + \Delta t) = L(t) + (in(t) - out(t))\Delta t$, where *in(t)* and *out(t)* are rates. Levels and rates can concern anything (e.g., people, rabbits, bricks, lines of code, etc.), depending on the application scope and goal of the model. The value of a rate at time t is defined based on the values of auxiliary variables, other rates and levels at time t. Likewise for auxiliary variables, which are not necessary, but are useful to write readable models.

The elements of a System Dynamics model are interconnected just like in the real world, to form a network, where causes and effects are properly represented. Models can be executed, so that the behavior of the modeled system can be simulated. Via System Dynamics models, it is quite easy to perform what-if analyses: you obtain different behaviors by changing the initial state of the system (given by the values of levels), how rates and variable are computed, how they depend on each other, etc.

III. The Proposed Model

As already mentioned, the proposed model describes in an operational way the time-boxed development process, especially in terms of maintenance activities concerning the reduction of TD. The proposed model aims at evaluating the productivity of development and maintenance activities, and the quality of the released product. Productivity is here defined as the ratio of the amount of product—measured in Function Points (FP) [17][18]—developed in a time period to the amount of effort/resources used.

To focus on the main objectives, we abstract from all those aspects of the model that deal with activities and software products that are not directly connected with TD management. For instance, in a real process, the productivity of individuals tends to increase because of learning effects, the number of developers allocated may change during a project, etc.: we exclude all of these variables because they would introduce noise in our investigation, which focuses on the effects of TD management decisions alone.

A. Assumptions

The main reason why practitioners and researchers are interested in TD is that maintaining code burdened with a big TD (i.e., low-quality code) costs much more than maintaining code with little TD (i.e., high-quality code). This is because more work is needed to carry out any code-related activity when code is of low quality (e.g., difficult to understand, poorly structured, full of hidden dependencies, etc.).

To account for the relation that links TD to maintenance cost, we need a measure of TD. To this end, we measure TD via a "TD index," an indicator that takes into account the internal qualities of code that concur to determine the amount of TD embedded in the code. Here, we are not interested in defining precisely the TD index, based on the measures of individual internal qualities, because this is not relevant for our purposes. Clearly, accurately modeling individual internal qualities of code would make the model more apt at reproducing the behavior of real development environments. But this is not our purpose: we aim at building a model that shows—at a fairly high level—the effects of decisions concerning TD management in a generic realistic development environment.

We assume that the TD index ranges between 0 (highest quality) and 1 (worst quality). The extreme values represent limiting cases, which may not occur in practice. When the TD index is 1, maintenance is so difficult that one is better off by simply throwing away the code and building a new version from scratch, and productivity is null, i.e., *prod* = 0. When the TD index is 0, maintenance activities attain their optimal productivity $prod_{opt}$. When 1>TD index>0, *prod* steadily increases from 0 to $prod_{opt}$ when the TD index decreases.

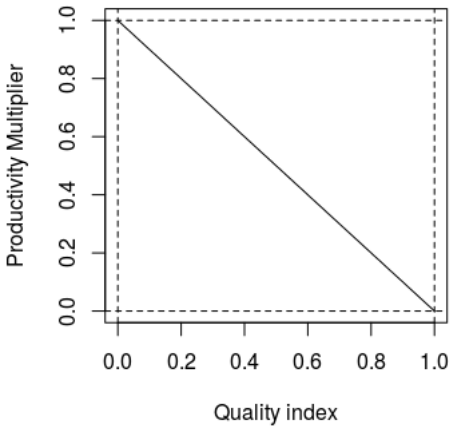

Figure 1. Effect of technical debt on productivity.

The value of productivity for a given value of the TD index *prod(TDindex)* can be expressed as *prodMult(TDindex)* $\times prod_{opt}$. Figure 1 shows a possible behavior of *prodMult(TDindex)*. Namely, Figure 1 implies that there is a linear relationship between TD and productivity: when the TD index is zero (i.e., quality is optimal) productivity is maximum, when the TD index is one (i.e., quality is as bad as possible) productivity is null.

We use the function illustrated in Figure 1 to build models to exemplify our proposal. Other monotonically decreasing functions (e.g., concave or convex function) that go through points $(0, 1)$ and $(1, 0)$ could be used as well. Here we use the linear model because we have no reason to do otherwise, especially considering that the TD index itself is not thoroughly defined.

Here, we assume that development is carried out in a time-boxed way. This is coherent with the organization of development in most agile processes. We assume that the development is composed of a sequence of "sprints," each of which has a fixed duration and involves a constant number of developers, hence a sprint "consumes" a fixed number of Person Days (PD). For instance, if sprints last 20 work days and involve 5 developers, then each sprint "costs" 100 PD. If at the end of 5 sprints 416 FP are released, we have achieved a productivity of 416/(5·100)=0.832 FP/PD; if at the end of these sprints 378 FP are released, we have achieved a productivity of 378/500=0.756 FP/PD. Quite clearly, in the former case the management of TD was more effective, a higher productivity was achieved, more functionality was released, and bigger returns can be expected.

A consequence of our assumptions is that the amount of effort spent is strictly proportional to development duration, which can be expressed in number of sprints. Given this

proportionality between effort and the number of sprints, we can express productivity as the amount of code released after N sprints. Thus, we measure the productivity values above as 416/5=83.2 FP/Sprint (instead of 416/500=0.832 FP/PD) and 378/5=75.6 FP/Sprint (instead of 378/500=0.756 FP/PD).

During each sprint, the developers can carry out two types of activities: 1) increase the functionality of the system, by adding new code, and 2) decrease TD, by refactoring code structure, removing defects and improving the qualities that make development and maintenance easier. Since in each sprint the amount of work is fixed, managers have to decide what fraction of work has to be dedicated to new code development—the remaining fraction being dedicated to TD management. Several different criteria can be used in setting such fraction, as illustrated in Section IV.

We assume that during each sprint a constant fraction of the new code affected by quality problems (hence, increasing the TD) is released. This fraction depends on several factors, like the experience and ability of developers, the availability of sophisticated tools, problem complexity, etc. We assume that these factors are constant throughout all the sprints: in this way, we do not generate noise and we can highlight the effects of TDM decisions.

B. The Model

The proposed System Dynamics model involves two level variables: `CodeSize` (measured in FP) and `TDIndex`.

The constants in the model are:
`nominal_maintenance_productivity`, the productivity in FP/Sprint in ideal conditions, i.e., when the TD index is zero. We assume that the nominal productivity is 80 FP/Sprint, corresponding to 0.1 FP/PersonHour, a fairly typical value [19].
`nominal_TDimprovement_productivity`, the amount of code that can be optimized—i.e., whose TD is completely repaid—in a sprint, when the effort is completely devoted to TD improvement. We assume that this value is 40 FP/Sprint. In real developments, this amount is not necessarily constant: a sprint could be sufficient to "clean" 40 FP or relatively good code, but not to "clean" 40 FP of very bad quality code.
`bad_fraction_of_new_code`, the fraction of the new code (released at the end of each sprint) that contributes to increasing TD. We here assume that the value of this constant is 0.2.
`available_effort`: the effort available at each sprint. As already mentioned, we assume it to be a constant. The actual value is not relevant, however, we can take 100 PD as a reference value.

The rate and auxiliary variables of the model are:
`fraction_of_effort_for_quality_maintenance`: the fraction of `available_effort` dedicated to repaying TD. This variable is computed via function `fracEffortForQuality`, which has the TD index as an argument.
`quality_maintenance_effort`: the effort available for improving the quality of code in a sprint.
`maintenance_effort`: the effort available for developing new code in a sprint.
`maintenance_productivity`: the productivity of developing new code in a sprint. It depends on the `nominal_maintenance_productivity`, the `maintenance_effort` and the decrease of productivity due to the TD (computed via function `productivity_considering_TD`).
`TD_dec_rate`: the TD decrease rate.
`TD_inc_rate`: the TD increase rate.

The values of the aforementioned variables are determined by the following equations:

```
available_effort=1
fraction_of_effort_for_quality_maintenance=
 fracEffortForQuality(TDindex)
quality_maintenance_effort=available_effort*
 fraction_of_effort_for_quality_maintenance
maintenance_effort=
 available_effort-quality_maintenance_effort
maintenance_productivity=
 nominal_maintenance_productivity*
 maintenance_productivity_considering_TD(TDindex)
TDimprovement_productivity=
 nominal_TDimprovement_productivity*
   quality_maintenance_effort
TD_inc_rate=bad_fraction_of_new_code*
 maintenance_productivity/CodeSize
TD_dec_rate=TDimprovement_productivity/CodeSize
```

where the following functions are used:
`maintenance_productivity_considering_TD(TDindex)`: the loss of productivity due to TD, as described in Figure 1.
`fracEffortForQuality(TDindex)`: this function describes the strategy used for tackling TD. In Section IV, we use a few different strategies, hence, a few different function definitions.

The levels are computed as follows (where all auxiliary and rate variables are computed at time t):

```
CodeSize(t+Δt)=CodeSize(t)+
    Δt*maintenance_productivity
TDindex(t+Δt)=TDindex(t)+
    Δt*(TD_inc_rate-TD_dec_rate))
```

IV. Simulating the Model

We simulate the model with a few different TD management strategies. The considered case is characterized as follows. Initially, the software system to be maintained has size 80 FP and its TD index is 0.2 (representing the quality gap between the "ideal" quality and the actual initial quality accepted to speed up development and release the product early). The nominal productivity (i.e., new code development productivity in ideal conditions, when no extra effort is due because of TD) is 80 FP/Sprint. The nominal TD repayment productivity (i.e., the amount of functionality for which the TD is completely repaid in a sprint) is 40 FP/Sprint. At the end of every sprint, 20% of the added code is "bad" code.

Our software organization goes through a sequence of 30 maintenance sprints. We assume that there are always enough new requirements to implement to use up the development capacity of sprints. This is a situation that occurs quite often in practice. We also assume that the same amount of effort is allocated to all sprints. In actual developments, this does not always happen. Anyway, simulations that do not depend on variations in the available effort provide better indications of the effects of TD management strategies, since they do not depend on accidental phenomena, like the amount of available workforce.

A. Constant Effort for TD Management

In the first simulation, we assume that the considered software development organization allocates a constant fraction of the effort available in each sprint, to tackle the TD. It is reasonable to expect that the achieved results depend on how big the fraction of effort dedicated to TD management is. Hence, we run the simulation a few times, with different fractions of the available effort dedicated to TD management, ranging from zero (i.e., nothing is done to decrease the TD) to 40%. The main results of the simulation are given in Figure 2, which shows, from left to right: the functional size of the software product version released after each sprint; the functional size increment due to each sprint (i.e., the enhancement productivity of each sprint); the evolution of the TD through sprints (i.e., the quality of the software product versions released after each sprint).

The amount of functionality delivered at the end of the sprints, and the corresponding TD index are also given in Table I.

TABLE I. RESULTS WITH DIFFERENT FRACTIONS OF EFFORT DEDICATED TO TD MANAGEMENT

Fraction of effort for TD management	Delivered functionality [FP]	Final TD index
0	960	0.77
0.1	1244	0.54
0.2	1461	0.3
0.3	1616	0.05
0.4	1480	0.01

We can examine the achieved results starting with the solid black lines, which represent the case in which no effort at all is dedicated to repaying the TD. It is easy to see that the results obtained by this TD management strategy (a no-management strategy, actually) are quite bad. In fact, after 30 sprints we get only 960 FP: about 500 FP less than the most efficient TD management strategy. Not only: the final product has TD index = 0.77, that is, a very low quality, probably hardly acceptable in practice. The effects of TD on maintenance productivity are apparent: the continuously growing TD makes maintenance less efficient over sprints and after the first 15 sprints, productivity has dropped from 80 FP/Sprint to less than 30 FP/Sprint, due to TD. So, just ignoring the TD is not a good practice. Definitely, we have to allocate some effort to decrease the TD, but how much effort should we dedicate to repaying TD?

By looking at Figure 2 and Table I, it is easy to see that dedicating 10% of the available effort to repaying TD improves the situation with respect to not managing the TD at all: the final size (1244 FP) is bigger, and the final TD index (0.54) is better, though not really good. When we dedicate 20% of the available effort to repaying TD the results improve further: the final size (1461 FP) is bigger, and the final TD index (0.3) is better, though still not very good.

In summary, by increasing the fraction of effort dedicated to repaying TD from 0 to 20% we improve both the amount of functionality that we are able to release, and the quality of the software product. Hence, it would be natural to hypothesize that, by further increasing the fraction of effort dedicated to repaying TD, we obtain improvements in both the amount and quality of delivered software. Actually, this is not the case: when 30% of the available effort is dedicated to repaying TD, we further improve both the released functionality (1616 FP) and the quality (TD index = 0.05), but if an even bigger fraction (40%) of effort is dedicated to repaying TD, we achieve practically ideal quality (the final TD index is 0.01), but substantially less functionality (the final size being 1480 FP).

The explanation of these results is that this is a case of Pareto-optimality: beyond a given point it is not possible to further improve quality without decreasing the amount of released functionality, and vice-versa. Increasing the fraction of effort dedicated to TD improvement clearly improves maintenance productivity by decreasing TD, but at the same time subtracts effort from enhancement maintenance activities. Hence, one should look for a trade-off, to achieve both a reasonably high productivity level and an acceptable quality level (i.e., a sufficiently small TD).

Via a series of simulations, it is possible to find the fraction of effort dedicated to repaying TD that maximizes the released functionality, hence maintenance productivity. In the considered case, allocating 32% of the available effort to TD improvement eventually results in yielding 1638 FP, the final TD index being 0.007.

Finally, it should be noticed that in the short term—i.e., in the first eight sprints or less—not managing TD does not seem to cause relevant negative consequences. For instance, in the considered case, if the goal is to achieve a 400 FP software product, not managing the TD may be a viable choice: you get the product faster than by managing TD. Of course, one should be sure that no further maintenance will be needed, otherwise maintenance cost would be quite high, that is, one has just postponed paying the debt, also adding some interest.

B. Variable Effort for TD Management

In the previous section, the fraction of effort dedicated to quality improvement was fixed, i.e., it was constant over the sprints. This can be used as a first assumption, but it may not be a good managerial choice, for at least the following two reasons. First, the initial TD could be greater than in the case described in Section IV-A. Hence, it would be a good practice to devote a substantial amount of effort to improve quality at the beginning of development, with the objective of decreasing the TD, and then proceed with easier and more productive maintenance. This corresponds to repaying (all or a substantial part of) the TD in the first sprints: the following sprints will have to pay low or null interests.

Second, the effort dedicated to TD management could be excessive. Consider the evolution of the TD index through sprints illustrated in Figure 2: when the fraction of effort dedicated to quality improvement is 40%, the TD is practically nil after 10 sprints. In the following sprints, the fraction of effort for TD management is partly used to balance the increase of debt caused by new code, and part is wasted. This effect is easy to see when you compare the effects of dedicating 30% and 40% of the available effort to TD management. After a few sprints, in both cases the TD index is practically constant (about 0.07 in the former case, about 0.01 in the latter case). Maintenance productivity is also constant in the two cases, but higher in the former case, as shown in the central graph of Figure 2. How is it possible that, when 30% of effort is dedicated to TD management, we are using some effort to manage a higher TD, and still we get a higher productivity?

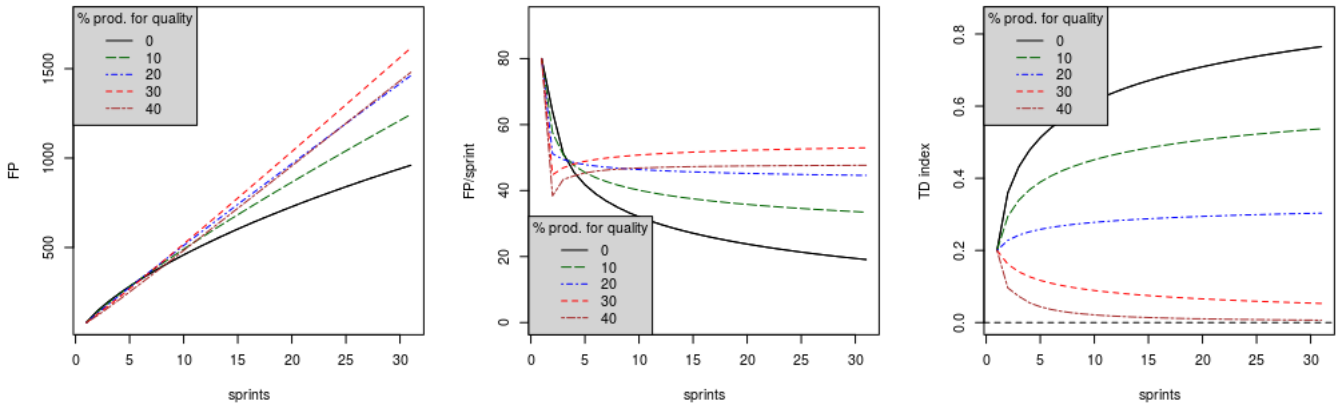

Figure 2. Size of delivered code, Sprint productivity and TD index, depending on a constant fraction of effort allocated to improving the TD.

Because the effort needed to keep TD close to zero is much less than the allocated 40%: the exceeding part is wasted.

A better strategy for TD management would be to allocate to TD improvement a fraction of effort that is larger when the TD is large and smaller when the TD is little. Of course, there are various ways to decide the fraction of effort to be dedicated to decrease TD. We adopt the function shown in Figure 3, which defines the fraction of effort for TD improvement as $1-(1-TDindex)^k$. By changing the value of k we decide how aggressive the approach to debt repayment is: with $k = 1$ the fraction of the effort dedicated to debt repayment is proportional to the debt; with $k > 1$ as soon as TD index raises above zero, a substantial fraction of the effort (the greater k the bigger the fraction) is dedicated to decrease TD.

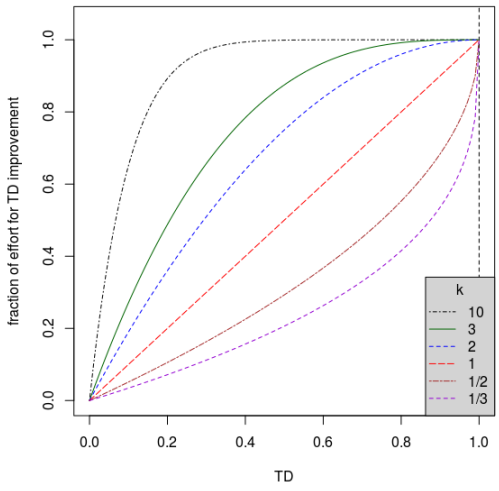

Figure 3. Percentage of effort dedicated to TD improvement, as a function 1-(1-TDindex)^k of TD.

In this section, the fraction of effort dedicated to TD management is decided at every sprint, as $1-(1-TDindex)^3$: a moderately aggressive policy. When debt increases, we try to decrease it fairly soon, to avoid paying large interests. Figure 4 shows the results of the simulation. The adopted policy provides good results: at the end of the sprints we get 1653 FP, more than in any of the simulations performed in Section IV-A. The final TD index is < 0.1, that is, a very good quality.

It is interesting to note that after a few sprints, the TD index remains constant, and, as a consequence, productivity remains constant as well. The reason is that, at the beginning of each sprint, the effort dedicated to TD management is adequate for repaying the existing TD, but, during the sprint, new TD will be created. This situation is perpetuated over the sprints. To completely repay TD, a policy should allocate enough effort to both repay the existing TD, and to *anticipate* the new TD, by performing maintenance in a way that preserves optimal code structure and quality.

However, the strategy simulated in this section dedicates a large fraction of effort to decrease the TD in the first sprints, which guarantees very good results, in terms of both the amount of functionality delivered and the delivered quality.

C. Dedicating Sprints to Technical Debt Removal

In time-boxed development, it is often the case that a sprint is either completely dedicated to enhancement or to decreasing TD (especially via refactoring). So, the policy for allocating effort to TD management is simple: if the TD index is sufficiently high (i.e., above a given threshold), the next sprint will be completely dedicated to TD repayment; otherwise, the next sprint will be dedicated completely to maintenance. In our case, if a sprint is dedicated completely to TD management, developers will be able to optimize a portion of code 40 FP large. Hence, we can allocate a sprint to TD management when a portion of code of at least 40 FP is affected by TD: this is the threshold for deciding to stop developing and have a refactoring sprint.

We simulated development with this criterion for allocating effort to TD management and we obtained the results illustrated in Figure 5. It is easy to see that this strategy results, on average, in two consecutive development sprints followed by a refactoring sprint. TD progressively decreases until it becomes practically nil (oscillating between 0.01 and 0.03). At the end of sprints, 1623 FP are released, that is, a bit less than with the policy described in Section IV-B. However, at the end of refactoring sprints the achieved TD index is better, compared to the TD index achieved in Section IV-B.

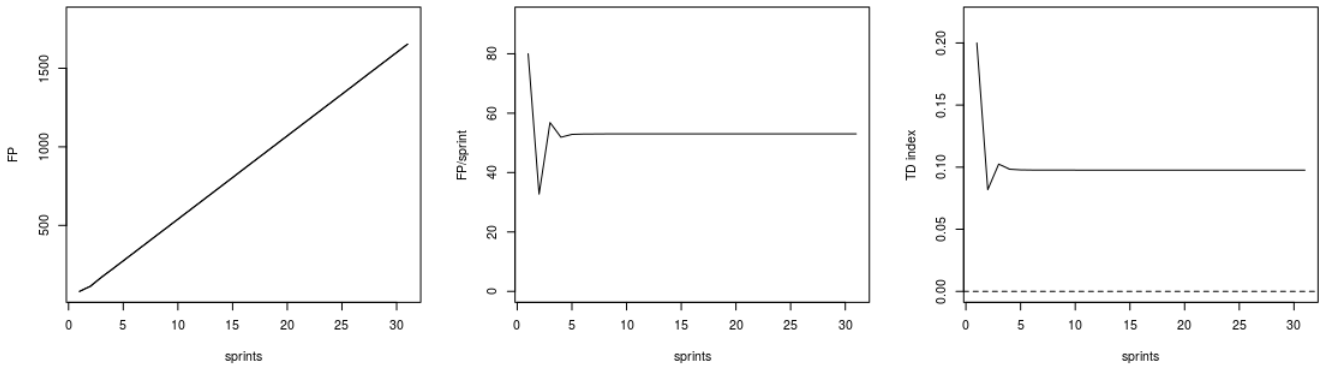

Figure 4. Size of delivered code, Sprint productivity and TD index through sprints, when the fraction of effort for TD improvement is 1-(1-TDindex)^3.

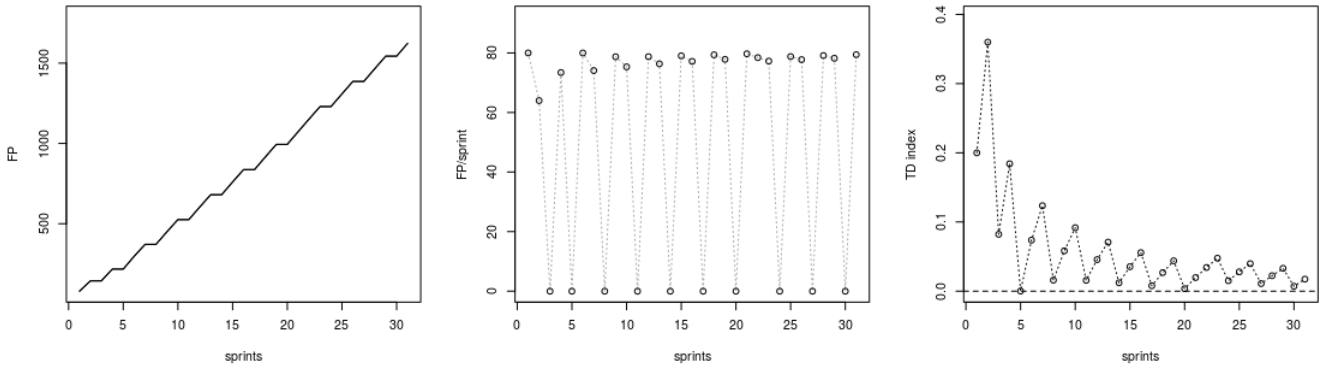

Figure 5. Size of delivered code, Sprint productivity and TD index through sprints, when sprints are dedicated to either TD management or maintenance.

As a final observation, we should consider that applying this strategy is relatively easy, while applying the 'variable fraction' strategy described in Section IV-B is more difficult: with that strategy, both enhancements and refactoring are performed in each sprint: event though this is a fairly natural way of working for developers, it is difficult to assure that exactly the planned amount of effort is dedicated to refactoring.

V. Discussion

The results obtained with the different criteria for allocating effort to TD improvement are summarized in Table II. In Table II, we have added the results—not given in Section IV-B—obtained when the fraction of effort dedicated to TD improvement is 1-(1-TDindex)$^{1/3}$. In such case, the fraction of effort dedicated to TD improvement decided at the beginning of each sprint is based on the current TD index, but the approach is not aggressive. On the contrary, a substantial fraction of effort is dedicated to TD improvement only when the TD index is relatively large.

The results given in Table II, along with the more detailed results reported in Section IV, suggest a few observations.

First, allocating a constant amount of effort to TD improvement does not seem to be a good idea. In fact, if the chosen fraction of effort allocated to TD improvement is too high or too low, the productivity of enhancement maintenance will be lower than possible. Also, the final quality of the product (as indicated by the TD index) could be quite low. In practice, allocating a constant amount of effort to TD improvement works well only if the right fraction of effort is allocated, but choosing such fraction may not be easy.

TABLE II. RESULTS WITH VARIOUS CRITERIA

Criterion	Delivered functionality [FP]	Final TD index
Constant (0%)	960	0.77
Constant (10%)	1244	0.54
Constant (20%)	1461	0.30
Constant (30%)	1616	0.05
Constant (40%)	1480	0.01
1-(1-TDindex)^3	1653	0.10
1-(1-TDindex)$^{1/3}$	1282	0.44
Threshold	1623	0.02

On the contrary, computing the amount of effort for TD improvement at the beginning of each sprint, based on the current TD index seems very effective, especially as far as optimizing the productivity of enhancement maintenance is concerned.

One could observe that in some situations it may be hard to separate clearly the effort devoted to enhancements from the effort devoted to TD improvement. This is particularly true when developers perform refactoring activities while they are enhancing the existing code. For this reason, an organization may want to have sprints entirely dedicated to refactoring and other TD improving activities, and sprints entirely dedicated to enhancements. In this case, the evaluations given

in Section IV-C show that allocating an entire sprint to TD improvement whenever there is enough TD to absorb one spring effort provides quite good results, in terms of both productivity and quality.

In any case, we have to stress that all the presented strategies for TD management are based on the quantitative evaluation of TD, which results in the TD index. So, devising a way to measure TD appears fundamental to managing TD effectively and efficiently.

VI. Consequences of a Wrong Evaluation of Technical Debt

Based on the considerations given in Section V above, an organization may decide to adopt the strategy that allocates entire sprints to decrease TD, whenever the TD index becomes big enough, i.e., when the effort spent in a sprint can be absorbed entirely by refactoring and other TD decreasing activities.

Now, the value of the TD index is computed based on the analysis of the code quality performed by tools. Let us suppose that the evaluation reported by tools is not accurate, or that the computation of the TD index based on such evaluation is biased. This will likely result in dedicating too much or too less effort to TD management. In this section, we study the dependence of the effectiveness of managerial decisions concerning TD management on the accuracy of the TD index used to take those decisions.

A. Revised System Dynamics Model

In the model given in Section III-B we have

```
fraction_of_effort_for_quality_maintenance=
 fracEffortForQuality(TDindex)
quality_maintenance_effort=available_effort*
 fraction_of_effort_for_quality_maintenance
```

where the function `fracEffortForQuality(TDindex)` specifies the strategy used for tackling TD, based in the TD index. In this model, variable TDindex is assumed to represent the *real* amount of TD currently associated with the code.

We modified the model as follows:

```
reportedTD=perceivedTD(TDindex)
fraction_of_effort_for_quality_maintenance=
 fracEffortForQuality(reportedTD)
quality_maintenance_effort=available_effort*
 fraction_of_effort_for_quality_maintenance
```

where function `perceivedTD(TDindex)` provides the amount of TD that is perceived by the project manager. Such value depends on the actual `TDindex` and possibly on many other factors. As already mentioned, here we are not interested in defining a detailed model that accounts for all the relevant factors that may affect development, but only to highlight the effect of a few factors specifically related to TD management. Therefore, we define function `perceivedTD(TDindex)` simply as returning `TDindex`×`TDperceptionFactor`, where `TDperceptionFactor` is a constant. Clearly, when `TDperceptionFactor` is one, the perceived value of the TD index is the real value of the TD index, while `TDperceptionFactor`< 1 (respectively, > 1) indicates an underestimation (respectively, overestimation) of the TD index.

The value given by function `perceivedTD(TDindex)` is assigned to variable `reportedTD`, which is then used as the argument of function `fracEffortForQuality` to decide how much effort should be dedicated to TD maintenance. With the adopted strategy, if this effort is greater or equal than the effort available in a sprint, the next sprint is dedicated completely to decreasing the TD.

B. Simulating the Effects of Wrong Evaluations of Technical Debt

We simulated the system with different values of `TDperceptionFactor`.

The first outcome we obtained is that when the TD index is moderately overestimated, the results tend to improve, even though only marginally. For instance, when `TDperceptionFactor`=1.2, i.e., when a TD index equal to 0.2 is perceived as 0.24, we get the results described in Figure 6. After 30 sprints, we get 1629 FP and a (real) final TD index slightly above = 0.02. That is, we slightly increased the amount of released functionality at the expenses of very little (practically negligible) decrease of quality.

Underestimating the TD might appear to be more dangerous: when the TD index is underestimated by 10%, we get the results in Figure 7.

After 30 sprints, we get 1588 FP and a (real) final TD index slightly above = 0.03. Although the loss of quality is marginal, we get 46 FP less than when perceiving the amount of TD exactly.

By increasing the underestimation, the results do not change dramatically. When the perceived TD is 75% of the actual TD, we achieve 1546 FP with a still quite good quality (TD index is 0.04).

Probably, we should be more worried about overestimation. In fact, tools performing static code analysis tend to reveal many "violations" of code correctness rules, that may induce project managers—with special reference to those not having a deep understanding of how tools work—to think that their code carries a much larger TD than it actually does.

With our simulated system, a breakpoint occurs when the TD index is overestimated by 135% or more. In such cases, we get the situation depicted in Figure 8. Figure 8 shows that the overestimation of TD induces the project manager to dedicate every second sprint to TD removal. This greatly decreases the amount of effort dedicated to enhancement. The released functionality at the end of the sprints is thus just 1280 FP.

C. Considerations on the Required Accuracy of Technical Debt Evaluation

The simulations described in Section VI-B above show that the correct evaluation if the quantity of TD is important to achieve optimal results. The effects of errors in evaluating the TD index are summarized in Table III.

It can also be observed that the adopted strategy, namely the allocation of entire sprints to TD removal when there is enough TD to justify such allocation, is fairly robust with respect to errors in evaluating the amount of TD. In fact, when the TD evaluation error is relatively small, the 'pattern' of enhancement and TD removal sprints remains unchanged. This is evident by looking at the central graphs of Figures 5, 6 and 7: in all these cases, after the initial sprints we have a TD

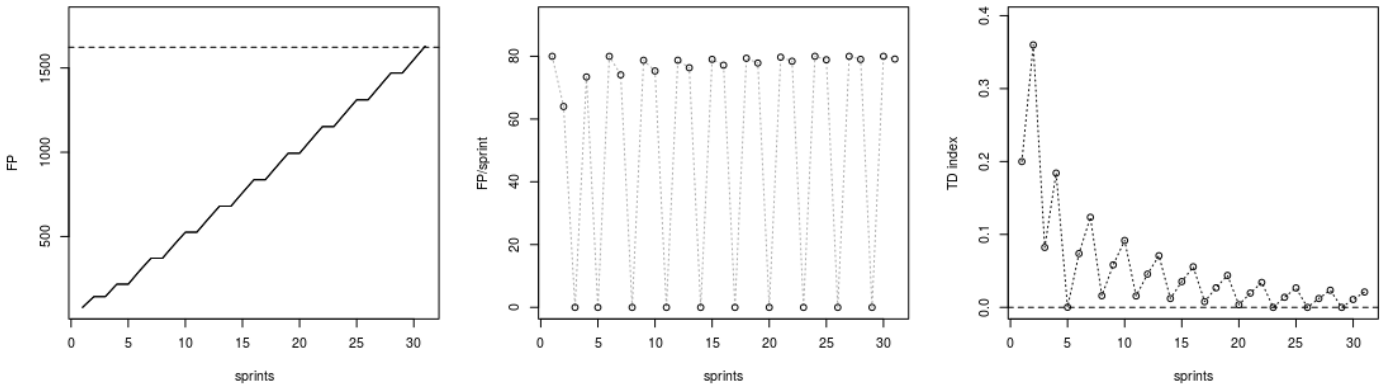

Figure 6. Size of delivered code, Sprint productivity and TD index through sprints, when sprints are dedicated to either TD management or maintenance and TD index is overestimated by 20%.

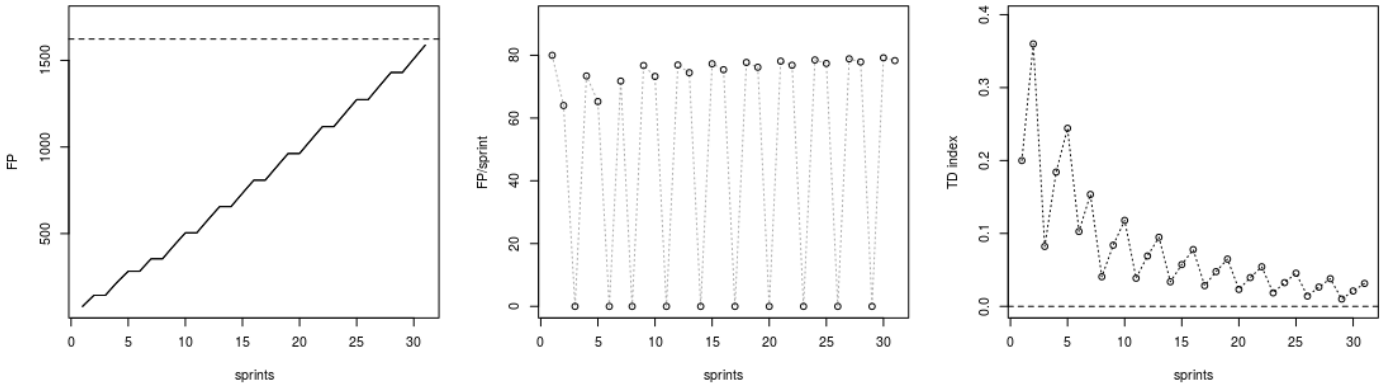

Figure 7. Size of delivered code, Sprint productivity and TD index through sprints, when sprints are dedicated to either TD management or maintenance and TD index is underestimated by 10%.

TABLE III. EFFECTS OF ERRORS IN EVALUATING TD

Error	Delivered functionality [FP]	Final TD index
-25%	1546	0.03–0.04
-10%	1588	0.02–0.03
0%	1623	0.01–0.02
+10%	1626	0.01–0.02
+25%	1629	0.01–0.02
+50%	1556	0.00–0.02
+100%	1565	0.00–0.01
+135%	1257	0.00–0.01

removal sprint every three sprints, with just an exception (in Figures 5 a sequence of three enhancement sprints is present). So, the variations in the amount of delivered functionality are due only to the fact that productivity depends on the amount of TD in the code.

On the contrary, when the overestimation of TD is large, we have that every second sprint is dedicated to TD removal (see the central graph of Figure 6): half of the project development effort is dedicated to removing non-existent TD.

In conclusion, it appears useful to evaluate the TD as correctly as possible, and it is absolutely necessary to avoid large overestimations of TD.

VII. Related Work

The term "technical debt" (TD) was forged by Cunningham [20]. Cunningham observes that sometimes code whose internal quality is not really optimal is released to achieve some immediate advantage, e.g., to ship a product in the shortest possible time, and that *"Shipping first time code is like going into debt. A little debt speeds development so long as it is paid back promptly with a rewrite. [...] The danger occurs when the debt is not repaid"* because *"excess quantities [of immature code] will make a program unmasterable."*

TD has received a good deal of attention from researchers. For example, a recent Systematic Mapping Study on TD and TD management covering publications from 1992 and 2013 detected the existence of 94 primary studies that were used to obtain a comprehensive understanding on the TD concepts and an overview on the current state of research on TD management [2]. As for TD management, the study reported that some activities—such as TD identification and measurement—received a good deal of attention, while other activities—such as TD representation and documentation—did not receive any attention at all. Finally, a clear lack of tools for managing TD was highlighted: only four tools are available and dedicated to managing TD.

In another Systematic Mapping Study [21], among others,

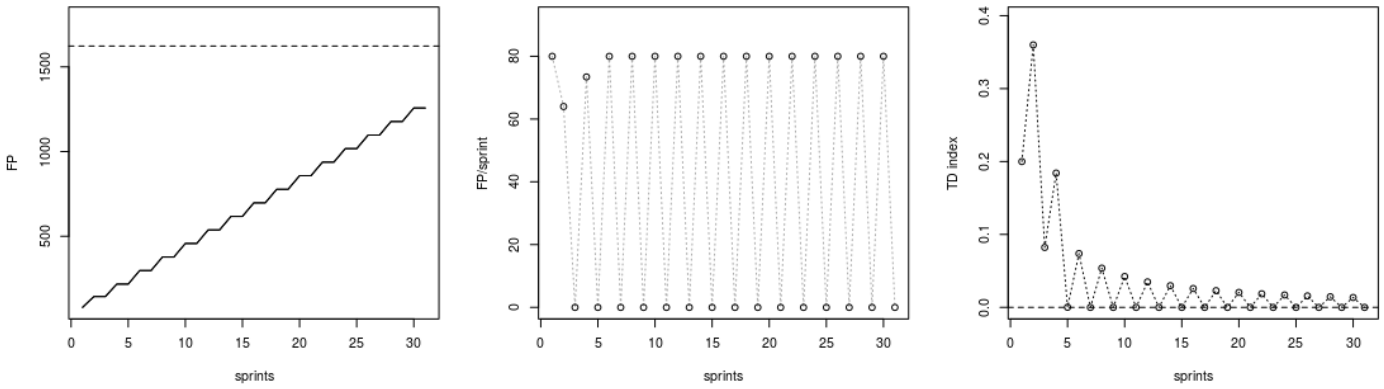

Figure 8. Size of delivered code, Sprint productivity and TD index through sprints, when sprints are dedicated to either TD management or maintenance and TD index is overestimated by 135%.

the following research question was addressed: *What strategies have been proposed for the management of TD, which empirical evaluations have been performed, and which software visualization techniques have been proposed to manage TD?* The findings of the study show that most studies deal with TD at the source code level (i.e. design, defect, code and architecture debt) and researchers detected the existence of TD throughout the entire lifecycle of the project. This implies that ensuring the quality of the project's source code is not the only way to enhance project quality. However, researchers limit the study to the existing problems in the source code. Several studies focus on strategies to manage TD. However, only five strategies (Portfolio Approach, Cost-Benefit Analysis, Analytic Hierarchy Process, Calculation of TD Principal, and Marking of dependencies and Code Issues) were cited and evaluated in more than two papers. Few studies addressed the evolution of TD during the development and maintenance phases of a project.

System Dynamics was first applied in Software Engineering by Abdel-Hamid and Madnick [22], who proposed a model that accounted for human resource management, software development, and planning and control.

The model by Abdel-Hamid and Madnick was used to study software effort and schedule estimation [23], project staffing [24], project control with unreliable information [25], as well as several other aspects of software project management and development.

A software tool for writing and simulating System Dynamics models dealing with software development was also developed [26].

System Dynamics models were also used for simulating, understanding and optimizing the software development process [27] and various activities involved in software development, like requirements engineering [28], reliably control [29], knowledge management [30], outsourcing [31], [32], security [33], and system acquisition [34].

System Dynamics was then extensively used to model software development and its management. A survey of System Dynamics applied to project management was published by Lyneis and Ford [35], while in [36] De Franca and Travassos propose a set of reporting guidelines for simulation-based studies with dynamic models in the context of SE to highlight the information a study of this type should report.

Cao et al. [37] proposed a System Dynamics simulation model that considers the complex interdependencies among the variety of practices used in Agile development. The model can be used to evaluate—among others—the effect of refactoring on the cost of implementing changes. The model proposed by Cao et al. is quite comprehensive: it includes sub-models of human resource management, Agile planning and control and Customer involvement, which are not present in our model. Besides, the models of Software production, Change management, and Refactoring and quality of design are more detailed than in our model. In fact, the model by Cao et al. aims at providing a complete and realistic simulation of real Agile processes, so it needs to be complete and detailed, while we just aim at showing the occurrence of phenomena that are described by the literature on TD.

Glaiel et al. [38] used System Dynamics to build the Agile Project Dynamics model, which captures each of the Agile main characteristics as a separate component of the model and allows experimentation with combinations of practices and management policies. Like our model, the APD model addresses developments that proceed through sprints and includes the representation of TD; nonetheless, the APD model is quite different from ours. In fact, the APD model is quite complex, as it aims at capturing several (if not all) of the characteristics of agile development, while our model is a proof of concept, aiming at showing how the TD works. As a result, the effects of basic managerial decision (like the proportion of effort to be devoted to quality improvement) on TD are more evident in our model.

We remind the reader that our model is by no means suitable for realistic simulations, being oversimplified. The ADP model is for sure more suitable for simulating the likely behavior of a real agile development project.

Finally, it should be noted that both Glaiel et al. [38] and Cao et al. [37] model agile software development processes, while we propose a model of a software development process that—although incremental and time-boxed—is not constrained by several features of typical agile development processes.

A consequence of this difference is that the models by

Cao et al. and by Glaiel et al. consider quality improvements exclusively connected with refactoring, while in our model quality improvement is a specific goal, which is supported by ad-hoc budget (the fraction of effort dedicated to quality improvement) and can be performed continuously and in conjunction with development activities.

Cao et al. develop a system dynamics simulation model that –although comprehensive– does not focus on technical debt and how to optimize its management, as we propose to do. Glaiel et al. model technical debt and its management as part part of the refactoring section of a larger model. As such, the effect and the management options for dealing with technical debt are somewhat hidden in the model. On the contrary, our model lets us focus on the technical debt, its effects and the consequences of specific management strategies.

In conclusion, to the best of our knowledge, no other paper addresses the TD management problem as we did. Although less comprehensive than the mentioned System Dynamics models, our proposal helps better understand the consequences of TD and the effectiveness of its management strategies.

VIII. Conclusions

The term "technical debt" indicates several concepts and issues related to software development and maintenance. The latter are complex and multifaceted activities: accordingly, it is not surprising that managing TD is quite difficult [6].

In this paper, we have provided a formal, executable model of time-boxed software development, where the effects of TD are explicitly and quantitatively represented and accounted for. The model is usable to show—via simulation—the effects that TD have on relevant issues such as productivity and quality, depending on how TD is managed, with special reference on how much effort is dedicated to TD repayment and when—in a sequence of sprints—such effort is allocated.

The model also accounts for errors in the evaluation of the amount of TD affecting the code. Measuring the TD is necessary, because the decisions of how much effort should be conveniently subtracted from code enhancement and dedicated to debt reduction is often based on the knowledge of how much debt has been accumulated. In fact, the assumption that more TD decreases productivity leads to increasing the effort for debt reduction, in order to restore high productivity levels. The proposed mode shows how to evaluate –via simulation– the effects of errors in the measure of TD.

The proposed model can be used to prove or disprove concepts and hypotheses, to perform what-if analyses, etc. However, our model is not intended to be used in practical software project management as-is, because, the model illustrated above is too abstract and contains hypotheses that could not match the target development environment. Whoever wants to use the presented model for practical project management should first enhance it; examples of models representing all the main aspects of software development can be found in the papers by Cao et al. [37] and Glaiel et al. [38].

We plan to extend the presented model in several directions: to account for different effects of TD on productivity (i.e., with functions different from the one in Figure 1), to explicitly model defects, to test different debt management policies, etc.

Acknowledgment

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An Explorative Study on Motion as Feedback: Using Semi-Autonomous Robots in Domestic Settings

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Abstract—**This paper presents motion as *feedback*. The study is based on empirical data from an explorative study of semi-autonomous robots used in domestic settings. We explore feedback received from stationary technology, e.g., a smartphone, and technology that is self-propelled, e.g., a semi-autonomous robot. The paper has its theoretical foundation in the *familiarity* concept used as a contextual and analytical tool for unpacking *feedback*. The data analysis is done through thematic analysis. The findings are structured in: *feedback* received from a smartphone app technology, *feedback* received from the robot-mediated via an app; and *motion as feedback* received from the robot. *Motion as feedback* is discussed in terms of: (a) what type of emotions feedback triggers in the users, and (b) making sense of the motion as *positive, negative, homeostatic, archival* and *transition feedback*. We argue that having *familiarity* in mind when designing new technologies, can make it easier for the user to *know-how* to *engage with* the technology. Our conclusion is that: a semi-autonomous robot technology can become more familiar to the user if it triggers positive feelings, if its motion is coherent, if its navigation is appropriate to the situation, and if its motion is not disturbing or interrupting the user; and lastly, *familiarity* needs to be considered when designing for a robot for the elderly.**

Keywords – feedback; motion as feedback; semi-autonomous robot; familiarity; emotions.

I. INTRODUCTION

This paper builds further on our reported work on how *feedback* from digital technologies may trigger the feeling of fear for technology when using those [1]. We have in our previous work used fear as an umbrella term for emotions, such as *angst, anxiety, concern, doubt, dread, unease, uneasiness, worry, aversion, fright, phobia,* and *presentiment* [2]. In this paper, we extend this work by looking at the *motion* of robots as a type of *feedback*. We do this by running a study where researchers test out a robot, and by introducing a robot in the homes of the elderly.

The questions that we address are: 1) What kind of emotions are triggered in the user by improper or lack of feedback when *engaging* with digital technology: a smartphone app or a semi-autonomous robot? 2) How is a motion made sense of by the users when *engaging* with a semi-autonomous robot, in their homes? Moreover, if motion is illustrated as a type of feedback – what do we learn from their experiences?

The rest of this paper is organized as follows. We continue by introducing some terminology used in this paper and a short background for the study. Section II gives an overview of the current state of the art on different types of robots used in home and outside the home. Section III elaborates on feedback as understood within Human-Computer Interaction (HCI). We introduce feedback as *visual* and *textual* feedback. Based on the literature, we describe *polarity-, homeostatic,* and *archival feedback*, which we later use in our mapping of *motion as feedback.* We continue then by introducing the reader briefly to *motion as feedback* and the robot's navigation. Section IV continues with positing this paper on a theoretical level, elaborating on the *familiarity* concept grounded in literature. Section V gives a detailed account of the methodology and methods for this study. Section VI presents in details the findings based on empirical data. Section VII discusses the findings through the lens of *familiarity* while elaborating on the *motion as feedback*. Finally, Section VIII concludes the paper and gives directions for further work.

A. Terminology

A domestic setting provides the opportunity for those who live there, or are around, to use technologies that are still, such as a smartphone, or technologies that move, such as a semi-autonomous robot.

A smartphone *is still technology.* We define still technology as *a technology that does not move by itself; it is not self-propelled, i.e., it does not change its location without the continuous intervention of a human or another object*. Examples of analog and digital *still* technologies are a table, a sofa, a notebook, a speaker, a lamp, a mobile phone, or a smartphone. One could argue that a smartphone is indeed a mobile technology. We agree with this if we talk about the way it is used. However, when it comes to its form of motion or locomotion, a smartphone or mobile phone does not move around by itself and change its location, unless they are moved by *someone* or *something* that can move. However, a smartphone or a mobile phone can vibrate, and one could argue that vibration is a type of movement. However, this

type of movement is not an intended movement of changing its location, or of navigating an environment.

We define a *semi-autonomous robot as an in-motion technology that can move by itself; it can be self-propelled, that follows a locomotion process, i.e., it can change its location without a necessary and continuous intervention of a human or another object*. Examples of in-motion analog and digital technologies are mechanical robots and semi-autonomous robots, which can navigate a place by themselves, such as semi-autonomous vacuum cleaner robots, or lawn mowers.

In this paper, we use this terminology interchangeably: smartphone app technology, in order to refer to still technology; and semi-autonomous robot technology for referring to in-motion technologies, here a semi-autonomous vacuum cleaner robot.

B. Background

According to the literature, robots are defined as: "physically embodied systems capable of enacting physical change in the world." [3]. Following [4], industrial robots refer to robots that move around or transport things, and usually operate on conveyor belts, in packaging, and assembling [4]. Industrial robots usually perform repetitive routine tasks, often having a predefined navigation path. Professional service robots are similar to industrial robots, but they are used outside the industrial setting: they can transport things, by navigating around the environment [4]. To these, robots used in healthcare also add up [3]. They refer to the micro-robotics that are used *inside* the body, protheses robotics that are used *on* the body, and robotics that are used *outside* the body. Other robots are used to support mental or behavioral therapy, such as those used for people with diagnoses on the autism spectrum disorder, those with cognitive impairments, or as companions [3]. However, they usually perform tasks to assists people: cleaning nuclear waste [4], supporting surgeries in hospital settings, or carrying around medicines or instruments, see for example the work from [5] or [6]. The robots that are outside the body and can move semi-autonomously usually have pre-defined paths and navigate in uncluttered environments.

Further, the third wave in HCI discusses digital technology in our homes [7]. However, we still seem to have less knowledge on the use of moving objects in the home than about the use of stationary technology – although several existent projects are studying the use of robots in the home. These are usually included under the category of personal service robots, following [4]. Amongst personal service robots are: robotic vacuum cleaners, lawn mowers, and assistive robots for the elderly or the un-abled [4].

This study is part of the Multimodal Elderly Care Systems (MECS) [8]. The project focuses on the design of a robot for the independently living elderly. We define elderly as old adults (≥ 65 years), according to definitions used in gerontology [9][10]. However, within the frame of the MECS project, this study consists of a qualitative interpretative phenomenological evaluation of the interactive systems as experienced by participants in their daily lives, and the phenomena surrounding them. We followed the HCI definition - a "discipline concerned with the *design*, *evaluation,* and implementation of interactive computing systems *for human use* and with the *study of major phenomena surrounding them*." [11, 15, emphasis added]. The setting for this study was the homes of our participants.

II. State of The Art

According to state of the art in robotics, published in 2016 U.S. Robotics Roadmap, the focus area of the field is currently on: aging well and quality of life, robotics used in the medical field in surgeries and interventions, and the robots used as "clinical workforce support" [3, 73]. The study also says that a *one-size fits all* approach is hard to be achieved in robotics [3].

A thorough overview of the robots used in studies for supporting independent living is given in [12]. There are several projects studying the use of robots in the home. A project concerning the care of the elderly is Acceptable robotiCs COMPanions for AgeiNG Years (ACCOMPANY) [13][14]. ACCOMPANY developed Care-O-Bot robot. Care-O-Bot is amongst one of the robot assistants used for housekeeping and home care [13][14][15][16]. Care-O-Bot is a state-of-the-art robot designed to be used in the home [17]. A couple of other projects studying these type of robots are named in the work of [17], such as Handy 1, Movaid, and Nursebot built for the elderly or the disabled; GuideCane, Hitomi, PAM-AID, PAMM, Smart-Cane PAMM, and Smart-Walker PAMM. These robotic prototypes were built to be walking aid for the blind, elderly, or the disabled [17].

At EU-level, several projects studied the use of robots in the home. Amongst the European Union projects are: Robot-Era Project [3], MARIO Project on Managing active and healthy aging with use of caring service robots, EURON RoboEthics Roadman, EP6, ETHICBOTS, BREATHE, and ICT & Ageing Project [18]. Another project was the Multi-Role Shadow Robotic System for Independent Living (SRS) [19]. The project focused on studying the frail elderly people: the elderly whose Activities of Daily Living (ADL) are limited by their health problems [19]. Many of the frail elderlies use walking chairs, sticks, or wheelchairs [19]. The study shows that teleoperated robots may be accepted in some situations, whereas direct physical interaction with a service robot can be, at times, difficult [19]. It seems that "housing-related needs" are central for learning and adopting the technology *if* these technologies function well [19, 303]. For instance, the study also indicates that men have more difficulties than women with housekeeping tasks, while women have difficulties in reaching things [19]. A similar study to ours talks about introducing personal service robots, a Roomba Discovery vacuum cleaner, in homes [20]. The home is

viewed as an ecology of products, people, activities, a social and cultural context of use, and a place – a bounded environment [20]. It seems that the expectations one has of technology are highly related to shaping the initial expectations of technology. The use of the robot also influenced the practice of housekeeping: in some households, the male participants set-up the robot; in others, only the women use it [20].

Companion robots are also used in studies with the elderly. An example of a companion robot is PARO, the seal robot [21][22][23]. The seal robot PARO was used in facilities for the elderly in the Nursing-care Robot Promotion Project, in Japan [22]. An initial study showed that the elderly participants suffering from various mental or behavioral issues, but who interacted with PARO over time improved their communication, reduced their aggression and wandering, as well as improved the sociability of the participants, over time [22]. PARO also seems to be widely accepted across cultures [24]. Other examples of companion robots are Pepper and NAO used in exploratory studies, as shown in [25]. AIBO, Furby, and NeCoRo are a few other robots representing animals that were used in therapy with children, or in nursing homes with the elderly [21][22].

Another project from the EU project within the Ambient Assisted Living (AAL) is Enabling Social Interaction Through Ambient (EXCITE) [26]. The project introduced the Giraff robot in several homes with the purpose of studying "social interaction through robotic telepresence" [26, 827], an idea that stemmed from the RoboCare project [27].

Finally, it seems that "20% of the world's population experience difficulties with physical, cognitive, or sensory functioning, mental health or behavioral health" [3]. In numbers, there are around 190 million people experiencing difficulties with ADL, including physical tasks and cognitive tasks [3]. Further, it seems that the aging of the workforce has consequences within the healthcare field [28][29]. A study from [30] shows that, for instance, in Sweden, the cost for the home care for the elderly would increase between 20 and 35% between 2013 to 2020, whereas this could instead be reduced by 50% as of 2020, with the digitalization of the home care services [30]. In Norway, the elderly population will increase by 21% by 2050 [31]. Furthermore, the active working force will not be able to tackle the healthcare needs imposed by this increase [31] and yet among the action plans taken at the European Union's level, regarding this societal challenge, is the digitalization of health through the use of Information Communication Technologies (ICT's) [32]. Moreover, several studies address directly or indirectly the issue of the digital divide between users with ICT literacy and those, with reduced ICT literacy. Elderly are often included in the group of users with reduced ICT literacy as shown in [33][34][35][36]. Yet, all the above yield at how important it is to make sense of the design of today's technologies, including those that *move*: semi-autonomous robots for the use in the homes of the elderly. Nevertheless, one of the designing principles for designing good smartphone technologies and semi-autonomous robots is to give informative feedback when an error occurs [37][38]. Understanding feedback is, therefore, highly relevant in this context. Next section gives an introduction to the main topic discussed in this paper: feedback.

III. FEEDBACK

In this section, we describe how feedback is currently discussed in the HCI literature.

Feedback is an abstract concept that was used in a number of disciplines. Diverse elaborations and explorations of feedback definitions are encountered from control theory and cybernetics to the definitions used in HCI [1][39]. Before going further, we wish to turn to the definition of feedback, within HCI, as explained by Norman (2013): informing the user, in some way, that the system is working, as a response to the user's action [40].

Feedback in the interaction with a desktop computer interface was well established a long time ago and often already understood by the user [41]. Here are a few examples based on Apple's User Interface Guidelines dating back to 1992: feedback to the user when typing in passwords by displaying a bullet character for each typed character by the user; feedback of a cursor showing a delay after user has moved a big document to the trash bin; a dialogue box feedback informing the user about his or her actions' result; when the user deletes everything from the trash bin, an *empty trash* text should be displayed; when selecting an option in a radio button, the user should see a bullet in the selected option; when an option from a menu is chosen by the user, the option is hoovered or the background color is changed; when an item is selected from a palette of patterns or colors, that option is highlighted or outlined; moving around windows on the desktop is illustrated immediately to the user through the windows new position; an active window is highlighted or outlined; when a user shall be informed about potential dangers, such as an unsafe document to be opened, or a non-reversible action, the user should be informed through a caution alert box, where the user has the possibility to cancel the action or to proceed further; or a button that is clicked or hoovered over shall be highlighted [41].

According to [42], feedback is an important concept that is studied, especially within education. However, within the HCI field, it seems still to remain ambiguous and primitive, and "is oversimplified" [42, 253]. While some of the literature identifies feedback as a response to the user's action [9], others talk about feedback as a way "to communicate the state of the system independently of the user's action" [43, 316]. Feedback can be visual, auditory, haptic, and some talk about it as bio-feedback in HCI studies that measure or self-track the human [1]. Others talk about eco-feedback in sustainability and environmental HCI studies, or affective feedback [1].

Further, language seems to play a central role in HCI, in auditory and textual feedback. However, we have also seen that language *per se* used in the interaction with computers or machines does not always work: see for instance the example of the natural language processing ELIZA used in early days of Artificial Intelligence (AI), mentioned in [44]; or the example of textual feedback using technical language of "it cannot connect to the *cloud services*" [1, 176]. [44] talked about how the HCI field evolved based mainly on conversational and linguistic development, a common language [44]. This was mainly a question of mutual intelligibility through language.

But the HCI field has evolved, and while *visual, auditory and textual feedback* still remain essential, it also seems to become more common to *interact with things that move*. As [45] has earlier put it: the conditions for the possibility that the world as an adjacent to everyday interaction becomes an interface for computation, we could, in his words, through this type of interaction "capitalize our familiarity, skill and experience in dealing with the everyday world around us" [44, 1]. In addition to the development of a *common language*, we also need to develop *a shared understanding*, *mutual intelligibility of the motion* of the robot: "A robot in the real world, however, must consider the execution of the plan as a major part of every task. Unexpected occurrences are not unusual, so that the use of sensory feedback and corrective action are crucial" (Raphael, cited in McCorduck, 1979, p. 224), in [44, 23]. How can then the movement itself of things be applied in order to facilitate human interaction with things? What experience of the robot's movements should be designed for? And what do these movements communicate to the user? How are these movements interpreted by the user as feedback? How do we describe patterns of movements, styles of movement, or ways of moving? How can these movement styles be mapped as feedback to the user?

Before going further, we would like to explain polarity feedback, homeostatic feedback, and archival feedback – types of feedback that we found in the existent literature. This is later our departure point for discussing *motion as feedback*.

A. Polarity Feedback: Positive and Negative

Polarity feedback can be regarded as *positive* or *negative* [42], *depending on how the feedback is interpreted by the user, compared to the user's expectations.* According to [42], feedback as information retrieval, in the broader sense of it, is formed by a message, a cognitive interpretation, and its context. For instance, a user sets the temperature on a thermostat in a room to be 25°C degrees. In this situation, the visual feedback can be translated as positive, if it shows the temperature set by the user, or at least close to what the user has set (23°C degrees, or perhaps 26°C degrees) could still be accepted. However, if the temperature of the room does not seem to be close to what the user has set, say 15°C degrees or 35°C degrees, the feedback is translated as negative feedback. In other words, positive feedback is when the system responds accordingly or at least close enough to the input of the user, meeting the user's expectations. On the other hand, negative feedback is when the system does not respond exactly or close enough to the user's input, resulting in a high difference between the system response and the user's expectations. Negative feedback does not necessarily need to have a negative value, (+)15 °C can still be considered a negative value.

B. Homeostatic Feedback

Feedback has a polarity, positive, and negative, but it can also be homeostatic [46]. *Homeostatic feedback* is a *type of feedback that is constant, regardless if the feedback is positive or negative; the state of the feedback is the same over a longer time period*. Polarity feedback and homeostatic feedback are not *mutually exclusive*: positive or negative feedback can also be at the same time homeostatic [42]. Taking the same example of receiving feedback from a thermostat on a room's temperature homeostatic feedback is when the thermostat shows over a longer period of time exactly 25°C degrees, according to the user's input. But homeostatic feedback can also be negative feedback of 15°C, or 30°C degrees, over a longer period of time. If the thermostat does not start, although the user has pressed a start button, it can also be translated into a homeostatic negative feedback.

C. Archival Feedback

The literature discusses archival feedback [46]. This type of feedback is distinguished from immediate feedback [46]. *Such a type of feedback logs and remembers the system's previous actions, in such a way that it can return to a previous state*. A concrete example is when the user uses the UNDO button: if the actions of the user were logged over time, then the UNDO button performs a positive action, e.g., the system goes back to a previous state. This type of feedback that logs and remembers previous states of the system is called archival feedback. If the UNDO button cannot perform this operation, pressing the UNDO button gives a negative feedback, e.g., nothing changes – the system stays the same. However, the system should inform the user anyway, that nothing was changed. This is then not an archival feedback, but rather the user receives a negative feedback on its input regarding the archival feedback.

D. On Motion - As Feedback

Following Mitcham's (1978) in [47] it seems that a tool is activated by the human agency, while a machine can, to a certain degree, operate independently [47]. Following this definition, we could say that a semi-autonomous robot used at home is in a way a machine – something that acts independently, but also a tool, since it is controlled at some degree by the user: through a button, or by using an app as a remote controller, or through a remote controller.

In general, humans know where they are, or how to navigate their way where they want to get [47]. One can navigate his or her way based on own knowledge or familiarity with the place, or by using a map. This is done through their own body's locomotion [47]. Wayfinding is different from navigation, by moving from a location to another region (compared to navigation, which is moving from one location to another location) [47, 219-242]. A semi-autonomous robot is moving within a home through both types of motion: first, through wayfinding, by creating a map of the place; and second, through navigation, moving around on the already mapped space. These types of movement can be classified as locomotion, or a global movement, according to [48]. Besides these movements, a robot also has its own motions, such as moving the head of a robot, moving an arm, without changing the robot's location. The authors classify this type of movement as a local movement, or to use the term from robotics, configuration movement [48]. In this paper, the local movement is considered as *still* type of motion. The paper is mainly concerned with the locomotion type of movement. Rather than going into the depths of motion and animation techniques here, we would like instead to focus on exploring further domestic robot's *motion as feedback*: What kind of feedback does the user receive and in, which situations? What are the implications of the motion for the feedback? How is the robot motion perceived by the users in terms of feedback?

We have earlier conceptualized feedback [39] based on Hall et al. (1968) proxemics [49]. We have identified that a semi-autonomous robot includes the same types of feedback as a smartphone app technology, but in addition, it has the motion element [39]. We observed that the motion of the robot could be considered as a type of feedback that it is manifested through *distributed feedback*, via extended proxemics, when the feedback from a robot is given via an app [39]. We noticed that this type of feedback was *distributed* when using an app. To simplify the discussions later, we illustrate (a) getting feedback from a smartphone app technology vs. (b) getting feedback from a robot (Fig. 1). We also noticed that while feedback from a smartphone is direct, feedback from a robot can be both direct, from the robot, or *distributed*, via an appWe build in this paper further on the earlier reported work, the *motion as a form of feedback*, by investigating the *motion* of the robot, and by looking at how it is made sense by the users. We do this by bringing up examples from our empirical data (Section VI). We make sense of *motion as feedback* based on our empirical data, by distinguishing between feedback from a smartphone and a semi-autonomous technology, reshaping and molding the notion, understanding and making sense of the motion as feedback. In this way, can these various types of *motions* be perceived as *feedback* by the participants? How can we classify then these *motions as feedback*? Introducing a common vocabulary may help us to talk about motions of semi-autonomous things in homes in a better way, similarly to perspectives from other fields, such as mathematics, physics, medicine, or biology: anthropomorphizing – moving like a human; zoomorphic – animal movement, robot morphing – moving like a machine. We continue in the next section by laying our theoretical foundation: the *familiarity* concept. The concept will later in the paper help us to unpack and understand the *feedback* notion.

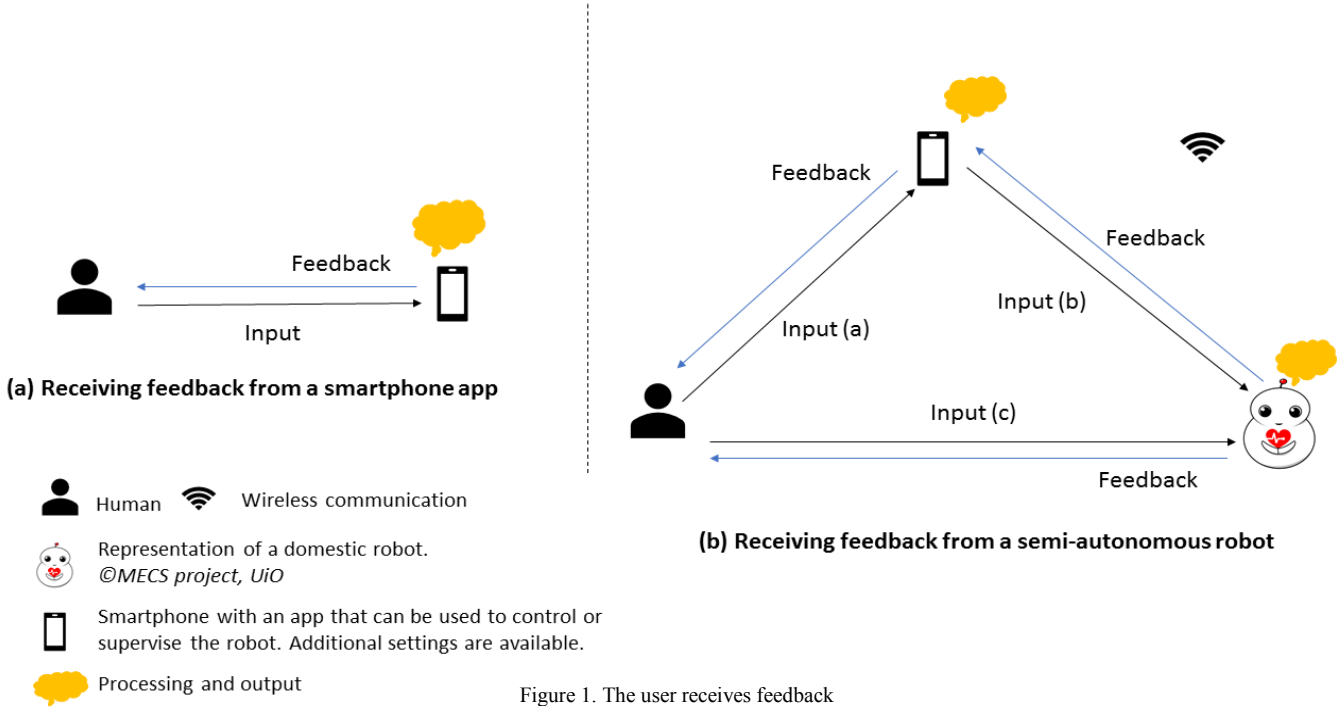

Figure 1. The user receives feedback

IV. THEORETICAL FOUNDATIONS: ON FAMILIARITY

According to [50], theory helps us "to structure knowledge, to evaluate and assess it, to construct it and share it" [50, 126]. Amongst their six models of using theory, there are also: theory as a contextual tool, where the researchers start with a research question and take a position, often referring to theory as concepts, ideas, or perspectives; and theory as an analytical tool, where the researchers use the theory to analyze and interpret the findings in the light of the theory [50]. In this paper, we have used both these types of using theory: for both the former and the latter one, we posit the paper within the frame of the familiarity concept used in HCI.

The concept of *familiarity* is illustrated in Heidegger's Being and Time as "[knowing] its way about" [51]. *Familiarity* can be described as an intimate, close, and friendly state, or interaction [52]. In Dreyfus' view, *familiarity* gives one the tools to respond correspondingly to different situations [53]. In HCI, *familiarity* has been used as a base for the design. For instance, this concept can be used in the skeuomorphic design. Skeuomorphic design refers to when the digital interface adopts some of the physical artifact's properties in order to accommodate better the user by making the digital artifact looking more familiar [54]. Such an example is, for instance, when a digital interface imitates the paper look of an old book. Others have used it within the design of tangible systems [55]. However, it seems the concept is still underexplored within HCI, while it seems to be important in the sense-making of using technology. For instance, [56] found that *familiarity* plays a central role in individuals' relationships with technology [56]. Later, [57] pointed out that *familiarity* concept did not get too much attention in the field of HCI, besides his previous work together with Van de Walle [57].

Inspired by the work of Heidegger, Mereleu-Ponty, and Dreyfus, [58] tried to make sense of everyday's examples of interacting with technology, the readiness of coping with it in everyday life situations. Further, *familiarity* is based on several key points [55]. Among these are: *familiarity* with digital technology depicts a "*know-how*" relationship [58] based on a tacit knowledge; *familiarity* is based on everyday use, on reading about it, and being taught how to use it; *familiarity* with digital technology means knowing how to use it, or using Turner's words, "*to be ready to cope with it*" [55, 25, emphasis added]. *Familiarity* is also a form of *engagement*, of what Heidegger calls involvement [59]. However, *familiarity* with technology is more difficult because involvement with technology can become complex [59]. Involvement represents a form of care, enfoldment, entanglement, according to [55]. *Familiarity* also has *an affective part* that builds upon feelings of closeness, of being at home, feelings of comfort, ownership, and warmness [55]. Inspired perhaps by Heidegger's "being-in-the-world," he calls this relationship of *co-existence* with technology as *being-with* [55]. According to the author, an appropriate way of *becoming familiar* with technology is to integrate it within the participants' everyday life [59]. He sees this type of relationship as a *co-existence relationship* with technology [59]. Turner (2008) also says that *familiarity* can be illustrated as one's perception change rather than knowledge creation [57] .

Finally, [60] also argued for *familiarity* as a basis for universal design. They mean that HCI is based on the distinction between man and machine [60]. Furthermore, [61] described it as an intimate or close relationship, where humans *engage with-* and *try to understand the technology* [61]. The authors propose *a salutogenic approach*, as a way of focusing on the factors that contribute to *well-being* and *health*, rather than treating or fixing a disability, incapability or weakness [61]. In this paper, we try to understand the participants' *engagement with the technology*, by making sense of the *feedback* received from the technology, being it a smartphone app or a semi-autonomous robot.

In the next section, we continue by introducing our methodology and methods used in this study.

V. METHODOLOGY AND METHODS

According to [62], interpretive research is afforded through "language, consciousness, and shared meanings" [62, 2]. Boland (1985) in [62, 2], says that "the philosophical base of interpretive research is hermeneutics and phenomenology." Further, we followed one of Ricoeur's thesis that hermeneutics builds upon phenomenology [63].

In addition to the earlier reported work [1], we have now included both researchers and several elderly people in the study. We describe next our study context, study design, the robots used in this study, selection of robots, participants, data collection, and data analysis, as well as ethical considerations.

A. Study Context

The study was performed in the old district area of Oslo, Norway. The area has approximately 3000 senior citizens, over 67 years old. Some of these elderlies choose to live in accommodation facilities for the elderly. The elderly usually live there independently, or together with their partners. However, the accommodation is provisioned with a 24/7 reception staffed with at least two personnel, available for the elderly, a gym, a restaurant for taking breakfast or lunch, which is also open to the public, a library where meetings or various courses are held, and an open area for coffee breaks and other events. Several studies have been performed in such facilities [64][65][66][67][68], but none of these report data on the use of robots or semi-autonomous robots in the homes of the independent living elderly.

B. Study Design

This study was divided into three stages. The first stage was a pilot phase, with the purpose of learning, and getting a pre-understanding of the context (stage 1). Next, several of the researchers involved in the project tried out the semi-autonomous robots in their homes (stage 2). After some of

the researchers have tried out the semi-autonomous robots, we started introducing the first available robot in the homes of the elderly (stage 3). In some cases, the robots were run in parallel in both homes of the elderly, and homes of the researchers.

C. Robots in this Study

In this study, we have used semi-autonomous vacuum-cleaner robots in the homes of our participants. Selecting such a robot was a bi-informed choice. On the one hand, our elderly participants reported earlier *familiarity* with semi-autonomous robots, such as vacuum-cleaners and lawn-mowers that they have seen on TV and were keen to test out. These types of robots are sometimes referred to as *domestic robots* or *domotics*. On the other hand, the study is part of the MECS project, that aims to develop a robot for independent living elderly. This study was made at an incipient phase of the project. The project did not have yet any fully developed robot for the independent living elderly, such as a safety alarm robot, in place at the time. Therefore, we chose to build on our senior participants' familiarity with the robots, e.g., by selecting semi-autonomous vacuum cleaners to be used in their homes.

We have initially investigated several potential robots to acquire for our study. We finally selected three of them for the purpose of our study: iRobot Roomba 980 [69], Neato BotVac, and Samsung PowerBot VR20H. Table I below gives a summary of the technical specifications of the robots.

TABLE I. SUMMARY: TECHNICAL SPECIFICATIONS OF THE SELECTED ROBOTS

Robot / Specifications	iRobot Roomba 980	Neato BotVac	Samsung POWERbot
Dimensions (Depth x Width x Height)	35 x 14 x 9.2 (cm)	33.5 x 32.1 x 10 (cm)	37.8 x 13.5 x 36.2 (cm)
Weight	4 kg	Ca 4.1kg	Cca 4.8 kg
App as a remote controller	YES. iRobot Home App	Yes. Neato Robotics	Yes. Powerbot, smart home app.
Charging	Battery and electricity	Battery and electricity	Battery and electricity

D. Selection of the Robots to be Used in the Elderly's Homes

When the robots were introduced in the homes of the researchers in the first stage of the project, we noticed soon that iRobot Roomba 980 and Neato were the most appropriate for the elderly, due to their reduced sizes, compared to BotVac robot. This led us to make the choice of only using iRobot Roomba 980 and Neato in the elderly's homes.

E. Participants

13 participants took part in this study: seven (7) of the participants were researchers that tested the robots as part of the pilot study, including the authors (SD, HJ), during the period of times ranging from about one week to about one month. At this stage, 2 females and 5 males participated. Six (6) elderly persons used the semi-autonomous vacuum cleaner for about one month: 5 females, and 1 male. Three of the elderly participants were included in the previously reported work [1]. The participants had different backgrounds and presented different levels of interest in modern technologies.

The researchers are represented in this study by both junior and senior researchers. The elderly participants (≥65 years), part of the MECS project, were recruited through MECS' partner organization. Due to the high commitment that the study required, including weekly visits, the use of the robot, photos, participant diary notes as domestic probes, observations, and interviews, only six elderly participants were willing to participate within the timeframe of study data collection. The participants were self-selected and took part in the study based on their free will. Some of the participants took part in the study through the snowball effect by finding out about the study from others.

F. Data Collection

The data was collected from researchers and the elderly. The data collected from researchers was retrieved through diary notes and photos (Table II). The data collected from the elderly participants were retrieved through interviews, elderly's diary notes used as domestic probes, photos, researcher's notes, and headnotes (Table III on the next page). Headnotes are "experiences, impressions, encounters, and evaluations that are continuously present in [the] memory," according to [70] following [71]. Each senior participant received a notebook to be used for their diary notes. We kindly asked the elderly participants to note down in their diaries the situations they encounter. These notes, or posts, as we named them, were written by the elderly, especially when something unusual or unfamiliar occurred.

TABLE II. OVERVIEW OF THE DATA COLLECTED FROM RESEARCHERS

#	Data collection methods - Researchers		
	Timeframe	*Documentation*	*Robot used*
1	One week	Yes. Diary notes, seven posts (one per day), ca 4 and a half A4 pages, analog format, 28 photos	Neato
2	Ca two week	Yes. 3 pages of A4 notes, digital format, 4 photos enclosed	Neato
3	Ca one week	Yes. Short notes on strengths and weaknesses of using such a robot, digital format	iRobot
4	One week	Yes. 1 page of notes, digital format	Samsung PowerBot
5	Ca one week	Yes. Half page was written notes on strengths and weaknesses, digital format	Neato
6	Ca one month	Yes. Four pages of written notes, 22 posts, digital format	Neato
7	Ca one month	Yes. Ca 19 A4 pages of written notes, analog format	Neato

G. Data Analysis

The process of analysis started already while being in the field, as a form of doing some preliminary work [72]. This has been followed by a multiple stage analysis process, where the data went through some analytical filters. Specifically, we have followed thematic analysis from V. Braun & V. Clarke to analyze the data collected in stage 2) and 3) [73]. This was done in 5 steps. We have first started by trying to familiarize ourselves with the data (step 1). We did this by creating a map of data and resources, which later resulted in Table II, respectively Table III. At this stage, we had put aside the initial research question, to be open for novelty, for what may come up and we did not think of, trying to focus on what the participants found interesting. Thereafter, our analysis was done in a bottom up fashion starting from coding each of the resources (step 2). We have then grouped the resources in three categories based on the data sources: researcher's diary, researcher's observation notes during elderly's observation and elderly's own diary notes, and interviews. At this point, the raw data became textual data, in the form of transcribed interviews, notes, or interview summaries. All the interviews with the elderly were transcribed verbatim by author SD. The transcribed interviews alone resulted in around 26000 words exclusive the pilot interview (circa 33500 words together with the pilot interview). At the same time, the author (SD) went through the photos taken (n=147). The coding was done by reading the material "line-by-line to identify and formulate all ideas, themes, or issues they suggest, no matter how varied and disparate" [74, 143]. This resulted in a variety of scattered codes.

Next step was collating the codes further into sub-categories for each of the data sources (step 3). This was done through color coded post-it notes by the author (SD). We cannot claim a full inter-reliability of the study, as the coding was done by one author (SD) [75]. However, following [75], validity, in this case, is not of "a particular concern", as the study focuses on exploring the potential challenges one may encounter when a robot is introduced in the home [75, 212]. Moreover, the findings were discussed at different points during data collection amongst the researchers in the project. In addition, the collated codes were discussed by the authors (SD, HJ) during the data analysis.

As a result, the data collected through researcher's diary, researcher's observation notes and elderly's diary notes, and interviews resulted in [n=51], [n=47], respectively [n=124] collated codes: a total of [n=222] codes. At this stage, we were searching for themes. We observed that some of the collated codes were present across several of the resources: written utterances during our drop-in visits (usually once per week, or on request), and utterances from the interviews. We

TABLE III. OVERVIEW OF THE DATA COLLECTED FROM THE ELDERLY

#	Data collection methods - elderly					
	Gender (Female F, Male M)	***Interview***	***Elderly's Diary notes***	***Researcher's notes***	***Photoswere taken by the researcherrs***	***Eventual details about the robot used, if any assistive technologies were used, and level of information technology literacy***
1	F	Circa 1 hour, audio-recorded pilot interview, transcribed verbatim (SD) AND Circa 1 hour and 45 minutes of untranscribed audio-recording from the installation of the robot	Yes. Circa 5 A4 pages, analogue format.	Yes. Circa 2 A4 pages.	Yes. 36 photos	iRoomba, 87 years old, walking chair, did not use the app
2	F	Circa 40 minutes, audio-recorded, transcribed verbatim (SD)	Yes. Circa 3 A4 pages notes, analogue format	Yes. Circa 2 A4 pages.	Yes. 4 photos.	iRoomba, walking chair, necklace alarm that she does not wear it, high interest in technology, used the app, has a smartphone,
3	M	Circa 25 minutes, audio-recorded, transcribed verbatim (SD)	Yes. One letter-size page, analog format, short notes.	Yes. Circa 4 letter-sized pages.	Yes. 10 photos.	Neato, wheelchair, not interested in technology, did not used the app, easy to use, has a wearable safety alarm
4	F	Circa 33 minutes audio-recorded, transcribed verbatim (SD)	Yes. One A4 page, analog format	Yes. Circa 2 A4 pages.	Yes. 36 photos	iRomba, wheelchair, interested in technology, did not use the app, easy to use, does not have a smartphone, wearable safety alarm
5	F	Circa 45 minutes audio-recorded, transcribed verbatim (SD)	Yes. One letter size page, analog format.	Not available	Yes. 13 photos	Walker, did not use the app, not interested in technology, does not have a smartphone, wearable safety alarm
6	F	Circa 43 minutes, audio-recorded, (transcribed verbatim) (SD)	Yes. 4 letter-size pages, analog format.	Yes. Circa 1 letter-sized page.	Yes. 16 photos	Interested in technology, no walker, wanted to use the app, but gave up, does not have any wearable alarm

looked for performative utterances [76]. This was carefully paid attention to due to two main reasons: in order to observe whether or not the researchers and elderly encounter the same type of challenges with the robot, and how information technology literacy influenced the attitudes towards the robot.

Finally, the collated codes and findings were discussed between the authors (SD, HJ) at multiple times. At this stage, we reviewed the themes resulted (step 4). The final analysis resulted in three main themes: robot, home space, and human emotions and perspectives on perceived autonomy (step 5).

H. Ethical Considerations

The project is in line with the ethical guidelines from the Norwegian Center for Research Data (NSD) (ref. nr: 50689). The data collected during this study were stored on the Services for Sensitive Data (TSD) facilities, owned by the University of Oslo, Norway, operated and developed by the TSD service group at the University of Oslo, IT-Department (USIT). All the data was anonymized. Prior to starting the study, the participants were given detailed information about the study. The participants could withdraw at any time without giving any explanation and without any consequences for them. The participants willing to participate signed informed consent before taking part in the study.

During the study, we had constant contact with our participants, through regular visits, often each Wednesday, on pre-agreed times, but also on demand, if they needed any support or had questions. Sometimes, we called them on the phone just to check if there was anything they wondered regarding the robot. They also received our contact details and could contact us at any time.

VI. FINDINGS

This section presents the findings from this study. The findings are structured in three categories: the user receives feedback from a smartphone technology (Sub-section A), the user receives distributed feedback via an app (Sub-section B), and robot motion as feedback and its implication for the user (Sub-section C). The findings are supported by empirical examples. A detailed account is given below for each of these.

A. Findings: The User Receives Feedback From A Smartphone Technology

In this section, we present a situation where the user receives feedback from a smartphone app technology. This is illustrated through textual feedback that is either improper or lacking. Fig. 2 illustrates the situation presented here.

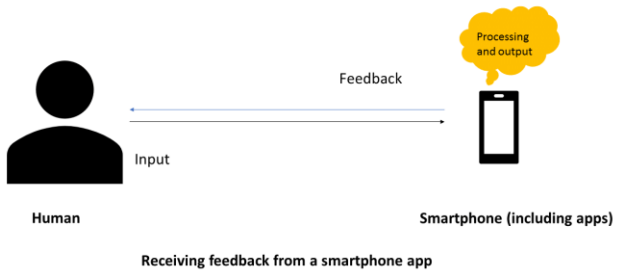

Figure 2. Feedback between smartphone technology and a (human) as user

1) Providing Improper Feedback

The user is provided with improper textual feedback [1]:

a) "SMS shows full. Do I need to buy a new phone?": One of the participants told us about her experience with the mobile phone and the feedback of SMS - full blinking icon. Her concern was that she could not store any longer the photos she received from her family. The participant was concerned that she had to buy a new phone, and that this would lead to losing the existent photos.

b) "Where is the 'No' option when updating software?": Another situation described by one of the participants was related to getting constant updates, where she gets either the option 'Now' or 'Later,' but not a 'No' option. She contacted the company providing the operating system via a handwritten letter and asked about this option. To her surprise, she got called up by the customer service, and got offered help on how to deal with the two options available, 'Now' and 'Later,' but the company had no plan to introduce a No-option. The participant explained that she knew how to deal with the updates, but what she wanted was that the feedback should embed a 'No'-option alternative. Regarding this design issue, this has to do with the continuous update of software and the point of view of the elderly on these always encountering updates. This example illustrates a situation where feedback messages do not provide enough options.

2) Lack of feedback

"You were terribly afraid of doing something wrong": In one of our interview sessions, one participant describes that when she learns using new technologies, she is so afraid of doing something wrong. A concrete example is that the technology, being it smartphone or tablet, does not provide any feedback on how *to get back to basics*: "so you were very afraid that... I did not feel I could come back to the base. But I was afraid to do something wrong."

By this, the participant means that the applications are built in such a way, that one is expected to have that intuitive knowledge, but for new users, it can be difficult to understand how to navigate within an app, and one can easily get stuck.

B. *Findings: The User Receives Distributed Feedback From A Robot via an App*

This sub-section illustrates the situation when a user receives feedback from a semi-autonomous robot technology via a smartphone, through an app. We illustrate first some of the implications that the use of such an app has for the user at the installation time. Thereafter, we illustrate some situations where the users received either improper feedback, or the feedback was lacking. An illustration of the situation is presented in Fig. 3 below.

Some of the participants have chosen to install the app in order to control the robot remotely. Several steps had to be followed in order to install the app. As the diary notes show, for Neato robotics app, for instance, one should create an online account. This, required an email address. This required a Wi-fi connection to the network. One of the issues that occurred during this step at the installation of the robot in one of the participants' homes was that the robot required a 5 GHz Wi-fi, while the participant's router had only 2.4 GHz.

The next step was to choose the right robot amongst several robots listed in the app. The final step was to connect to the robot. Once the app was installed, a map of the local space was created within the app after the robot has moved around. The map provided the approximate area, including obstacles, edges of space, and door limits (Fig. 4).

One of the participants gives a rich description of his experience on installing the app: "Today, it's time to get this thing going. First, I need to connect to the vacuum. This involves enabling Wi-fi on the vacuum, then connect your phone to the vacuum's Wi-fi access point (yes, the vacuum has its own Wi-fi access point). Then you can use

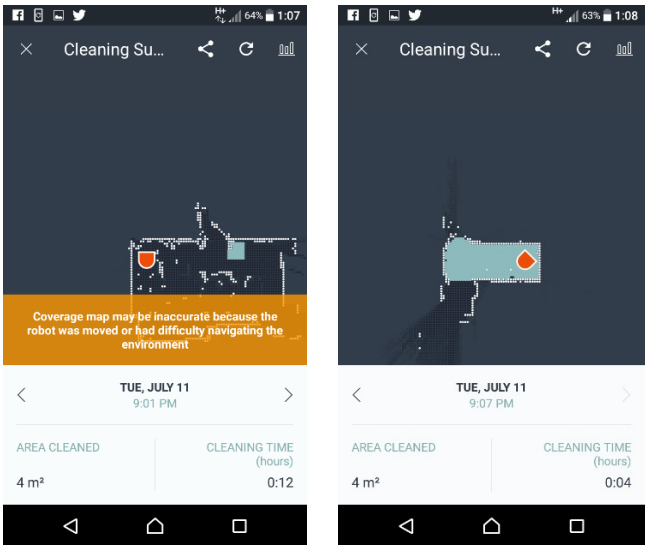

Figure 4. Example on the map is shown in a robot app that was generated by the robot

the Neato app to choose the actual Wi-fi point to connect to. On the one hand, this makes it easier to configure the robot since you connect only to it and you get the richness of a mobile app to input information (including passwords to access point), but it's not without some flaws. First, I assumed it would show the access points right away; it didn't. So, I typed in the access point and the password. I should also point out that I connected it to the "guest" Wi-fi, not our main Wi-fi. It's suddenly at this point that I realize how little I trust this thing belonging to the main network, and I start to think about other ways to partition the network. […] Regardless, the phone tells me that the process may take up to 3 minutes and that I should watch

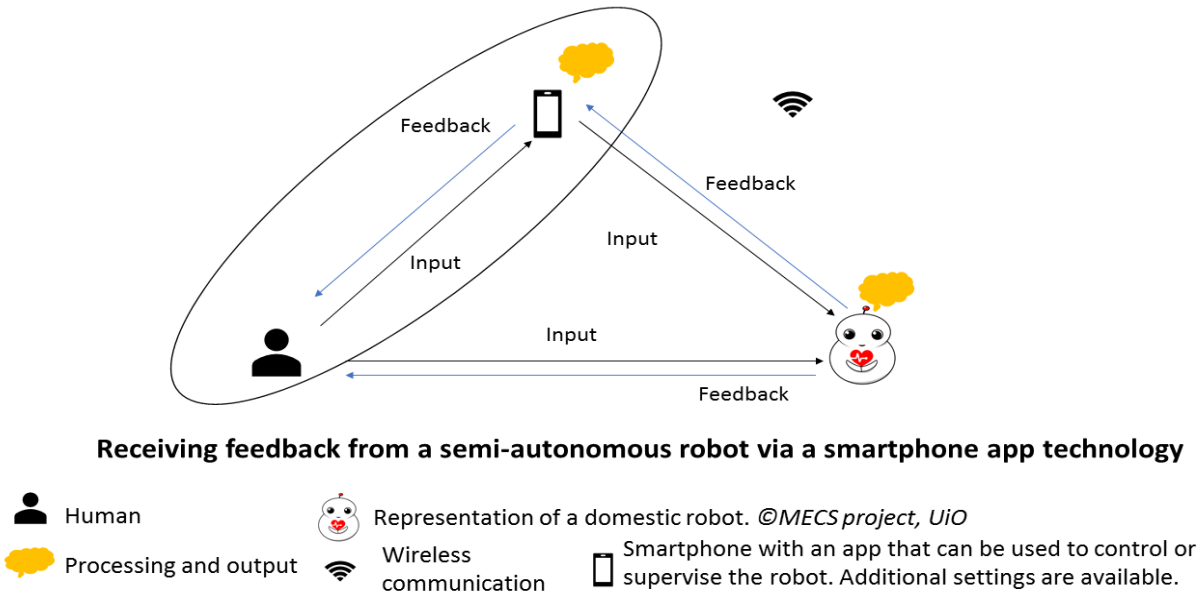

Figure 3. Feedback from a semi-autonomous robot technology to a (human) user mediated via an app

the robot's display screen during this time. I do, but it only shows the current setting of Wi-fi on. When I try to move back, I accidentally turn off Wi-fi, and I put the system in an uncertain state. I try to re-enable the wi-fi, but now the phone and the robot are confused. The phone, after 3 minutes, reports that the wi-fi information was "incorrect" and urges me to try again. But the robot refuses to rebroadcast its Neato access point. […] I switch the vacuum off using its hardware switch and then turn it back on. I go through the process again (with a lighter touch on my fingers). […] Then, I can choose the network and enter the password. This time it connects shortly thereafter. At this point, the robot asks for a name, I just give it Neato, and I set it out for its first vacuum tour" (Diary notes, Researcher).

Further, we found out that many of the in-app instructions and paper instructions that came along with the robot were available only in *English*. Many of the elderly participants pointed out that they do not feel comfortable about using technologies in English, and it would have been better to have it in their mother tongue, Norwegian. Here is an example of what one of the participants say: (Participant): "Yes. So it was another time when it got stuck in the charger, and it blinked. It was something about the light, but I did not understand what it was. I have missed a Norwegian instruction manual. It would have been very nice to have one." (Interviewer): "You are not the first person saying this. […]" (Participant): "Because even if I understand pretty well English, these technical things are a lot worse, because you do not understand them so well: technical language is more difficult!" (Interview, Elder person).

1) Providing Improper Feedback:

Another issue that seems relevant to the use of the app was when a power outage occurred, and the app stopped working, as it required an Internet connection. During a power outage, the app controlling the domestic robot stopped working, according to one of the elderly participants. The participant got a message that the app "cannot connect to the cloud services". The use of technical terms, such as "cloud service" when giving feedback to the user, seems to be inappropriate. She said: "It was just standing still there, or when I pressed on it where it says something about cloud-service. It didn't do anything, but I thought you would come tomorrow" [1]. The technical term "cloud service" confused the elderly user. The user, in this case, relied on the researchers help to come along the next days.

Another participant wrote in his diary notes that the robot urged for attention through a feedback message: *"Please clear my path (2000) and a red cross"* (Diary notes, Researcher), without understanding the meaning of the error 2000. Another participant referred to the message he received from the app as a "cryptic message." One of the participants explained that the app does not give proper feedback regarding the area of the room: *"The area cleaned shown on the map is 4 mp2. But the hall and room 3 are more than 4 mp2."* (Diary notes, Researcher).

2) Lack of Feedback:

It seems that one of the participants has used the app to schedule the robot. However, the participant did not get any notification (e.g., lack of feedback) when the robot once started to run: "Went out to meet some friends, when I got home, I found the robot running. Apparently, I had turned on a schedule when I had last used the app. I'm not sure *how* I did this, but I did it. The Wife was home, so she picked up the rug in the entryway." (Diary notes, Researcher) Another similar situation is illustrated in one of the participant's diary notes: "We went out for a walk, and when we came home the robot was vacuuming, it had sort of cleaned the rug in the entryway, but not really. […] A bit annoyed, I looked at its schedule. It seems it will be going at 9:30 tomorrow evening. We'll be ready for it this time. I enjoy that it has created a staggering vacuuming schedule, but a bit annoyed that it just launches itself out there." (Researcher, Diary notes).

C. Findings: Robot Motion as Feedback and its Implications for the User

In this section, we present situations where the users interact or engage with semi-autonomous robot technology. We make sense of the movements illustrated as *feedback*, as they happened. The situations illustrated that: *the incoherence semi-autonomous robot's motion triggered various feelings*, including stress, anger or other feelings related to robot personification; *the users received indirect feedback to do facilitation work*, such as moving things around in home, lift the robot and move it manually to another place; and *that the robot's motion creates noise*. An illustration of the situations described here is given in Fig. 5.

1) Movement Triggers Feelings

a) Feelings of Incoherence in Robot's Motion: Some participants pointed out incoherence in the robot's movement. The feeling of incoherence was triggered by the non-regular pattern of the movement, the user not being able to predict it. Indirectly, the robot motion gave a feeling of incoherence. Here are some examples: "I think it starts in one room, and then it goes to another, and then it goes again to the first room. I think it is a bit strange that it does not finish in the first room, and it goes perhaps to the kitchen, and then it comes back, and it continues likes this, and then goes out again. I think it was very strange (break), really, very strange." (Interview, Elder participant); "[…] And suddenly it started going by itself one morning. I thought it was very strange." (Interview, Elder participant); "One time when I pressed on HOME, it started going around by itself, so I had to carry it back" [the participant means here that she pressed on the HOME button, but she had to carry manually the robot back to its charging station].

b) Feelings of Anger, Stress, or Annoyance: Some of the participants found it stressful to follow the robots'

movement: “There? [it reads out loud from own diary notes]: Puhhh… It was a bit stressful to keep an eye on it. […] Yes, I think it was a bit stressful because it went so many times over the same place. And I think it is a waste, such a waste. It went back and forward, and I wanted then to... I just put my foot in his way, so it couldn’t go another way. You decide very little over it.” (Interview, Elder participant); In another elderly’s participant diary notes was written: “[…] Is this helping, or it will be Stressful [note that the participant writes the word Stressful starting with capital S]” (Diary notes, Elder participant). Another participant points out feelings of anger triggered by the robot motion: “So it was a bit stressful there! I was angry at it.” (Interview, Elder participant). Another participant said: “At the beginning, it was a little odd to have a device moving on its own while we are sitting in the living room or having dinner. Since this was our first experience with this kind of technology, it makes sense to be annoyed or even scared by this robot at the beginning. However, having a remote control to terminate the robot manually or to change the current function overcomes the fear!” (Diary notes, Researcher).

c) Feelings of Personification – Robot as a Companion: However, besides feelings of incoherence in movement, stress, and anger, the robot also awaked feelings of personification – they viewed the robot like a pet, or someone in the home, that they talked to (Interview, Elder participant). Some of the participants personified the robots by giving them names such as King Robot, Frida, or Snilla.

2) Robot Enacts the User to do Facilitation Work

a) The Robot gets Stuck in Obstacles: There were several situations when the robot got stuck, in curtains, under the bed or sofa, in cables, or things around the home. Here are some exemplifications from both elderlies and researchers: “I got my brother fixing the cables under the bed, so they are not in its way. […] If it had gotten stuck there, I wouldn’t have been able to come down there. I was very afraid of this. So no cables were supposed to be there! I felt so much better then!” (Interview, Elder participant); (Interviewer): “Okay… But you also wrote in your diary notes that you had to clean a bit before you could run the robot.”; (Participant): “[…] I have lots of chairs here. I have put those two on top of each other because otherwise, it stops all the time. So I have removed them. And the cables […] Yes, I have cleaned a bit.”; (Interviewer):” Did they get stuck in the cables on the floor?” (Participant): “I have tried to remove those. Yes, because it stopped a bit... or it brought those with it. So I had to clean.” (Interview, Elder participant). Some situations are illustrated below (Fig. 6).

Figure 6. Situations where the robot got stuck and needed facilitation work

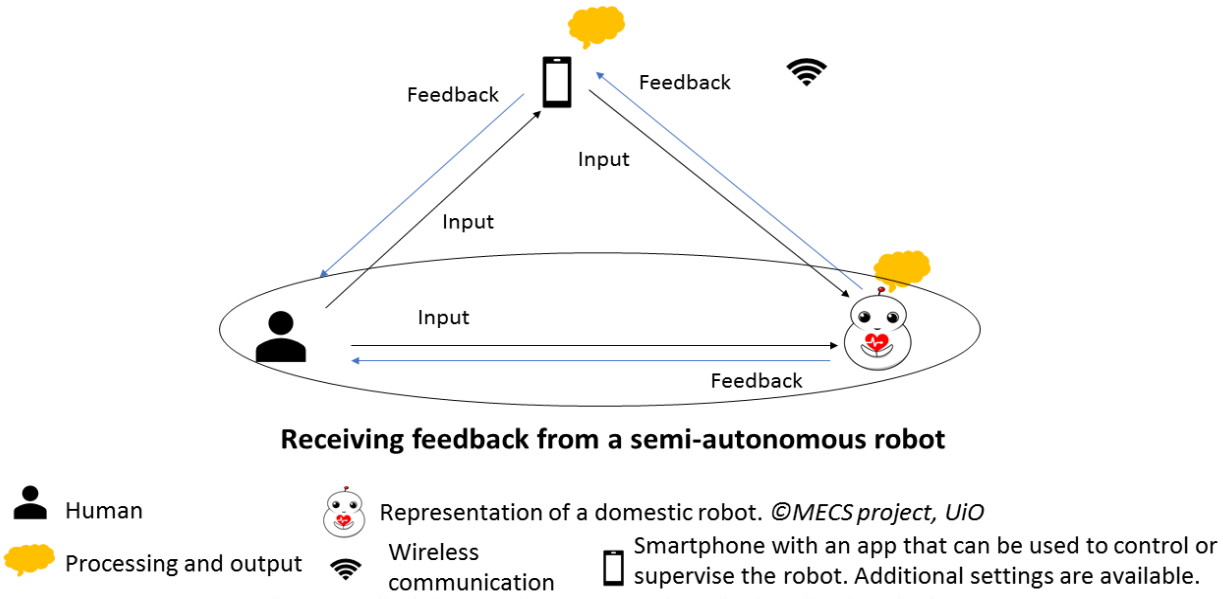

Figure 5. Feedback from a semi-autonomous robot technology directly to the (human) user

A few other examples are: "[…] A chair had to be taken outside of the room, two pillows and a basket were set on a table, two cables had to be taken up. Two doors had to be closed. […]" (Diary notes, Elder participant); "The robot got stuck in the carpet's tassels and stayed still. It took some time to free R from the tassels, so I took away the carpet. […]" (Diary notes, Elder participant); "R got stuck under a little table, I have freed R and lifted the machine to the charging station." (Diary notes, Elder participant); (Interviewer): "Do you see this as a problem?" (Participant): "Well… As I am quite strong, it works. But not everyone can lift and carry it." (Interview, Elder participant); "On a shelf, it was a lamp, but its cable was down on the floor. The robot got stuck, and it dragged the lamp down. As a result, the lamp got disassembled in 2 pieces. Luckily it was a plastic lamp & it didn't break. I could put it together." (Diary notes, Researcher). One of the commented on how a robot generates other types of work – additional and facilitation work is needed to be done. "[…] The *goal* I had was to make the *floor clean*; but to get to this – I needed to install something on the floor… A paradox." (Diary notes, Researcher).

Several participants suggested that one needs to do some facilitation work regarding the surface where the robot should navigate: "It started working, but it got stuck on the TV stand. I got a message about 10 minutes out. I then came back and freed it. It went for a while but got lost under the table. I pulled out the chair, and it seemed to go OK. Afterward, it did OK, though it tried to climb the entrance to the laundry room." (Diary notes, researcher); "I pressed "HOME" button, it started. After a while, it got stuck. I remembered the previous installation at home when the app gave notifications about this – when I was out-of-the-house. This information was disturbing at that time since I did not want to do anything with it. It interrupted a nice train journey I remember now and started off a train of thoughts of where it was stuck, and why (since I had done my best to make a "clean floor" there as well." (Diary notes, Researcher). Another participant pointed out: "Managed to move small, light things like a tiny rug, map tube" (Diary notes, researcher). A few others said: "After getting tired of the robot getting stuck, I put the stripe on the area it always got stuck, and it worked fine. Yay!" (Diary notes, researcher); "I had to move the chairs that were under the table because it was too small. I've noticed that it didn't reach." (Interview, Elder participant); "Yes, it pulled the cables a few times. Especially those behind the sofa, it is a long cable, and it pulled it out. Now I have fastened it, so it doesn't go on it any longer." (Interview, Elder participant); "Isn't it supposed that robots do their job on their own, without needing one's assistance?" (Diary notes, Elder participant); "A few times I had to move because it got stuck a lot. So next time I had to move those things out [talks about furniture] But I think it is a bit confused because it seems to have memory. When I moved the furniture, I think it was a bit confused, I think. But yes, I had to move the furniture." (Paraphrasing from an interview with an elder participant).

b) The Robot Escapes and Indirectly Asks for Facilitation Work: Two of the elderly participants encountered situations when the robot would escape from their apartment. Here are some examples from our data: (Participant): "[reads out loud from his diary notes] Her name is Frida. It behaved well. It got away one of these days. I forgot to lock the entrance door, and it disappeared in the hall."; (Interviewer 1): "[surprised] Okay. So it disappeared??"; (Participant): "Yes, yes. That one is wild. It went fast over the doorstep."; (Interviewer 1): "So you had to go and bring it back."; (Participant): "Yes, yes, yes. Yes, but maybe after it finished, it would have come back by itself. I don't know."; "I also had that door open, and it was out in the hall. But after, I closed the door, and it had to stop there.". Some examples when the robot tries to go over the doorsteps are exemplified in the images below (Fig. 7).

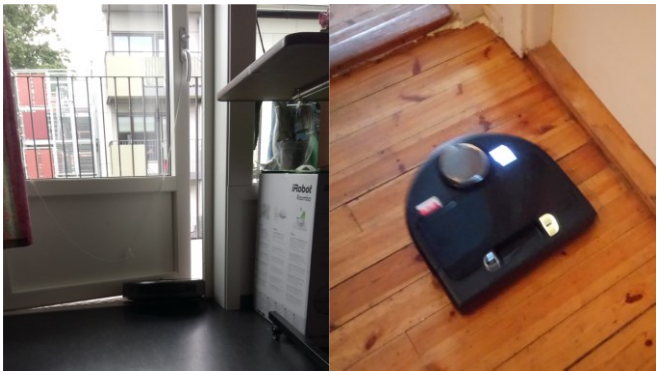

Figure 7. Robot escapes

c) Motion Creates Noise

Several participants, both researchers and elderly, reported that the motion of the robot created noise. Noise, in this case, can be accounted as a form of feedback for the motion, with the meaning of: "the robot is ON, and navigating around." Here are a few excerpts from our data exemplifying this: "R has started just now. The Radio attenuates the sound from R." (Diary notes, Elder participant); "[…] I have pressed on clean, but it was just standing there and making noise. I had to lift it to the charging station, press clean and R continued its tour." (Diary notes, older participant); "Back to the engine sound. I guess this is to be worked with; to make it quieter. Perhaps it could be possible to make user settings; how much power should be used, and this will again regulate the sound/noise. It is hard to think of the sound as nothing but noise… The sound from the movement is very low in comparison to the sound from the vacuum engine. It is also more pleasant to the ear." (Diary notes, researcher participant); "Checked the schedule, and thought nothing was on. So, I went out, but it turned out that it was actually

going at 9:30. I wasn't there, but the wife was trying to sleep and complained about all the noise it made. But it got stuck somewhere, constantly asking for attention. When I finally got home, it was waiting at the front door, stuck in the carpet. It complained that it wanted the roller cleaned. I just put it away for tomorrow." (Diary notes, researcher participant); "Noise, can't use together with TV watching" (Diary notes, researcher participant); "Any way to pause cleaning once it starts, e.g., to take a phone call? Via app?" (Diary notes, researcher participant).

Finally, in this section, we have illustrated situations on the motion as feedback and its implications for the user, based on empirical data. In the next Section, we continue with discussing and unpacking further motion as feedback through the lens of familiarity based on the situations presented here, and also coming back to our initial stated research questions.

VII. DISCUSSION

"The designer of any artifact that is a tool *must communicate* the artifact's intended use and, in some cases, the rationale for its behavior, to the user. There is a strong sense, therefore in, which the problem with such a premise, however (as archaeologists well know), is that while the attribution of some design intent is a requirement for an artifact's intelligibility, the artifact's design per se does not unequivocally convey either its actual, or its intended use. While this problem in the interpretation of artifacts can be alleviated, it can never fully be resolved, and it defines the essential problem that the novice user of the artifact confronts. Insofar as the goal of design is that *the artifact should be self-evident*; therefore, *the problem of deciphering an artifact defines the problem of the designer as well*." [44, 14-15, emphasis added].

What kind of *emotions* are triggered by *improper or lack of feedback when engaging* with a smartphone app or semi-autonomous robot technology? How is a *motion* made sense of and understood by the users when *engaging* with a semi-autonomous robot, in their homes? If the *motion* is illustrated as a type of *feedback* – what do we learn from their experiences?

It seems that *emotion* and *motion* are, at least etymologically, interconnected. Etymologically, *emotion* dates back to the 12th century from the old Franch *emovoir,* which means to *stir up,* and from the Latin *emovere,* which means to *move out, remove, agitate* [77]. In the late 17th and 18th century, the term illustrated "a sense of strong feeling," and later was extended to any feeling, according to the Online Etymological Dictionary [77]. The term *motion* dates back to 13th -14th centuries and it means *"the process of moving," movement, change*, coming from the Old French *mocion*, and from the Latin *motionem*, with the meaning of *"a moving, a motion, an emotion"* [78]. The term *locomotion* dates back to the 17th century and is formed from the Latin *locus,* which stands for a *place,* and the term *motion* [79]. Further, findings from our data present issues related to the robot, to the home space, and to human's emotions and perspectives on perceived autonomy. We choose to limit our discussions related to the issues encountered that are related to the robot's movement. The research questions are analyzed and reflected upon, based on the findings presented in Section VI, the Sub-sections A-C. We do this through the lens of the *familiarity* concept by reflecting on the *motion as feedback*.

A. The Role of Familiarity for the Emotions Triggered by the Engagement with Technology

The first question that we address is: *What kind of emotions are triggered in the user by improper or lack of feedback when interacting or engaging with a smartphone app or a semi-autonomous robot technology?*

An intuitive interface is an interface that the user naturally knows how to use it, whereas *a familiar interface* is an interface that the user has been exposed to over time and learned how to use it [80]. Raskin (1994) suggested that we should use the word *familiar* instead of *intuitive* [57][80]. We have earlier noticed that elderly participants *feared* interaction with *unfamiliar* digital technology because they did not master it, they did not feel able to learn it, and it was not in their zone of proximal development. At the same time, we also noticed that *the language* used for giving feedback to the users, in a breakdown situation, was often inappropriate: either by providing improper feedback or through lack of feedback. We talked about improper feedback as textual feedback using technical terms for transmitting a message. This triggered in the elderly feelings of *fear,* including its derivatives: *angst, anxiety, concern, doubt, dread, unease, uneasiness, worry, aversion, fright, phobia,* and *presentiment* [81].

Many of the studies on feedback within HCI are inspired by human-to-human conversational interactions [43][46]. However, specifically, [44] noticed earlier that human-machine communication was using English as the "natural language" for communicating between humans and machines [44, p. 28]. This choice was anchored in Austin's (1962) "*How to do things with words*," that language through its utterances can be a form of action, but this requires an appropriate interpretation of its interlocutor [76]. We noticed in our study that the interlocutor could not always interpret the use of technical terms. This is an issue of *mutual intelligibility*, as [44] would call it. Therefore, designers should consider avoiding the use of those in textual feedback. Similar findings to ours were presented in the study of eco-feedback from [82], that pointed out that householders participants did not understand the language used in the textual feedback. In addition, the Macintosh User Interface Guidelines, dating back to 1992, pointed out that feedback should be proper, and inform the user as much as possible, instead of providing the user with a technical language such as: "The computer unexpectedly crashed. ID = 13" [41, 9]. We encountered a similar situation in our

findings when one of the participants received the error message: "*Please clear my path (2000) and a red cross*". This type of error message is improper because it did not make sense for the participant. Feedback should be *appropriate* and *timely* [41]. In addition, another study showed that seniors that are not *familiar* with particular technical terminology do not use these words [60]. In our findings, a similar situation occurred when one of the participants pointed out the use of *technical language* in the feedback they received via an app: "it cannot connect to the *cloud services.*" [1, 176]. These are, however, examples from the everyday' participants' interaction with the robot but are nevertheless important to be accounted to make sense of them. [58] explained that making sense of everyday examples of interacting with technology, of coping with it in everyday life situations is an indication of our *familiarity* with the technology. This relies upon the *know-how*, following Dreyfus in [59].

Feedback, however, has cognitive attributes that can be interpreted by the users. For instance, [42] talks about the *mind* and the *text*, and how the information transmitted can change the state of someone's mind and/or affect, depending on the conceptualization and interpretation of the information. We have seen concrete examples in this study of how someone's interpretation of robot motion changed his/her state of mind to stress, anger, or feelings of personification. However, apart from the *emotions* triggered by smartphone app technologies, moving further to the emotions triggered by the semi-autonomous robot, we noticed the following: the incoherence in motion triggered various feelings, including stress, anger or other feelings related to robot personification. When a technology triggers *emotions* within a user, being positive or negative, it means that the user *engages* with it, rather than *interacts* with it [83]. Interaction is a form of "'dialogue' with the technology" [83, 62]. *Engaging* with the technology also has an *affective* part, in comparison to interaction [83]. We have also observed that amongst different mechanisms *to engage with technology*, to be able to *maintain a dialogue* with it, *to cope, to co-exist with it*, one is *feedback*. If, for instance, *motion feedback* supports this *engagement* with the technology in itself, rather than just the interaction with it, we become more *familiar* with it. The repertoire of *emotions* awaken by the participants' experience of the robot is the result of their interaction, *engagement*, or even *familiarity* with it. The *emotions* triggered in both elderly and researcher participants were often of stress, anger, annoyance. However, we observed that, in general, elderly often felt as non-experts when using the robot and did not have the same deep tacit knowledge as the researchers in this study, that seemed to be more *familiar* with using the same technologies, or similar ones. We also observed that both the independent living elderly and the researchers in this study were challenged in many ways by interacting with a semi-autonomous robot technology: perhaps more than with a smartphone app technology. Many of these challenges arose due to additional interaction elements: the (sometimes incoherent) motion of the robot and the use of the app. The participants often had to learn the *know-how, to co-exist with* the robot, and *to accommodate it*: not the opposite – the robot did not necessary accommodated them, although it was its purpose. On the other hand, [84] talk about *unfamiliarity* of the users with a new technological machine makes it *more difficult to cope with it* – this does not mean that the machine lacks technological advancement, but perhaps *it is not designed in a familiar way for the users*.

Finally, we have noticed that the robot, through its motion, did not only trigger negative feelings but also feelings of personification: the participants associated the *motion feedback* of the robot with *aliveness*. The movement of the robot put the robot somewhere in between a static object, and a fully autonomous object: it was something that could move by itself, be self-propelled, i.e., it could change its location without a necessary and continuous intervention of a human or another object. Nevertheless, this idea of *aliveness* as a *familiar characteristic* has been earlier noticed, based on "autonomous motion, or reactivity" [44]. These feelings of personification can be translated as awaking *positive emotions* in the elderly. However, making sense of the *motion* itself as *feedback,* and how it can be understood through the lens of familiarity remains to be discussed. We explore this next.

B. Making Sense of the Motion as Feedback

The second set of questions addressed in this paper is: *How is a motion made sense of and understood by the users when interacting or engaging with a semi-autonomous robot, in their homes? If the motion is illustrated as a type of feedback – what did we learn from their experiences?*

Humans are usually *familiar* with their own *movement,* with seeing things that move around outdoors: bicycles, cars, trains, ships, airplanes. However, one is not yet familiar with semi-autonomous *things* that move within a home. This phenomenon has been discussed within Robotics and Human-Robot Interaction (HRI), but it still remains to be explored within HCI. A *home* is not a static linear environment, but rather things happen in a dynamic and non-linear fashion: people in the home move objects around: a chair is moved to another place, a bag is placed on the floor, a sock is forgotten on the floor and so on. A robot, whose main surface of navigation is *the floor,* may encounter these objects and treat them as *obstacles*: both in its wayfinding and in its navigation. Familiarity is also a form of engagement, or what Heidegger calls *involvement* [83]. One becomes familiar with the technology through repeated, everyday exposure to it [59][60]. But a semi-autonomous robot that moves within the home seems to be still unfamiliar so far: perhaps because we are not yet exposed in our daily lives to robots that move semi-autonomously in our homes. Turner (2011) talks about the inclusiveness of technology, that it must fit users' everyday

lives [58]. *Did the robot fit the participants' everyday lives?* The elderly in this study were willing to adopt a robot in their homes, out of curiosity, willing to learn more about such semi-autonomous robot technologies, to become familiar with it, but also perhaps they sought out some sort of practical coping, that ameliorate some of the direct consequences of aging, such as bending while doing cleaning work. Housekeeping, for instance, seems to be considered not only a physical task, but also a goal-oriented task that requires some degree of cognitive functioning [3].

However, the authors refer to information retrieval only as a *text regarding* these types of feedback, not as a *motion* [42][46]. The human is considered here as an interpreter of the *motion as feedback*. *Motion feedback*, similarly to visual feedback, can also be translated into *positive, negative, homeostatic feedback*, or *archival feedbac*k. Based on our study, we have observed that the *motion as feedback* can be mapped out to four situations: (1) when the robot is still, (2) when the robot goes from a still state to motion, (3) when the robot goes from a motion state to a still state, and finally, (4) when the robot is in motion. We ground our mapping on empirical examples from our data to illustrate motion as feedback, but we do not argue that other ways of are not possible. Besides *polarity feedback, homeostatic feedback,* and *archival feedback*, we introduce the notion of *transition feedback*. *Transition feedback* emerged during our mapping of *motion as feedback.* Transition feedback refers to *motion as feedback* when the robot changes its state from *still to motion* (2), or from *motion to a still state* (3). Next, we map *polarity feedback, homeostatic feedback, and archival feedback* to *motion as feedback*.

1) When the Robot is Still

When the robot stands still, the *motion as feedbac*k can be translated into homeostatic feedback: the robot does not perform any change in its motion state. The homeostatic feedback can be either positive or negative, depending on if the user has previously pressed the button to start it, or not. For instance, if the user presses the CLEAN button, which means that the change of the robot should be changed from still to motion, but the robot remains still, the feedback is negative.

2) When the Robot Goes from a Still to a Motion State

The transition between the still state to a motion state of a robot can be translated as positive or negative feedback, depending on the correspondence between the user's input and expectations. Positive feedback is given when the user presses the CLEAN button, and the robot moves around cleaning. This is also transitioning state feedback, as the robot changes its state. An example of negative feedback for this situation is when the robot starts moving around by itself, without being enacted by the user.

3) When the Robot Goes from a Motion State to a Still State

The robot turns back to its charging station when the user presses the HOME button can be translated into positive feedback, as the robot responds to the user's input. At the same time, this can also be translated into transitioning feedback since the robot changes its state, from motion to a still state. A second situation is when the robot turns back to its charging station when it is almost out of battery. This motion feedback can be translated as positive archival feedback since the robot acts accordingly to its resources, e.g., needs to be charged. However, from the point of view of the user, this can be translated as negative feedback, since the robot does not meet the expectation of the user: to be in motion once that the user has pressed CLEAN. It can also be translated into *transition motion feedback* since it is changing its state. A third situation is when the robot remembers the path and turns back to its charging station after finishing cleaning. This can be translated as positive archival feedback because it remembers its way back, based on a logged history or a previously created map. A fourth situation is when the robot gets stuck and enacts the users through indirect or invisible feedback to do facilitation work. In other words, the robot gives a negative *transition motion feedback* to the user by changing its state, from motion to a still state.

4) When the Robot is in Motion

We could see in our findings that when the user presses the HOME button, but the robot does not go back to its home station, and yet here the *archival feedback* was missing. This can be translated as negative homeostatic motion feedback. We can say that when the user presses the HOME button and the robot returns to the home station, the user understands the robots' navigation to the base station as immediate positive feedback: it responded to the user's action. Another situation is illustrated when the motion of the robot is incoherent: it only cleans a small surface, without navigating the whole area. This can be translated as negative homeostatic motion feedback. When the robot is in motion, and the motion feedback is manifested through the noise, it can be translated into positive homeostatic feedback. However, in the view of the user, this is translated as negative feedback since the noise itself creates feelings of annoyance, disturbing the user.

When the robot remembers the map of the rooms when is not running for the first time in the area (coherent navigation), the motion of the robot can be translated into positive archival homeostatic motion feedback, since the robot remembers the map of the room and can navigate accordingly. Opposite to this situation is when the robot escapes a room previously navigated, i.e., the navigation path of the robot does not respect the boundaries. This can be translated as negative motion feedback.

We illustrate some examples of positive, negative, homeostatic and archival motion feedback in Table IV.

C. Familiarity with the Motion as Feedback

Based on this study, we have observed that the *familiarity*, or for that matter *unfamiliarity,* of the *motion as feedback* can be based on already established notions of the polarity of feedback, homeostatic feedback, and archival

feedback. However, these notions were used so far in relation to textual or visual feedback [55][60]. We have classified motion as feedback, based on the motion state of the robot and empirical examples from our data: 1) motion as feedback when the robot is still, 2) motion as feedback when the robot is transitioning from a still state to a motion state, 3) motion as feedback when the robot is transitioning from a motion state to a still state, and 4) motion as feedback when the robot is in motion. To the already existent types of feedback, we have observed that for semi-autonomous robots, transitioning feedback for situation 2) and 3) is a new type of feedback. We have mapped and illustrated the four situations based on the robot's states and their corresponding feedback (Fig. 8 on the next page).

Further, [85] compared and synthesized the design principles from Schneider (1999) [37][38], from Constantine & Lockwood (1999) [86], and from Nielsen (2005) [87]. The author found out that the principles related to error handling and error recovery, based on the three named guidelines are necessary for any type of interactive system [85, 45]. Specifically, the author means that errors should be avoided [85, 45]. If we translate this to the familiarity of *motion as feedback,* it implies that any feedback that can be translated as a form of *negative feedback* illustrates some sort of *unfamiliarity*: either of the robot as a response to a user action, or of the *emotions* triggered in the user. The authors say: "in other words, the environment would behave in a manner familiar to the user as if they were not actually using a computer system." [85, 45]. We can observe that negative feedback occurred in all types of situations. This means that the semi-autonomous robot did not respond or act in a *familiar* way. Further, according to the authors the concept of UNDO, of *archival feedback,* which we translated as a way for the robot for going to a previous state, is "unnatural" and conflicts "with the principle of familiarity" [85, 45]. We observed this type of *archival feedback* in situation 3) when the robot transitioned from a motion state to a still state, and in 4) when the robot maintained its motion state. For *motion as feedback*, this idea that the archival feedback is unnatural and conflicts with the *familiarity* concepts seems to do not always hold. We argue rather that there are situations when the robot acts in a familiar way for the user. Here are our arguments: the robot turns back to its charging station when the user presses HOME button – this is in line with the user's expectations; the robot turns back to its charging station when it is almost out of battery – the robot is at least in line with the needs of its system for more resources; the robot remembers the path and turns back to its charging

TABLE IV. MAKING SENSE OF MOTION AS FEEDBACK

Robot state	Example of situation	Motion as negative feedback	Motion as positive feedback	Motion as homeostatic feedback	Motion as archival feedback
1) The robot is *still*	The robot stands still.			X	
	The user presses the button, but nothing happens.	X		X	
2) The robot is transitioning *from a still state to a motion state* (transition feedback)	The user presses the CLEAN button and the robot moves around cleaning.		X	X	
	The robot starts moving around by itself without being enacted by the user.	X		X	
3) The robot is going *from a motion state to a still state* (transition feedback)	The robot turns back to its charging station when the user presses HOME button.		X		X
	The robot turns back to its charging station when it is almost out of battery.	X	X		X
	The robot remembers the path and turns back to its charging station after finishing cleaning.		X		X
	The robot gets stuck and enacts the users through indirect or invisible feedback to do facilitation work.	X		X	
4) The robot is *in motion*	Motion feedback manifested through noise.	X	X	X	
	The robot remembers the map of the rooms when is not running for the first time in the area (coherent navigation).		X	X	X
	The motion of the robot is incoherent (it only cleans a small surface, without navigating the whole area).	X		X	
	The robot escapes (e.g., the navigation path of the robot does not respect the boundaries).	X		X	

station after finishing cleaning – the robot is acting in a familiar way to user's expectations, it acts accordingly after finishing its job.

Further, in this section, we have followed Turner (2011), of making sense everyday examples of interacting with technology, the readiness of coping with it in everyday life situations [58]. This sense-making lead us to a mapping between polarity feedback (positive or negative), homeostatic feedback, and archival feedback to motion as feedback. In addition, we observed that doing this mapping by using the states of a robot, still and in motion, and their corresponding transitions, we could define the *transition feedback type*. We have also observed that different feedback for different states can trigger *emotions* (positive or negative) in the user. If we follow the idea that the interaction is a form of dialogue' with the technology, we are still concerned that current design remains *unfamiliar* to the user in specific situations, regardless if the user is experienced or not. To come back to Suchman's (1986) idea that a "*tool must communicate*", and that "*the artifact should be self-evident*" [44, 14-15], it seems that our *artifact, tool,* and *machine,* the robot, was not able to communicate in a number of situations that we illustrated based on our empirical data. This problem of *unfamiliarity,* as opposed to *familiarity,* reveals a deeper underlying problem: "*the problem of deciphering an artifact defines the problem of the designer as well*." [44, 14-15].

If the robot does not follow a *familiar* way of navigating a space, responding to the user's expectations, this may lead, in the case of the elderly and their use of a safety alarm robot, to additional falls for them. A concrete example is when the robot *transitions* from a still state to a motion state, without giving any *feedback* to the user, besides the feedback in the form of *transition motion feedback*, and noise as homeostatic feedback. Falls amongst elderly is a well-known problem [88]. The situation presented above may lead the user to additional falls if the user is not aware of the *transition and homeostatic feedback*. Introducing a robot that does not respond accordingly, by giving negative feedback, being it homeostatic or archival, may have negative consequences on the user. Further, the report about falls amongst the elderly shows that fall may lead to fear of falling, and other negative physical and mental health consequences [88]. The literature also shows that falls amongst elderly people (≥65 years old) are very common, and hospitalized due to fall injuries seem to occur five times more than due to other causes [89]. Another problem with the *motion as feedback* is when the robot escapes. In the situation of the use of a robot in the home, e.g. a safety alarm robot for the elderly, such a type of negative and homeostatic feedback may lead to a non-detected fall. The situation of the robot getting stuck, as negative and homeostatic motion feedback, may also lead in a real situation to a non-detected fall, and in other implications for the user: bending over to move the robot.

Lastly, we can say that looking at the *motion as feedback* with the help of *familiarity concept* contributed to understand the potential challenges and implications when introducing a robot in the homes of the independent living elderly. Moreover, it also contributed to map and discusses *motion as a positive, negative, homeostatic, archival,* and *transition motion feedback*.

VIII. Conclusion and Future Work

In this paper, we have presented *motion as feedback* through empirical data from an explorative study of semi-autonomous robots used in domestic settings. We started the

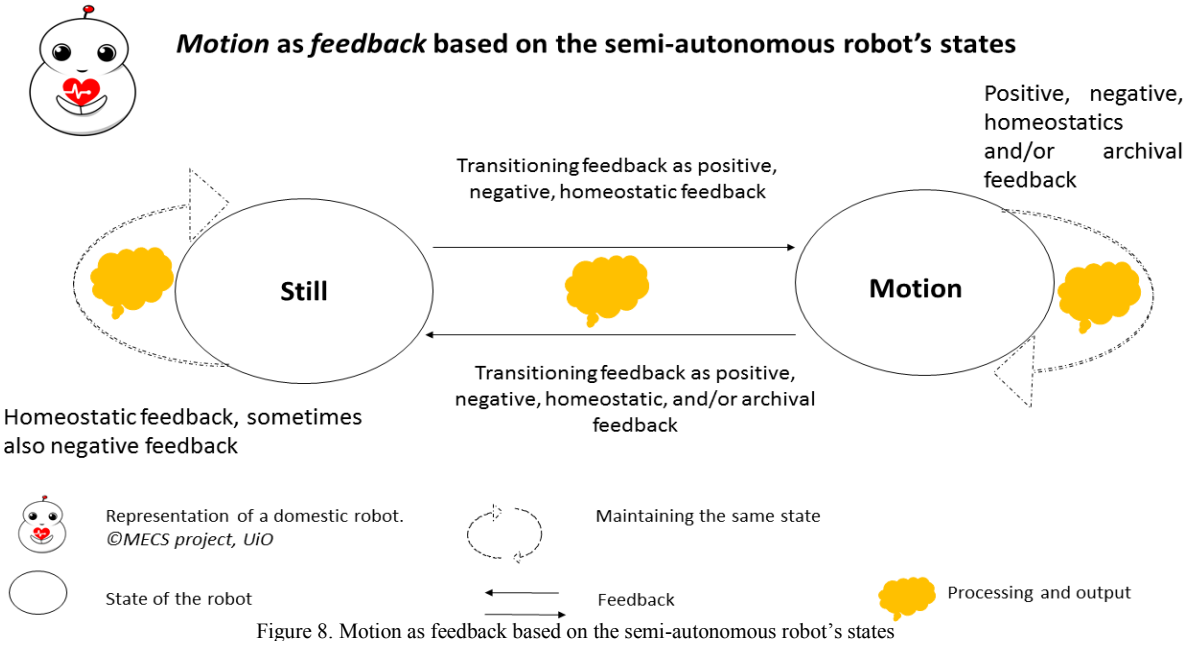

Figure 8. Motion as feedback based on the semi-autonomous robot's states

paper by stating our research questions, introducing some terminology and the background for this study. In Section II, we gave an account on the state-of-the-art. Section III introduced the reader to the concept of feedback within HCI, where it often is understood and designed as visual, auditory, haptic, or textual. We drew attention upon the significance of the use of natural language when interacting with computers, or designing feedback, dating back to the work of Suchman (1985) [41][44]. We elaborated on *polarity-, homeostatic,* and *archival feedback* based on the existent literature. We briefly described *motion as feedback* based on robot navigation. We have framed *feedback* from a smartphone app and semi-autonomous robot technology, to be able to discuss robot's *motion as feedback*, and differentiate it from *feedback* received from stationary technology, we have framed feedback from smartphone app and semi-autonomous robot technology.

Further, in Section IV, we have elaborated on our theoretical foundations, explaining the *familiarity* concept. Section V illustrated in detail the methodology and methods for this study, including the ethical aspects. In Section VI, we have presented our findings structured in: the user receives feedback from a smartphone technology; the user receives distributed feedback from a robot - mediated via an app; and motion as feedback and its implications for the user. Finally, in Section VII, we discussed the *motion as feedback*: the role of *familiarity* for the *emotions* triggered by the *engagement* with the technology, discussing how *feedback* can support *familiarity* with technology; and making sense of the motion as feedback, based on polarity-, homeostatic-, and archival feedback. The *transitioning feedback* emerged here. We continued by discussing *familiarity with the motion as feedback.* We argue that having *familiarity* in mind when designing new technologies, can make it easier for the user to *know-how* to use the technology.

Our conclusion is that a semi-autonomous robot technology can become more *familiar* to the user if it triggers (more often) positive feelings in the user (than negative feelings). Finally, from a System Engineering perspective, following HCI requirements derive from the findings: if its motion is coherent, if its navigation is appropriate to the situation (e.g., going back to the charging station when it is out of battery, not getting stuck, remembering the map of the rooms to be navigated, without "escaping"), and if its motion is not disturbing or interrupting the user (e.g., when taking a phone call, or when eating). Taking a *being-with* approach to *familiarity* for semi-autonomous robot technology to make sense of the robot's motion helped us in being able to distinguish amongst *motion as positive, negative, homeostatic, archival,* and *transitioning feedback*. This approach changed how we view that the participants *engaged with* the technology: it changed their routines at home through the enactment of facilitation work, their schedule, their relationship with the technology itself and with others that live or visit the same home – once part of the home or one's daily's live, it became a subject for discussion suddenly. It was part of their everyday lives. However, we can conclude that through *making sense of motion as the feedback,* we may observe that the semi-autonomous robot was *part of,* but *not* yet *integrated* within their homes and their daily lives. The robot did not accommodate the participants, but rather, the participants had to accommodate the robot. *Familiarity* was defined as an intimate, close, and friendly state, or interaction [81]. However, we showed through this study that while using *familiarity* as a lens *to analyze* the participants' experiences with the semi-autonomous robot technology, the relationship between the participants and the robot remains *unfamiliar* in many situations. The robot still remains in many situations un-familiar to the participants, the *know-how* relationship is not fully developed, and the participants do not always have tacit knowledge on how to interact with it. Finally, the *co-existence* with such robots in domestic settings is not fully developed yet. We can conclude that familiarity *per se* plays a central role in individuals' relationships with technology [56].

Coming back to the State of the Art described in Section II, this study supports the findings from the ACCOMPANY project and Care-O-Bot robot [13][14][15][16]: many of the elderly need support with the ADL. Specifically, the need for support with the housekeeping related needs was nevertheless present also in this study, along with the findings from [19]. However, some of the studies made with the robots used in Robot-Era Project [3], ACCOMPANY [13][14], MARIO, EURON RoboEthics Roadman, EP6, ETHICBOTS, BREATHE, or ICT & Ageing Project [18] were centering their focus around the functionalities of the robot, and the user acceptance of the robots. These robots were also specifically designed for home care of the elderly. The studies made on the companion robots: PARO [21][22][23], AIBO, Furby, NeCoRo [21][22], Pepper and NAO [25], or Giraff [26] focused nevertheless on how a robot may impact the elderly's behavior across time. Many of the studies used quantitative statistical data for the evaluation of the robots. While this is nevertheless important, our study provides an example on how existent robots on the market can be used instrumentally in explorative interpretative qualitative studies for understanding more about the participants' everyday experiences, and how their daily activities may change when introducing such robot in their homes. The study is primarily about the lived experiences of the participants. These experiences are instrumentally used as a foundation for understanding more about design, design of robots for their use at home, design implications of feedback, and motion as feedback distributed or not via an app.

We suggest as future work to elaborate further on the relationship between motion*, transitioning motion feedback,* and the role of *familiar feedback* in *engaging* with technology, rather than *interacting* with it. Further, one could explore more the affordances of motion as feedback, following the definition of affordances as given by [90], or

as seen in HCI. Introducing moving technologies in the home lays the foundation for further explorations. One way to build further on this study is by conducting a quantitative statistical study on the acceptance of the robots in the home, on the movement types of robot, or by using the concept of animacy as shown in [48]. Exploring the abstract concept of *feedback* as a coordination mechanism and/or as a boundary object is also of high interest and relevance for those interested in theoretical anchored explorations. Another way for continuing this study is by conducting a qualitative interpretative study by analyzing the division of work tasks and types of work performed by the human and the robot. Here we encourage the analysis of work tasks and types of works to be done by borrowing established concepts used outside of HCI field, such as Computer Supported Cooperative Work. Nevertheless, studying the boundaries between when the interaction between the human and a robot becomes a cooperation between the human and the robot is of high relevance, especially now with faceless interaction devices: conversational based devices on face- or faceless interactions based mainly on speech, such as, e.g., Sophia the Robot, or with Google Home Mini.

Finally, this study was conducted to understand the potential challenges (e.g., robot motion as feedback is not understood by the participants, the robot motion enacts the participants to do facilitation work, the robot escapes, etc.) that may occur when introducing a robot in the homes of the independent living elderly. Introducing modern technologies in the homes of the elderly, such domestic robots requires scrutiny of the design of current and eventual future technologies that will be used by them. Understanding which challenges the elderly encounter *when* they interact with a semi-autonomous robot, in their everyday lives in domestic settings, contributes to our understanding on potential challenges on the future home care robots for the independent living elderly.

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Automatic Schema Matching as a Complex Adaptive System: a new Approach based on Agent-based Modeling and Simulation

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***Abstract* — In this work, we have investigated the use of Complex Adaptive System theory, derived from systemic thinking, to seek innovative responses to the challenges that Automatic Schema Matching approaches always face (e.g., complexity, uncertainty). We propose a conceptual model for the Simulation of Automatic Schema Matching, and we describe how we modeled it using the approach of Agent-Based Modeling and Simulation. This effort gives rise to a tool (prototype) for schema matching. A set of experiments demonstrates the viability of our approach on two main aspects: (i) effectiveness (increasing the quality of the found alignments) and (ii) efficiency (reducing the effort required for this efficiency). The results obtained have first provided proof of the viability of our approach, but also demonstrated a significant paradigm shift in this domain, where automatic schema matching has never been addressed by adopting systemic thinking.**

Keywords - Schema Matching; Systemic Approach; Complex Adaptive Systems; Agent-Based Modelling and Simulation.

I. INTRODUCTION

One of the key tasks in developing solutions for interoperability between heterogeneous information systems is schema matching. Indeed, it is omnipresent in several fields, involving the management of metadata (i.e., schemas, ontologies). This is the case of integration, exchange or migration of data, the semantic Web, e-commerce, etc. [1] [2] [3].

Several definitions exist for the schema matching process. Rahm and Bernstein [2] in their study of the different approaches for solving the problem of schema matching, define a schema as a set of elements connected by a given structure. The schema must be represented by a notation, to capture in a natural and logical way the notion of element and structure, such as, an object-oriented model, an entity-relation model, XML, or in the form an oriented graph. The task of schema matching is to find semantic mapping relationships between elements of data schemas. Such a process is illustrated in Figure 1. Generally, it aims at finding a pairing of elements (or groups of elements) from the source schema and elements of the target schema such that pairs are likely to be semantically related [2] [4].

Automatic Schema Matching (ASM) is a complex task in more than one way: (i) the heterogeneity and ambiguity intrinsic to the elements of schemas to be matched, (ii) the uncertain character of the matching results, (iii) the challenge of optimizing the pairing (combinatorial explosion), etc.

For a long time, this task remained a manual task reserved mainly for experts with a good understanding of the semantics of the different schemas, and a proficiency of transformation languages. On the other hand, as schemas became more complex, this task began to become tedious, time-consuming and error-prone.

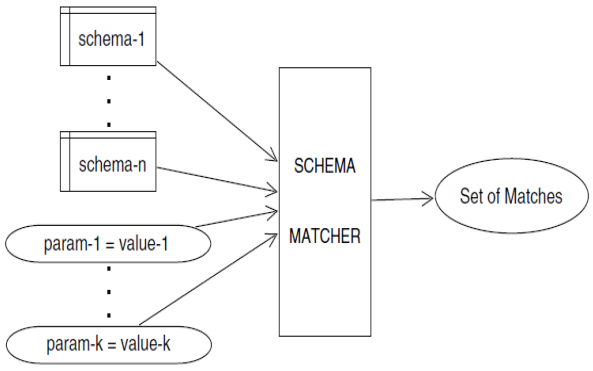

Figure 1. Matching process inputs and outputs

Schema matching existing approaches still rely largely on human interactions, either for the matching results validation, during the post-matching phase, or for the matching process optimization, during the pre-matching phase. Although this human involvement in the automatic matching process could be considered as acceptable in a lot of matching scenarios, nevertheless, it should be kept to a minimum, or even avoided, when dealing with high dynamic environments (i.e., semantic Web, Web services composition, agents communication, etc.) [5]. Thus, the existing approaches are not suited for all the matching contexts due to their intrinsic limitations. We can summarize those limitations as follows:

- Lack of autonomy to the extent that the user involvement is still needed for the results validation and analysis, but also for matching process configuration and optimization

(tuning) to improve the matching result quality and then reduce uncertainty.

- Lack of adaptation in sense that the optimization task of the matching tool must be repeated and adapted manually, for every new matching scenario.

Thus, we were motivated to investigate other paradigms to approach the issue of ASM, as a complex subject appropriate for an approach, which would allow to see this problematic as a whole, that is, as a system whose execution, configuration, and optimization depend not only on the different components of the system, but also on taking into account the relationships and interactions between these components. We try to answer the following general question: "How can we, with the help of a generic approach, better manage complexity and uncertainty inherent to the automatic matching process in general, and in the context of dynamic environments (minimal involvement of the human expert)?"

More specifically, we asked the following questions:

(i) How can we model the complexity of the matching process to help reduce uncertainty?

(ii) How can we provide the matching process of autonomy and adaptation properties with the aim to make the matching process able to adapt to each matching scenario (self-optimize)?

(iii) What would be the theoretical orientation that may be adequate to respond to the above questions?

In our work, we have investigated the use of the theory of Complex Adaptive System (CAS) emanating from systemic thinking, to seek, far from the beaten path, innovative responses to the challenges faced by classical approaches for automatic schema matching, (e.g., complexity, uncertainty). The central idea of our work is to consider the process of matching as a CAS and to model it using the approach of Agent-Based Modeling and Simulation (ABMS). The aim being the exploitation of the intrinsic properties of the agent-based models, such as emergence, stochasticity, and self-organization, to help provide answers to better manage complexity and uncertainty of Schema Matching.

Thus, we propose a conceptual model for a multi-agent simulation for schema matching called Schema Matching as Multi-Agents Simulation (SMAS). The implementation of this conceptual model has given birth to a prototype for schema matching (Reflex-SMAS).

Our prototype Reflex-SMAS was submitted to a set of experiments, to demonstrate the viability of our approach with respect to two main aspects: (i) effectiveness (increasing the quality of the found matchings), and (ii) efficiency (reducing the effort required for this efficiency). The results came to demonstrate the viability of our approach, both in terms of effectiveness or that of efficiency.

The empirical evaluation results, as we are going to show in Section IV of this paper, were very satisfactory for both effectiveness (correct matching results found) and efficiency (no optimization needed to get good result from our tool).

The current paper is organized as follows: Section II discusses schema matching through a state of the art that identifies the important factors affecting the schema matching process. Section III presents the chosen paradigm to address the problem. Section IV shows the results obtained by our approach, and how we can compare them to those obtained in other works. Finally, the last section concludes and summarizes this work.

II. CURRENT APPROACHES OF SCHEMA MATCHING

The schema matching process is often used as a prerequisite for solving other issues, such as data integration or exchange. Indeed, as part of a process of integration or exchange of data, the matching process becomes the task that is responsible for finding an alignment that is semantically equivalent between a source schema and a destination schema. This alignment, in the case of data integration for example, will participate in finding "answers to requests" made to several disparate data sources by consolidating the schemas of these disparate sources into a common schema (i.e., a global scheme). In the case of data exchange, finding an alignment between a source schema and a target one serves for the exchange of data between heterogeneous enterprise systems or applications (such as Enterprise Resource Planning systems, databases, or legacy systems) by helping transform data from the source system format to the target system format.

Generally, Schema Matching is a manual task reserved for human experts with a good understanding of the semantics of different schemas. However, this task can be a tedious, time-consuming and error-prone task.

For many years, several researches have investigated the problematic of automating the task of Schema Matching (including matching ontologies). The main goal is the development of techniques (algorithms, tools, etc.) allowing the automatic or semi-automatic discovery of the correspondences between the elements.

Many algorithms and approaches were proposed to deal with the problem of schema matching and mapping [2][6]-[16]. Although the existing schema matching tools comprise a significant step towards fulfilling the vision of automated schema matching, it has become obvious that the user must accept a degree of imperfection in this process. A prime reason for this is the enormous ambiguity and heterogeneity of schema element names (descriptions). Thus, it could be unrealistic to expect a matching process to identify the correct matchings for any possible element in a schema [17] [18].

Despite the profusion of approaches, human involvement is always required, for the automatic matching process itself, or for the optimization of the performances. They also rely largely on immediate human interaction for the validation of the result of the process, or for configuration/optimization of the process during the pre-matching phase. This human interaction is generally conceivable for many contexts; on the other hand, in other contexts where environments are highly dynamic (e.g., semantic Web, composition of Web services, communication between agents), expert involvement must be reduced to a minimum.

The vision of a complete automation of the matching process of schemes is compromised by a human involvement.

A comprehensive literature review, of the existing matching tools and approaches, allowed us to identify the most important factors affecting, in our opinion, the schema matching process. Moreover, some causal relationships, between those different factors, participating to the schema matching difficulties and challenges, were identified.

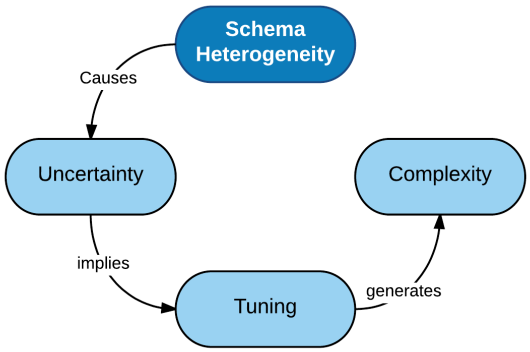

Figure 2. Schema Matching impacting factors causality diagram

As shown in Figure 2, the factors influencing the Schema Matching are:

- Heterogeneity: in general, the task of matching involves semantics (understanding the context) to have complete certainty about the quality of the result. The main challenge in all cases of automatic matching is to decide the right match. This is a very difficult task mainly because of the heterogeneity of the data.
- Uncertainty: the cause for this uncertainty lies mainly in the ambiguity and heterogeneity, both syntactic, and semantic, which often characterize the Schema Elements to match.
- Optimization: the uncertainty about the matching results implies the optimization of the process to improve the matching quality, and the testing of different combinations (e.g., different Similarity Measures, Aggregate Functions, and Matching Selection Strategies). Each step of the matching process involves choosing between multiple strategies, which leads to a combinatorial explosion (complexity).
- Complexity: the matching process optimization generates complexity because of the search space (combinatorial explosion). In addition, changing matching scenarios exacerbates this complexity to the extent that the result of the optimization often becomes obsolete with changing scenarios.

One of the commonalities between all existing approaches is the thinking behind these approaches, namely, reductionism (as opposed to holism). The reductionist thinking is a very common and efficient thinking approach. It is at the basis of the almost totality of previous schema matching approaches, and then, on their characteristics that are, in our view, the root causes preventing the automatic matching schemes to cope fully with the challenges and difficulties.

Reductionism, as opposed to systemic (holism), is a philosophical concept that refers both to the way of thinking solutions as well as to their modeling methodology (Figure 3). Reductionism advocates reducing system complexity or phenomenon to their basic elements, which would then be easier to understand and study [19]. This reductionist approach, despite its high efficacy in several areas, shows, however, its limits within certain contexts. In fact, for explaining certain phenomena or solving certain problems, the approach consisting of reducing or abstracting the reality to a linearization of simple relationships of causes and effects between a complex system underlying fundamental components, appears as a highly limiting and simplifying approach.

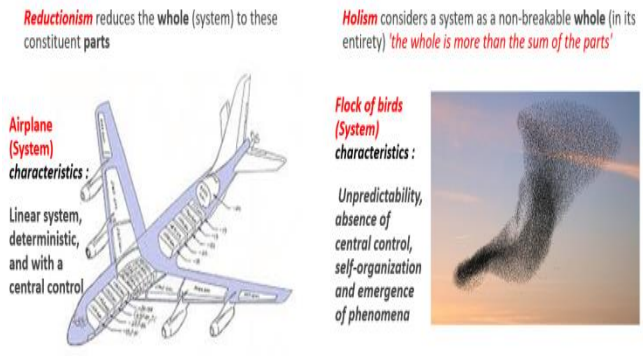

Figure 3. Reductionism vs. Holism

With regard to schema matching, it seems clear, as Figure illustrates it, that all current approaches follow the reductionist thinking. They abstract the matching process to a linear function with a set of inputs and outputs. This function is decomposed into a series of modules, each of

which is responsible for the running of a stage of the process (e.g., selection and matching execution).

In fact, the matching process can be summarized to three important steps: (i) the stage of selection and execution of the matchers (calculation of similarities), (ii) the stage of the combination of the results (the best similarity scores) based on aggregation functions, and finally (iii), the step of the selection of the alignment (selection of the most promising matches) based on thresholds or maximums.

So, in order to solve the automatic Schema Matching problem, the existing solutions are adopting a linear and analytical approach. At each stage of the matching process, problems are analyzed and broken down into sub problems and then for each specific sub-problem, dedicated and specific solution are proposed.

Some fundamental and intrinsic characteristics, common to all current Schema Matching systems, may partially explain their inability to overcome the limitation of the complexity and other challenges, such as uncertainty. Those characteristics are declined as following: these systems are (i) complicated and not complex, (ii) linear (analytical, deterministic and predictable) and not non-linear, (iii) centralized rather than decentralized (parallelism and emerging solutions), (iv) and finally, configurable and not adaptable (self-configuration, self-optimization).

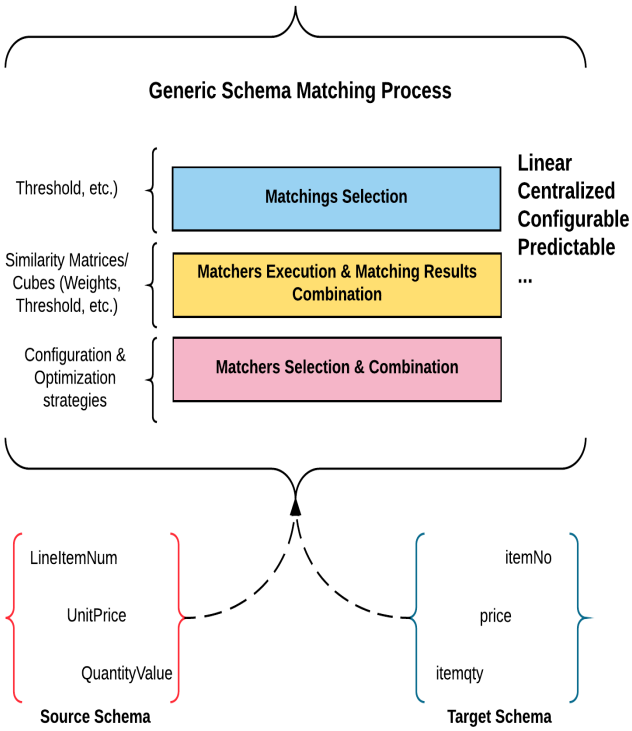

Figure 4. Generic Schema Matching process (linear process with an analytical-based resolution)

We can, thus, postulate that the Reductionist school of thought, leading to complicated and not complex systems, could be the root cause that prevents existing approaches from coping with the challenges of uncertainty and complexity.

The need to explore new approaches to make systemic and holistic responses to the problems of matching leads us to raise the question: how can we have a matching solution that could give us high-quality matching results, for different matching scenarios and this with a minimal optimization effort from the end-user?

Our premise is that a good part of the answer may come from the theory of CAS where modeling the complexity of adaptation and evolution of the systems is at the heart of this theory. Having a schema matching approach that can face and overcome the challenges facing the existing schema matching tools requires, in our view, a paradigm shift, placing the notions of adaptation, evolution, and self-organization at its center. We strongly believe that the theory of CAS, which is exploited to explain some biological, social, and economic phenomena, can be the basis of a programming paradigm for ASM tools.

Our hypothesis is that, to realize the vision of complete automation, it would be necessary to operate paradigm-shift and move from reductionist and complicated solutions to a holistic (systemic) solution based on the paradigm of Complex Adaptive Systems (CAS) with the Multi-agents Simulation as the cornerstone at the heart of our proposed approach.

Our goal is to find an innovative solution, for the challenges of automatic matching, by exploiting multi-agent simulations, taking place in an artificial world, and taking advantage of the computing power of current computers.

« *Simulation models provide virtually unlimited power; or rather, they provide unlimited virtual power. If you can think of something, you can simulate it. Experimenting in a simulated world, you can change anything, in any way, at any time - even change time itself.* » [20].

Figure 5 below represents the different CAS fundamental characteristics that could allow the matching system to move from a chaos state (i.e., initial state) to a state of equilibrium (i.e., final state of the system).

Figure 5. From chaos to equilibrium

The initial state of the system is a state of chaos where the agents are unstable because of their matching status (indeterminate matching). After the start of the simulation, the adaptation stage begins where the agents interact

searching for the best match. Over the cycles of the simulation, consensual matchings (self-organization) begin to form (i.e., local solution representing a local equilibrium to the pair of agents), and thus make emerge the final solution of the alignment (global solution).

The final state of the system is reached once a balance for the system in its entirety is found, thereby signaling the end of the simulation.

III. SCHEMA MATCHING AS A SYSTEMIC APPROACH

As part of our research we investigated the use of the theory of CAS (systemic thinking), to try to find an innovative response to challenges (i.e., complexity, uncertainty) that the conventional approaches for schema matching are still facing.

We think that the CAS could bring us the adaptation capability to the realm of schema matching tools (self-configuration and self-optimization), which should relieve the user from the complexity and effort resulting from configuring and optimizing the automatic schema matching systems.

Before going any further, let us first try to explain our vision of the problematic of ASM under the prism of the theory of CAS. First and foremost, we wonder about the nature of ASM solutions, whether they can be considered as systems. The answer is unequivocally positive. Even if one strictly stands for the definition of the term system, which means "a coherent set of closely related parts", it is clear that the automatic matching of schemas is a system, because of ASM is a coherent set consisting of several components, related to each other, in this case schemas, matchers, etc. Now, if we come to the systemic meaning of the term, the automatic matching of schemas is a system whose different components, for example elements of schemas (which can be represented by agents seeking to find the best match), must interact within this system with the objective of producing a final result called alignment.

Next, consider why a system of ASM can be described as complex. To this end, let us recall the distinction between a "complex" system and a "complicated" system [21]. First, in complex systems, relationships between agents (i.e., system elements) are more important than the agents themselves, unlike complicated systems where elements and their relationships are of equal importance. Second, in complex systems, simple rules can produce surprising and complex responses, while in complicated systems, the results of simple algorithms are simple and predictable. And finally, in complex systems the agents have the latitude to respond according to the limits of their rules, as opposed to the complicated systems, where the response of the components is completely determined.

On the basis of this distinction, we consider that the ASM process must be thought and modeled as a complex system (our approach) and not as a complicated system (current approaches). So, our conceptual model for schema matching, based on the theory of complexity, sees the schema matching process as a complex adaptive system.

As illustrated in Figure 6, in this model, each schema element of the schemas to match (source or target schema) is modeled as an autonomous agent, belonging to a population (source or target schema population). Each agent behaviors and interaction, at the micro level, with the other agents in the opposite population and with its environment, brings out at the macro level, a self-organized system that represents the global solution to matching problem (i.e., relationships between schemas elements). In other words, the resolution of the matching problem goes through individual effort deployed by each agent, locally, throughout the simulation to find the best match in the opposite population.

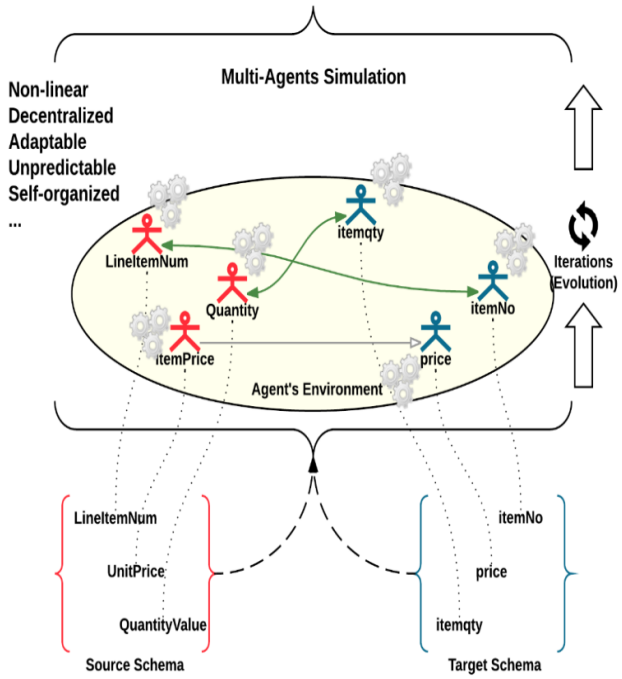

Figure 6. Schema Matching as Multi-Agents Simulation (non-linear process with emergence-based resolution)

We think that many intrinsic properties of our model, derived from the ABMS modeling approach, can contribute efficiently to the increase of the matching quality and thus the decrease of the matching uncertainty. These properties are:

- Emergence: the emergence of the macro solution (schema matching) comes from local behaviors, rules and interactions between agents (micro solutions).
- Self-organization: the cooperation of source and target schema elements (represented as agents) helps to reach a consensus about their best matching.
- Stochasticity (randomness): the randomness within the model, gives the ability to perform statistical analysis on

the outcome of multiple simulations (meta-simulation) for the same matching scenario.

Briefly, our idea is to model the Schema Matching process as interactions, within a self-organized environment, between agents called "Schema Attribute Agent". In the rest of the paper, we are going to refer to the "Schema Element Agent" simply as agent. Each schema element is modeled as an agent belonging to one of two populations: source or target schema group. Furthermore, the schema matching process is modeled as the interaction between the two populations of agents.

In our model, the internal architecture of the agents is Rule-based (reflexive agent). The agents have as a main goal to find the best matching agent within the other group of agents.

The foundation of the rules governing the agent's behaviors is stochasticity (randomness). In fact, a certain degree of randomness is present in each step executed by each agent during the simulation.

The main random elements influencing the simulation are as follows:

- Similarity Calculation based on similarity measures selected randomly from a similarity measures list.
- Similarity Scores aggregation based on aggregation functions selected randomly from an aggregation function list (MAX, AVERAGE, WEIGHTED).
- Similarity score validation based on generated random threshold value (within interval)

As opposed to deterministic solutions for schema matching (all the existing matching solutions), the nondeterministic and stochastic nature of our agent-based simulation increase the confidence in the quality of the matching results. Even though the agent's behaviors are based on randomness, our model can often produce the right matchings at the end of each simulation run.

In the context of our operational model, the agent during the perception phase, perceives its environment by interrogating it, by performing similarity calculations (which can be considered as an act of recognition) or by capturing certain events. The result of this phase will be a set of percepts, allowing the agent to identify the agents of the other group, available for matching. The capture of events, coming from the environment, is another action of perception: for instance, the event that is triggered when the agent is chosen by another one as a matching candidate. During the decision phase, the agent from the results of the perception phase, reasons, deliberates and decides on the action to be selected. The decisions, involving the choice of actions, are the following: (i) the decision concerning the convergence of similarities and the selection of a candidate matching, (ii) the decision concerning the reset of the beliefs concerning the candidate matching, and (iii) the decision on consensual matching. During the action phase, the agent executes the actions selected during the previous phase. The current iteration of the simulation ends with this phase.

Figure 7 illustrates the internal states of each agent. It allows representing the transitions between the internal states, during the perception-decision-action cycle of the agent.

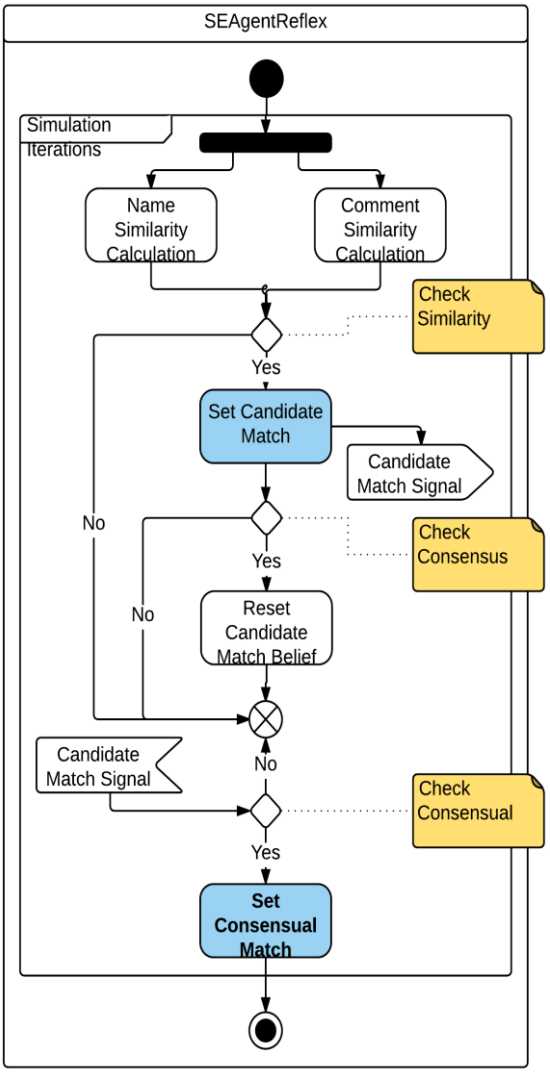

Figure 7. Agent behavior

The behavior of the agent is driven by the goal of finding a consensual match. The consensus-selection approach is a naive approach, consisting of waiting for a consensus that must coincide for both agents (which may imply a longer duration for the simulation).

The main key-features of our conceptual model are summarized as follows:

- Stochastic Linguistic Matching: similarity calculation based on similarity measures selected randomly from a similarity measures list. Similarity Scores aggregation based on aggregation functions selected randomly from an aggregation function list (MAX, AVERAGE, WEIGHTED). Similarity score validation based on generated random threshold value (within interval). Figure 8 illustrates this process.

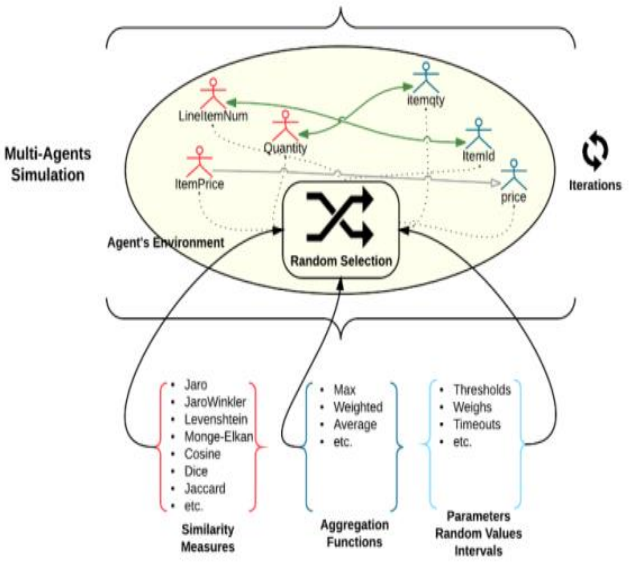

Figure 8. Stochastic Matching

- Consensual Matching Selection: to form a valid pairing/correspondence, the two agents (form opposite populations: source and target schemas) should refer to each other as candidate match (in the same time). Figure 9 is an illustration of such a process.

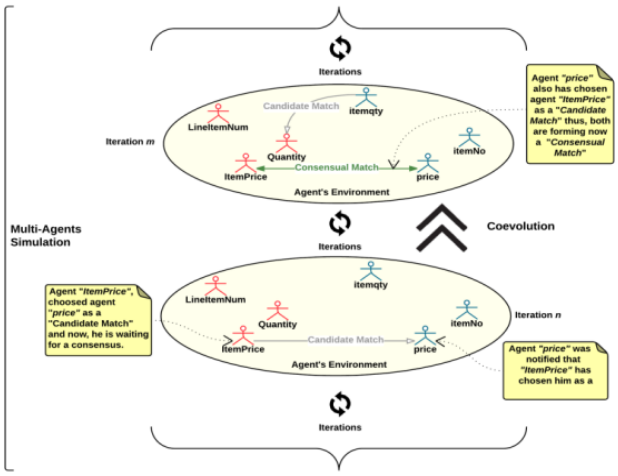

Figure 9. Consensual Matching

- Meta-Simulations and Statistical Analysis: performing statistical analysis on multiple simulation runs data is a good way to improve the confidence in the matching result obtained from our model. It is illustrated by Figure 10.

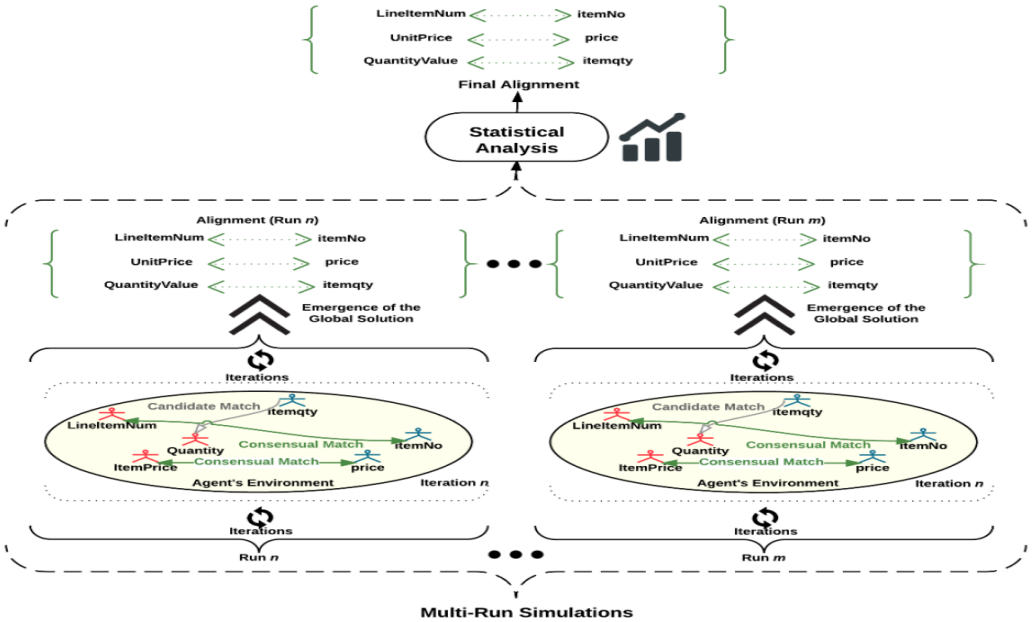

Figure 10. Meta-simulation and statistical analysis

We believe that the conceptualization and the modeling of schema matching as multi-agent simulation will allow the design of a system exhibiting suitable characteristics:

(i) An easy to understand system, composed of simple reflexive "agents" interacting according to simple rules.

(ii) An effective and efficient system, autonomously changing over time, adapting, and self-organizing; a system allowing the emergence of a solution for any given matching scenario.

As depicted in Figure 1, our Reflex-SMAS prototype core was implemented in Java using the open source ABMS framework Repast Simphony (2.1) [22], [23], and the open source framework for Text Similarity DKPro Similarity (2.1.0) [24]. The open source R language (R 3.1.0) [25] was used for statistical data analysis.

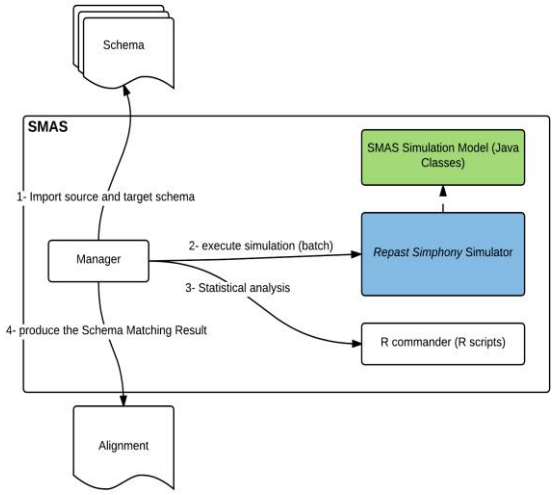

Figure 11. High-level Architecture for Reflex-SMAS

In the next section, we are going to describe the empirical evaluation of the prototype Reflex-SMAS.

IV. EMPIRICAL EVALUATION

The validation of agent-based simulation models is a topic that is becoming increasingly important in the literature on the field of ABMS. Three types of validation could be identified [26]: (i) Empirical Validation, (ii) Predictive Validation, and (iii) Structural Validation.

As we will see in detail, the empirical validation is the type of validation that we have adopted for the evaluation of our Agent-based Simulation Model for Schema Matching (i.e., prototype Reflex-SMAS).

First, we will start with the description of the methodology used as our validation approach, and then we continue by providing a summarized view of our validation results.

A. Evaluation Objectives and Strategy

We are seeking, through this empirical evaluation, to validate the following aspects of our prototype Reflex-SMAS:

- That our solution is, indeed, an effective and efficient automatic schema matching system, capable of autonomously changing behaviors and evolving over time, to adapt, and to self-organize and thus make the solution for any matching scenario to emerge. The effectiveness must be translated mainly by an increase in the quality of the found alignment and a reduction of the uncertainty. Efficiency, on the other hand, must be materialized by reducing the effort required for this efficiency, in particular reducing the user effort required to configure or optimize the matching system, without significantly impairing the response time, which should remain within the limits of the viable and the acceptable (especially for the use of matching in highly dynamic environments).
- That our solution is easy to understand, and therefore, could display a high degree of maintainability (e.g., adding new matchers).

The proof strategy consists on conducting experiments and then collecting and analyzing data from these experiments. Thus, the validation approach that we have adopted is considered as a hybrid validation approach combining two validation approaches coming from two different fields, namely Schema Matching and ABMS. On one hand, from the field of Schema Matching, we are leveraging a popular evaluation method consisting of the comparison of results with those expected by the user [27]. On the other hand, from the field of ABMS, we are using the Empirical Validation, which is mainly based on the comparison among the results obtained from the model and what we can observe in the real system.

Thus, the strategy adopted for the validation of our prototype (implementing our multi-agent simulation model for schema matching) consists of:

- Defining different synthetic matching scenarios (three matching scenarios namely "Person", "Order" and "Travel") with different sizes and different level of lexical heterogeneity, so we can evaluate the prototype matching performance in different situations (adaptation).
- Conducting experiments, compiling results and evaluating the matching performance by comparing, for those three matching scenarios, the matching results (matchings) obtained from our prototype Reflex-SMAS with the results expected by the user.

In the first matching scenario "Person", we need to match two schemas with small size (i.e., six elements) showing a medium lexical heterogeneity level. The second

matching scenario "Order" is composed of schemas with medium size with a high lexical heterogeneity level. The schemas in the last matching scenario "Travel" have a relatively big size with a low lexical heterogeneity level.

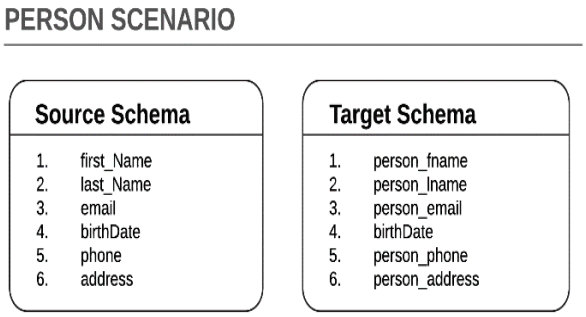

Figure 12. Matching Scenario "Person"

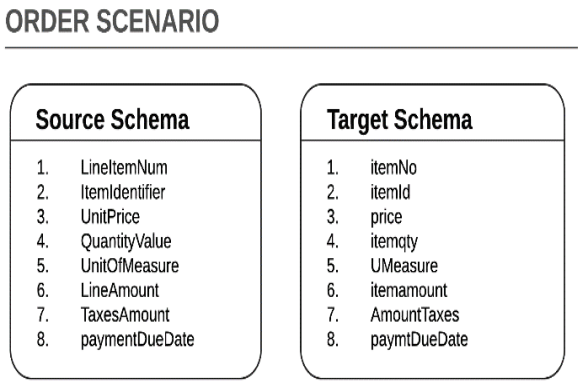

Figure 13. Matching Scenario "Order"

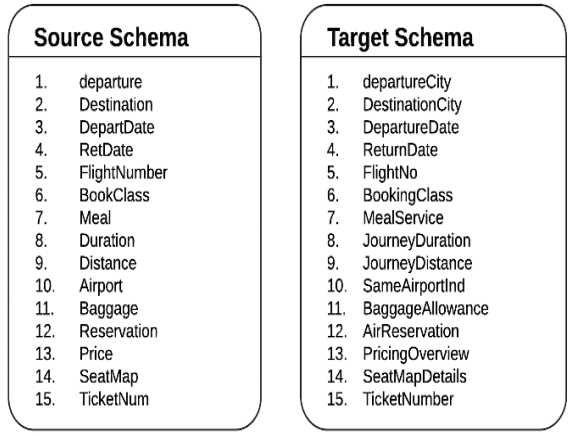

Figure 14. Matching Scenario "Travel"

In order to assess the relevance and level of difficulty that can represent those synthetic matching scenarios (i.e., "Person", "Order" and "Travel"), we decided to evaluate them, first, using the well-known matching tool COMA [28]–[30]. Since, the COMA tool was not able to resolve all the all expected matches for those scenarios, we can say that the proposed synthetic matching scenarios, should be enough challenging scenarios for our validation (from their level of heterogeneity perspective).

Regarding the experiments execution and results compilation, we have decided to run series of three meta-simulations for each scenario (each meta-simulation includes 10 simulations).

The final matching result is based on a statistical analysis of each meta-simulation outcome. In other word, the matching result relies on the calculation of the frequency of occurrence of a found match on the ten simulations composing the meta-simulation. Furthermore, executing for each scenario the meta-simulations three times is a choice that we made to help with the assessment of the experiment repeatability.

B. *Experiment Results*

This section summarizes the results obtained from the experiments conducted to evaluate the Reflex-SMAS tool. After executing the set of three meta-simulations for each matching scenario, we have compiled the results for the performance for each meta-simulation for all scenarios. As indicated in Table I, our tool was able to correctly find all the expected correspondence by the user (a 100% success rate) after each meta-simulation, and for each scenario.

TABLE I. REFLEX-SMAS EXPERIMENT COMBINED RESULTS

Scenario	M.S.	M. to F.	C.M.F.	% C.M.F.
Person	1	6	6	100%
Person	2	6	6	100%
Person	3	6	6	100%
Order	1	8	8	100%
Order	2	8	8	100%
Order	3	8	8	100%
Travel	1	15	15	100%
Travel	2	15	15	100%
Travel	3	15	15	100%

M.S: Meta Simulation
M. to F: Matchings to Find
C.M.F: Correct Matchings Found
% C.M.F: % Correct Matchings Found

Regarding the response time, it corresponds to the execution, in parallel, of 10 individual simulations. At the level of the individual simulations, we are interested in the

discrete time analysis (i.e., iterations), which represents in some ways the measure of the effort expended by the agents to form consensual matching. The figure below shows the response time with respect to each meta-simulation and each scenario. By examining the graph, we can deduce the correlation between the response time and the nature of the different scenarios. We can for example see that the size of the schemas (i.e., "Travel" scenario) or the high lexical heterogeneity (i.e., "Order" scenario) correlates negatively with the number of iterations necessary to find the solution for each meta-simulation. On the other hand, we can notice in Figure 15, that the execution time (in minutes) of the different meta-simulations for the different scenarios oscillates, approximately, between 2 and 3 minutes.

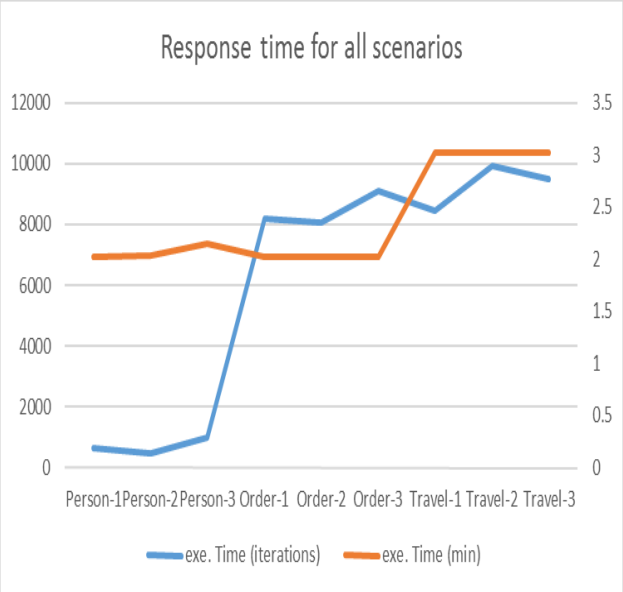

Figure 15. Number of iterations for all scenarios

Now, if we compare the results of our Reflex-SMAS prototype with COMA tool results, we can clearly notice that our tool outperformed the COMA tool in all the syntactic matching scenarios. Table II shows the compared result for Reflex-SMAS vs. COMA.

TABLE II. REFLEX-SMAS VS. COMA EXPERIMENT COMBINED RESULTS

		Reflex-SMAS		***COMA***	
Scenario	**M. to F.**	**C.M.F.**	**% C.M.F.**	**C.M.F.**	**% C.M.F.**
Person	6	6	100%	5	83%
Order	8	8	100%	6	75%
Travel	15	15	100%	13	87%

Figure 16 shows a comparison of the performance obtained for scenarios "Person", "Order" and "Travel" with our prototype compared to those obtained with the COMA tool.

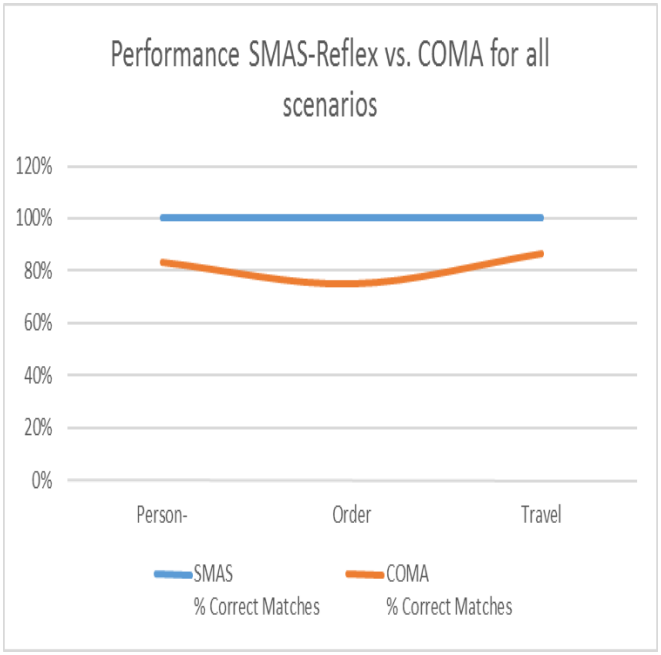

Figure 16. Comparative result between Reflex-SMAS and COMA

To challenge the “perfect” results obtained with our tool Reflex-SMAS for the synthetic matching scenarios, we were curious to know to what extent the performance obtained at the meta-simulations, may be impacted by a reduction in the number of individual simulations composing a meta-simulation. Therefore, we decided to conduct further experimentation, reducing, this time, the number of individual simulations of a meta-simulation from ten simulations to only three simulations.

The performance obtained in the experiment with the meta-simulations composed of three individual simulations instead of ten, has dropped for the scenarios "Order" and "Travel". It means that our matching tool Reflex-SMAS was not able to find all the expected matchings during some of the meta-simulations for those two scenarios (due to the high level of heterogeneity of the scenario “Order” and the big size of the scenario “Travel”). Unquestionably, we can conclude that the number of individual simulations, composing the meta-simulation is an important factor to ensure good matching performance (better quantification of the uncertainty regarding the outcome of the matching process) especially when it comes to scenarios involving large schemas and/or having a high level of heterogeneity.

V. CONCLUSION AND FUTURE WORK

As part of our research, we have proposed an approach arising from systemic thinking, situating it more precisely, in the field of CAS. This approach has resulted in a multi-agent simulation approach based on a non-deterministic, stochastic (random), unpredictable and non-centralized model, where each simulation can give rise, even with the same inputs, to different outputs. The multiplication of the simulations allows the expansion of the space of possibilities and consequently the increase of the potentialities of a better quality of the pairing (i.e., reduction of the uncertainty on the matching obtained).

Our Reflex-SMAS prototype was subjected to a series of experiments whose objective was to demonstrate the viability of our approach in two main aspects: effectiveness and efficiency. This empirical evaluation step showed us clearly its capability of providing a high-quality result for different schema matching scenarios without any optimization or tuning from the end-user. The experiments results are very satisfactory. Thus, we can conclude that approaching the schema matching as a CAS and modeling it as ABMS is a viable and very promising approach that could greatly help to overcome the problems of uncertainty and complexity in the field of schema matching.

Our approach, which is part of the current of systemic thinking and which lies in the lineage of solutions coming from the field of CAS, brings a new perspective to the field of ASM, and represents, in this sense, a significant paradigm shift in this area.

As future work, we are planning to enhance the conceptual model of our prototype to tackle challenges, such as complex schema (n:m cardinalities) by exploiting other Similarity Measures, such as Structural Similarities (schemas structures).

On the other hand, in order to open up new perspectives and to overcome the limits of purely reactive behavior, we are thinking on a "conceptual" evolution of the internal architecture of our agent, evolving it from a reactive agent to an agent of rational type. This evolution, as illustrated by Figure 17, consists in the implementation of a decision-making model under uncertainty, at the level of the decision-making phase of the agent, giving it the ability to reason and to choose between conflicting actions. The rational agent we are aiming for, should have a memory, a partial representation of its environment and other agents (its perception), and a capacity for reasoning, allowing it to make a rational choice (to choose the action with the greatest utility) that can guarantee it to maximize its satisfaction (measure of performance). We also speak of cognitive agent because it possesses explicit representations of it goals on which it is able to reason in order to produce action plans.

The result of this conceptual evolution could give rise to a new version of our prototype, and of course, it must be verified that the change from a reactive behavior to a rational one does not penalize the performance of the simulations.

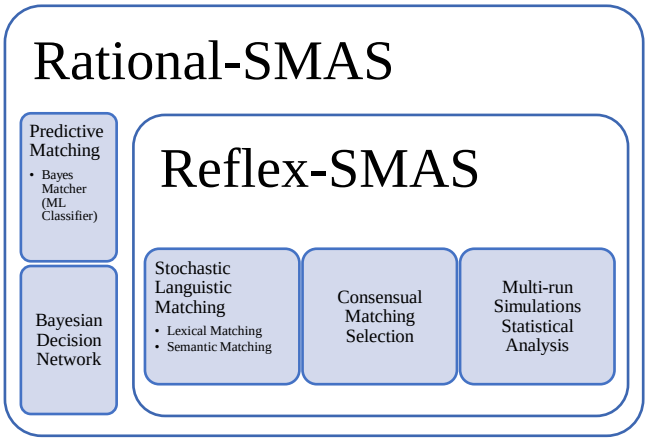

Figure 17. Towards a rational SMAS

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Trend Discovery and Social Recommendation in Support of Documentary Production

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***Abstract*—Recent market research has revealed a globally growing interest on documentaries that have now become one of the biggest content-wise genre in the movie titles catalog, surpassing traditionally popular genres such as comedy or adventure films. At the same time, modern audiences appear willing to immerse into more interactive and personalized viewing experiences. Documentaries, even in their linear version, involve high costs in all phases (pre-production, production, post-production) due to various inefficiencies, partly attributed to the lack of scientifically-proven cost-effective Information and Communications Technology tools. To fill this gap, a set of innovative tools is delivered that focus on supporting all stages of the documentary creation process, ranging from the documentary topic selection to its final delivery to the viewers. This paper elaborates on two specific tools that primarily focus on the interests and satisfaction of the targeted audience: the Integrated Trends Discovery tool and the Social Recommendation & Personalization tool. It presents their design, functionality and performance, discusses the extended evaluation and validation that has been carried out and concludes with exploring the future plans and potential regarding these tools.**

Keywords-documentary production; social-media analytics; Integrated Trends Discovery tool; Social Recommendation & Personalization tool; evaluation; validation; benchmarking.

I. INTRODUCTION

From the earliest days of cinema, documentaries have provided a powerful way of engaging audiences with the world. They always had social and market impact, as they adapted to the available means of production and distribution. More than any other type of films, documentarians were avid adapters of new technologies, which periodically revitalized the classical documentary form. The documentary is a genre that lends itself straightforwardly to interaction. People have different knowledge backgrounds, different interests and points of view, different aesthetic tastes and different constraints while viewing a programme. Therefore, it becomes evident that some form of personalized interactive documentary creation will enhance the quality of experience for the viewers, facilitating them to choose different paths primarily with respect to the documentary format and playout system. The convergence between the documentary production field and of digital media enables the realization of this vision.

As the range of Information and Communications Technology (ICT) platforms broadens, documentary makers need to understand and adopt emerging technologies in order to ensure audience engagement and creative satisfaction, via the use of personalization and interactive media. One of the major challenges for stakeholders in the arena of documentary creation is the development of processes and business models to exploit the advantages of those technical achievements, in order to reduce the overall cost of documentary end-to-end production, to save time and to deliver enhanced personalized interactive and thus more attractive documentaries to the viewers.

This paper is based on [1] that has been prepared within PRODUCER [2], an H2020 EU project that aims to pave the path towards supporting the transformation of the well-established and successful traditional models of linear documentaries to interactive documentaries, by responding to the recent challenges of the convergence of interactive media and documentaries. This is achieved via the creation of a set of enhanced ICT tools that focus on supporting all documentary creation phases, ranging from the user engagement and audience building, to the final documentary delivery. In addition to directly reducing the overall production cost and time, PRODUCER aims to enhance viewers' experience and satisfaction by generating multi-layered documentaries and delivering more personalized services, e.g., regarding the documentary format and playout.

In order to provide the aforementioned functionality, the PRODUCER platform implemented 9 tools, each focusing on a specific documentary production phase. These tools are: Integrated trends discovery tool, Audience building tool and Open content discovery tool (that support the documentary pre-production phase), Multimedia content storage, search & retrieval tool and Automatic annotation tool (that support the core production phase), Interactive-enriched video creation tool, 360° video playout tool, Second screen interaction tool and Social recommendation & personalization tool (all four focusing on the documentary post-production phase). The architecture of the PRODUCER platform is presented in more detail in [3].

As already mentioned, this paper is based on [1], where an initial prototype implementation was described for two of the PRODUCER tools: the Integrated Trends Discovery tool and the Social Recommendation & Personalization tool. In the current paper, the final version of the prototypes is presented along with a thorough evaluation.

In the rest of the paper, Section II elaborates on the design & functionality of the Integrated Trends Discovery tool while Section III focuses on the description of the Social Recommendation & Personalization tool. In Section IV, the results of the evaluation of the tools are presented. Finally, in

Section V, conclusions are drawn and future plans are presented.

II. Integrated Trends Discovery Tool

This section elaborates on the ITD tool, i.e., its innovations, architecture, user demographics inference mechanism and respective evaluation.

A. Rationale and Innovations

In recent years, there is an increasing trend on utilizing social media analytics and Internet search engines analytics for studying and predicting behavior of people with regards to various societal activities. The proper analysis of Web 2.0 services utilization goes beyond the standard surveys or focus groups. It is a valuable source of information leveraging internet users as the largest panel of users in the world. Analysts from a wide area of research fields have the ability to reveal current and historic interests of individuals and to extract additional information about their demographics, behavior, preferences, etc. One of the valuable aspects of this approach is that the trial user base consists of people that have not participated in the user requirement extraction phase.

Some of the research fields that demonstrate significant results through the utilization of such analytics include epidemiology (e.g., detect influenza [4][5] and malaria [6]) epidemics), economy (e.g., stock market analysis [7], private consumption prediction [8], financial market analysis and prediction [9], unemployment rate estimation [10]) politics (e.g., predicting elections outcomes [11]).

On the other hand, there are limitations on relying only on these information sources as certain groups of users might be over- or under-represented among internet search data. There is a significant variability of online access and internet search usage across different demographic, socioeconomic, and geographic subpopulations.

With regards to content creation and marketing, the existing methodologies are under a major and rapid transformation given the proliferation of Social Media and search engines. The utilization of such services generates voluminous data that allows the extraction of new insights with regards to the audiences' behavioral dynamics. In [12], authors propose a mechanism for predicting the popularity of online content by analyzing activity of self-organized groups of users in social networks. Authors in [13] attempt to predict IMDB (http://www.imdb.com/) movie ratings using Google search frequencies for movie related information. In a similar manner, authors in [14] are inferring, based on social media analytics, the potential box office revenues with regards to Internet content generated about Bollywood movies.

The existing research approaches mainly focus on the post-production phase of released content. Identifying the topics that are most likely to engage the audience is critical for content creation in the pre-production phase. The ultimate goal of content production houses is to deliver content that matches exactly what people are looking for. Deciding wisely on the main documentary topic, as well as the additional elements that will be elaborated upon, prior to engaging any resources in the documentary production process, has the potential to reduce the overall cost and duration of the production lifecycle, as well as to increase the population of the audiences interested, thus boosting the respective revenues. In addition, the existence of hard evidence with regards to potential audience's volume and characteristics (e.g., geographical regions, gender, age) is an important parameter in order to decide the amount of effort and budget to be invested during production.

There are various social media analytics tools that are focusing on generic marketing analysis, e.g., monitoring for a long time specific keyword(s) and websites for promoting a specific brand and engaging potential customers. These web marketing tools rely on user tracking, consideration of user journeys, detection of conversion blockers, user segmentation, etc. This kind of analysis requires access to specific websites analytics and connections with social media accounts (e.g., friends, followers) that is not the case when the aim is to extract the generic population trends. In addition, these services are available under subscription fee that typically ranges from 100 Euros/month to several thousand Euros/month, a cost that might be difficult to be handled by small documentary houses.

The ITD Tool aims to support the formulation, validation and (re)orientation of documentary production ideas and estimate how appealing these ideas will be to potential audiences based on data coming from global communication media with massive user numbers. The ITD tool integrates existing popular publicly available services for: monitoring search trends (e.g., Google Trends), researching keywords (e.g., Google AdWords Keyword Planner), analyzing social media trends (e.g., Twitter trending hashtags). In more details, the ITD tool innovations include the following:

- Identification and evaluation of audience's generic interest for specific topics and analysis/inference of audience's characteristics (e.g., demographics, location)
- Extraction of additional aspects of a topic through keyword analysis, quantitative correlation of keywords, and association with high level knowledge (e.g., audience sentiment analysis)
- Discovery and identification of specific real life events related to the investigated topic (e.g., various breakthroughs of google/twitter trending terms are associated with specific incidents)
- Utilization of data sources that are mainly openly accessible through public APIs, which minimizes the cost and increases the user base.

B. Architecture & Implementation Specifications

A functional view of ITD tool's architecture is provided in Fig. 1. Its core modules are described hereafter.

RestAPI: This component exposes the backend's functionality through a REST endpoint. The API specifies a set of trend discovery queries where the service consumer provides as input various criteria such as keywords, topics, geographical regions, time periods, etc.

Trends Query Management: This component orchestrates the overall execution of the queries and the processing of the replies. It produces several well formulated queries that are

forwarded to the respective connectors/wrappers to dispatch the requests to several existing TD tools/services available online. Given that each external service will reply in different time frames (e.g., a call to Google Trends discovery replies within a few seconds while Twitter stream analysis might take longer) the overall process is performed in an asynchronous manner, coordinated by the Message Broker. The Query Management enforces querying policies tailored to each service in order to optimize the utilization of the services and avoid potential bans. To this end, results from calls are also stored in ITD tool's local database in order to avoid unnecessary calls to the external APIs.

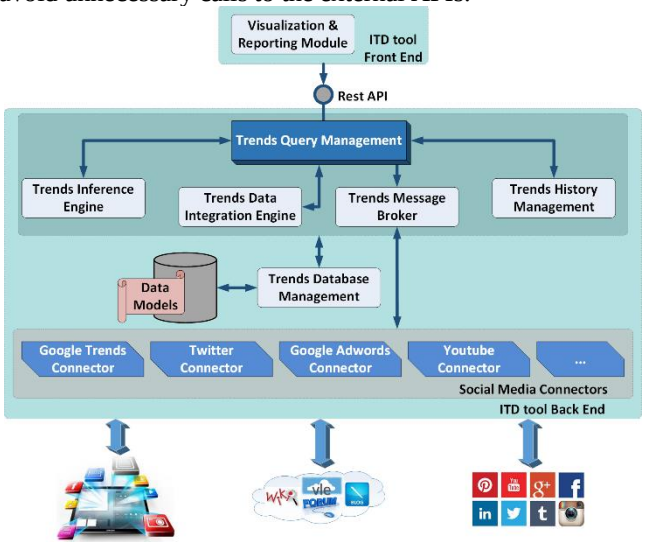


Figure 1. Architecture of the Integrated Trends Discovery Tool.

Trends Message Broker: This component realizes the asynchronous handling of requests. It is essentially a messaging server that forwards requests to the appropriate recipients via a job queue based on a distributed message passing system.

Social Media Connectors: A set of software modules that support the connection and the execution of queries to external services through the provided APIs. Connectors are embedding all the necessary security related credentials to the calls and automate the initiation of a session with the external services. Thus, the connectors automate and ease the actual formulation and execution of the queries issued by the Query Management component. Some example APIs that are utilized by the connectors are: Google AdWords API, Twitter API, YouTube Data API v3.

Trends Data Integration Engine: This module collects the intermediate and final results from all modules, homogenize their different formats, and extracts the final report with regards to the trends discovery process. The results are also modelled and stored in the local data base in order to be available for future utilization.

Trends Database Management & Data model: The ITD tool maintains a local database where the results of various calls to external services are stored. The Database Management module supports the creation, retrieval, update and deletion of data objects. This functionality is supported for both contemporary data but also for historic results (Trends History Management). Hence, it is feasible for the user to compare trend discovery reports performed in the past with more recent ones and have an intuitive view of the evolution of trend reports in time.

Trends Inference Engine: In some cases, the external services are not directly providing all information aspects of the required discovery process and the combination and analysis of heterogeneous inputs is required. To this end, the application of appropriate inference mechanisms on the available data allows the extraction of additional information escorted by a confidence level that expresses the accuracy of the estimation. Details on the rationale and mechanisms of this module are presented in the following section.

The technologies used for the implementation of the ITD tool can be found in Table I.

TABLE I. ITD SOFTWARE SPECIFICATIONS

Licensing	**Open source**
Core Implementation Technologies	Python 2.7
Additional technologies utilised	Nginx server Django 1.10 (Python framework) djangorestframework 3.5.1 Celery RabbitMQ Redis
Database details	MySQL 5.x
Exposed APIs	REST
Exchanged data format	JSON
GUI description	HTML5, Javascript, CSS3, Angular JS 1.6, Angular-material 1.1.3

The tool is developed as an open source project and the source code can be found at [15].

C. Knowledge Extraction Approaches

As discussed in the previous section, during the preproduction phase of a documentary, producers are highly interested in estimating audiences' interests in correlation with high level information like the gender, the age and the sentiment of potential audiences. In a similar manner, after a show has been aired, useful results can be inferred through the analysis of the Internet buzz that the show has created. In other cases, merging information from different, previously unrelated, sources may provide a higher confidence on the final outcome. To this end, various data processing and inference mechanisms are deemed necessary. The ITD tool follows a modular approach with regards to this aspect. The ITD tool provides the necessary means for collecting all relevant data at one place and then different data analytics algorithms can be applied allowing the extraction of additional knowledge according to the scope of the user. As a proof of concept and for supporting the needs of the production teams within the scope of the PRODUCER project, inference algorithms were developed for: i) extracting audience's characteristics through Twitter data and ii) analyze popularity of targeted TV shows by be complementary use of Google Trends service with Twitter. The design principles and the actual evaluation results of both approaches are presented in Section IV.

D. Graphical User Interfaces

The Front-End allows the user to create a new query and visualizes the respective results. The overall process consists of two steps supported by two pages (Fig. 2).

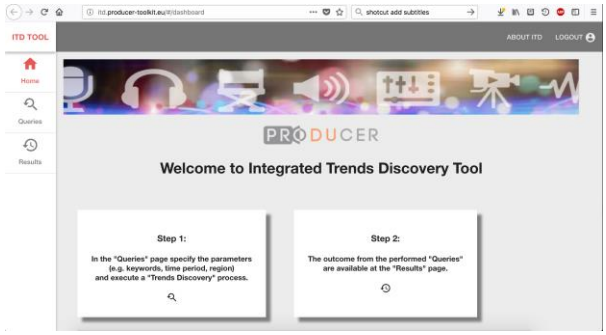


Figure 2. The "Home" page of the ITD tool.

First the query's parameters within the "Queries" (Fig. 3) page are specified and based on these parameters a discovery process is initiated.

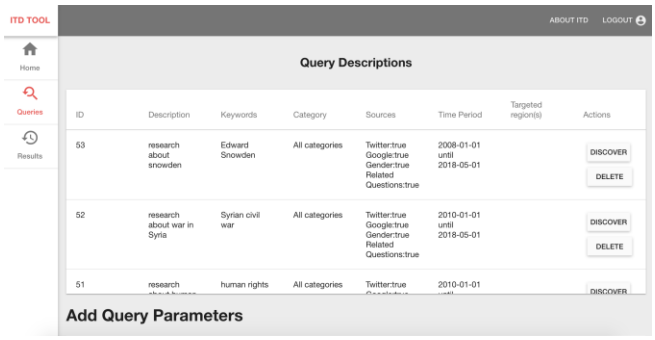


Figure 3. The "Queries" page of the ITD tool.

After a successful completion of the query the results are presented on the "Results" page (Fig. 4 and Fig. 5), which provides the following output: (i) a graph of terms (each term is escorted by a user's popularity metric and is correlated with other terms, where a metric defines the correlation level), (ii) interest per location (country/city), (iii) interest per date(s) allowing the identification if significant dates and seasonal habits, (iv) sentiment and gender analysis related with the researched topic and (vi) questions related to the topic.

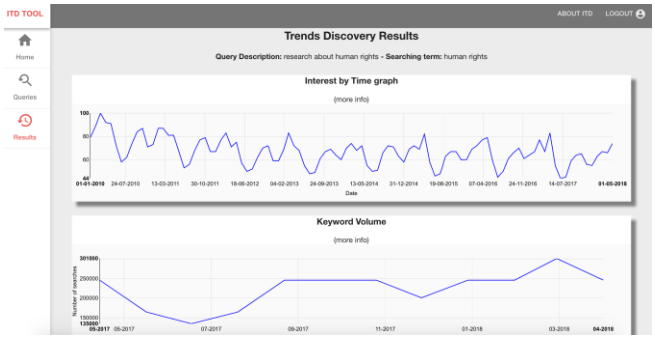


Figure 4. A snapshot of "Results" page focusing on "Interest by Time" and "Keyword Volume".

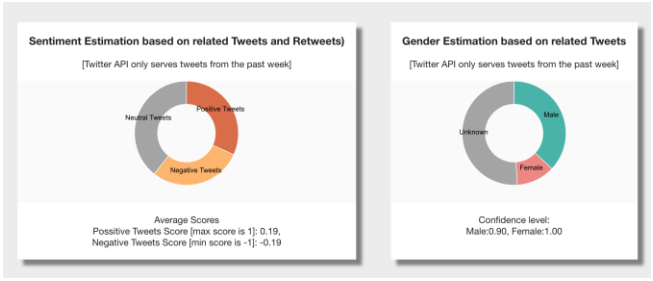


Figure 5. A snapshot of "Results" page focusing on "Sentiment and Gender Estimation".

Finally, the front-end allows the reviewing of results from past queries and the conversion and download of the query results in CSV format.

III. Social Recommendation & Personalization Tool

This section elaborates on the SRP tool, i.e., its functionality, architecture, recommendation extraction algorithm.

A. Rationale & Goal

Personalization & Social Recommendation are dominant mechanisms in today's social networks, online retails and multimedia content applications due to the increase in profit of the platforms as well as the improvement of the Quality of Experience (QoE) for its users and almost every online company has invested in creating personalized recommendation systems. Major examples include YouTube that recommends relevant videos and advertisements, Amazon that recommends products, Facebook that recommends advertisements and stories, Google Scholar that recommends scientific papers, while other online services provide APIs such as Facebook Open Graph API and Google's Social Graph API for companies to consume and provide their own recommendations [16].

The Social Recommendation & Personalization (SRP) tool of PRODUCER holistically addresses personalization, relevance feedback and recommendation, offering enriched multimedia content tailored to users' preferences. The tool's functionalities can be used in any type of content that can be represented in a meaningful way, as explained later. The application is thus not restricted to documentaries.

The recommendation system we built is not restricted to the video itself, but applies to the set of enrichments accompanying the video as well. Interaction with both video and enrichments is taken into consideration into updating the user's profile, thus holistically quantifying the user's behaviour. Its goal is to facilitate the creation of the documentary and allow the reach of the documentary to a wider audience. To do so, the SRP tool is responsible for proposing content to the user or to the producer of the film relevant to specific target groups, via a personalization mechanism.

B. Architecture & Implementation Specifications

SRP tool's architecture is presented in Fig. 6 and it consists of the following components:

RestAPI: This component is responsible for the exchange

of information between the frontend of the SRP tool or any application willing to use the SRP tool's functionality, and its backend.

Frontend: This component is responsible for the Graphical User Interface via which the user interacts with the tool. More information on this component will be presented in subsection D.

User Interaction Monitoring: As the user interacts with the content and the frontend of the tool, interactions and data are being sent to the backend in order to be processed by the tool and perform the corresponding actions.

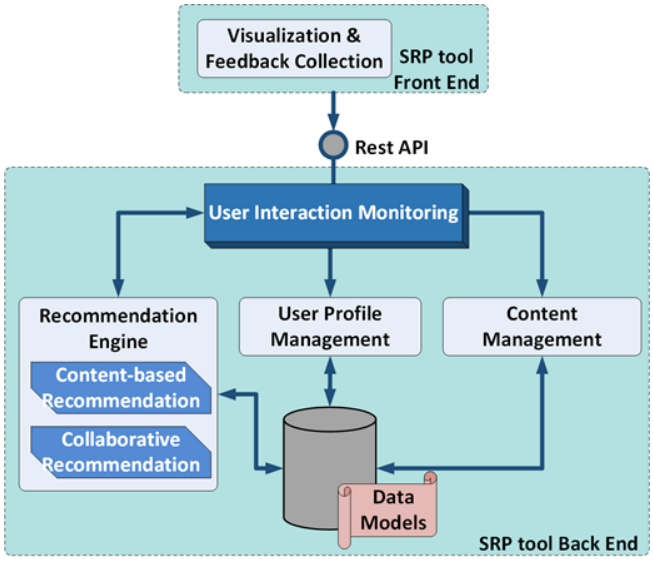


Figure 6. Architecture of the Architecture of the Social Recommendation & Personalization Tool.

Data Models: The database where all the data that the tool needs in order to operate seamlessly are stored.

Content Management: The module that processes the ingested content in order to provide a meaningful representation to the underlying algorithms.

User Profile Management: The module that keeps user profiles updated as far as their demographics and actual preferences are concerned, based on their interaction with the content and the platform.

Recommendation Engine: The core part of the tool where the recommendation process takes place and provides the users with the appropriate content.

Various state-of-the-art technologies were utilized in order to achieve the performance and security necessary for the optimal operation of the system. The software specifications for the SRP tool can be found in Table II.

TABLE II. SRP TOOL SOFTWARE SPECIFICATIONS

Licensing	**Open source**
Core Implementation Technologies	Python 3.5.2
Additional technologies utilised	Nginx server uwsgi Django 1.10 (Python framework) djangorestframework 3.5.1 gensim 0.13.4.1 Postgresql 9.5.7 Docker Docker-compose
Database details	PostgreSQL
Exposed APIs	REST
Exchanged data format	JSON
GUI description	GUI application communicating with the backend of the tool. Users have to signup/login to use the tool's backend functionalities.

The tool is developed as an open source project as well and the source code can be found in [17].

C. Functionality & Design

This section elaborates on the details regarding the features and mechanisms supported by the SRP tool. In order for the recommendation engine to work, the content must be properly indexed and the system should have information about the user's preferences. The Content Management module ingests the content's data and maps each content item to a vector as described later in this section. The interaction of the user with the content allows the creation of a similar vector for the user which later can be used to provide recommendations either on a personal level or for a specified target group. The rest of the section further elaborates on each of the functions performed by the SRP tool.

As already stated, the first process the SRP tool has to perform is to index the content in a meaningful way, an important step as also indicated in [18][19]. Each video/enrichment is mapped to a vector, the elements of which are the scores appointed to the video/enrichment expressing the relevance it has to each category of the defined categories. The categories used come from the upper layer of DMOZ (http://dmoztools.net/), an attempt to create a hierarchical ontology scheme for organizing sites, Since the videos in the PRODUCER project are of generic nature, a common ontology scheme seems fit. The feature terms used are presented on Table III.

TABLE III. FEATURE TERMS

Art	Business	Computer	Education	Game	Health	Home
News	Recreation	Science	Shopping	Society	Sport	Child

Each multimedia content item is therefore described as follows: $X_P = [X_{P_1}, X_{P_2}, \ldots, X_{P_N}]$, where P_i are the specified categories and X_{P_i} is the relevance the content has to the specific category. Each element of the vector X_P needs to be generated in an automatic way from the metadata accompanying the video since such a representation is not already available nor is manually provided by the content creators. To achieve this, a previous version of the tool used a naïve tf-idf algorithm while in the current version of the SRP tool, a more sophisticated approach is considered. More specifically, the X_P are appointed using the Word2Vec model [20] a model of a shallow two-layer neural network that is trained to find linguistic context of words. It takes as input a word and returns a unique representation in a multidimensional vector space. The position of the word in

this vector space is such that words that share common contexts are located in close proximity with each other.

Since the multidimensional vector representation is not useful to us in the way it is, we apply the same procedure on the feature terms used in our vector representations. By doing so, each feature term also has a multidimensional vector representation on the same space as the words and the similarity between the word and each category can be computed. To calculate the overall similarity score, we use a linear combination between the maximum score from all words on the document and the average score of the words. The average score is used in order to reduce the chance that a word that appears few times in the text, but is very relevant to the category in question, skews the result too much in its favor.

In our algorithm we use a pre-trained model from the Wikipedia dataset which consists of millions of documents on a large variety of themes and as a result is a pretty generic dataset covering all the topics that are of interest.

In order to be able to identify content relevant to target audiences, the tool needs to collect information and preferences of viewers since user profiles constitute another integral part of a recommendation system. The representation of each user on the system follows the same principals as the content vector representation, where the vector's elements signify the importance each term has to the user. As a results each user is represented by a vector $U = [U_{P_1}, U_{P_2}, \dots, U_{P_N}], U_{P_i} \geq 0, \forall i$, where U_{P_i} is the value each user gives to each feature term.

Within the platform the SRP tool operates, the viewer registers and provides some important demographics (i.e., gender, age, country, occupation and education). This information is used in order to create an initial user vector for the user, based on the preferences of users similar to his demographics group. Alternatively, instead of providing this information explicitly, the viewer can choose to login with his/her social network account (e.g., Facebook, Twitter) and the information could be automatically extracted.

The user profile created via this process is static and is not effective for accurate recommendation of content since: a) not every user in the same demographic group has the same preferences and b) his/her interests change dynamically. Thus, in addition to the above process the SRP tool implicitly collects information for the user's behavior and content choices. Using information about the video he/she watched or the enrichments that caught his/her attention, the SRP tool updates the viewer's profile to reflect more accurately his/her current preferences.

The created user profile, allows the tool to suggest content to the viewer to consume, as well as a personalized experience when viewing the content by showing only the most relevant enrichments for his/her taste. Through a content-based approach, the user's profile is matched with the content's vector by applying the Euclidean similarity measure as:

$$sim_{up}^{cf}(i,j) = \frac{1}{1 + \sqrt{\sum_k (U_{i_k} - X_{j_k})^2}} \quad (1)$$

where U_i is the user's profile vector and X_P^j is the content's vector. Other similarity metrics were also tested and will be presented in Section IV.

The collaborative approach is complementary with the content-based recommendation using information from other viewers with similar taste, to increase diversity. The idea is to use already obtained knowledge from other users in order make meaningful predictions for the user in question. To do so, the similarity between users is computed as follows:

$$sim_{uu}(i,j) = \frac{1}{1 + \sqrt{\sum_k (U_{i_k} - U_{j_k})^2}} \quad (2)$$

where the H more similar users from the user's friends list are denoted as close neighbors. We then compute the similarity of the neighbors to the item:

$$sim_{up}^{cbf}(i,j) = \sum_{s=1}^{H} sim_{up}^{cf}(i,s) \cdot sim_{uu}(s,j) \quad (3)$$

The final similarity between the user and the item is calculated via a hybrid scheme by using the convex combination of the above similarities:

$$sim_{up}^{h}(i,j) = (1-\theta) sim_{up}^{cbf}(i,j) + \theta sim_{up}^{cf}(i,j) \quad (4)$$

where $\theta : 0 \leq \theta \leq 1$ is a tunable parameter denoting the importance of the content-based and the collaborative approach on the hybrid scheme. A value of $\theta = 0.5$ has been shown to produce better results than both approaches used individually [21].

Based on the collected data above and the constructed viewers' profiles, the producer of the documentary can filter the available content based on the preferences of the targeted audience. For this purpose, the k-means algorithm [22] is used to create social clusters of users. Based on the generated clusters, a representative user profile is extracted and is used to perform the similarity matching of the group with the content in question. The SRP tool assigns a score to each item and ranks the items based on that score.

After the creation of the documentary, the SRP tool can be used as an extra step in order to provide a filtering on the enrichments that are paired with the video, so that they do not overwhelm the viewer, filtering out less interesting ones. After specifying the target audience, the SRP tool can provide the list of suggested enrichments that the producer can either accept automatically or select manually based on his/her preferences, enabling the delivery of personalized documentary versions, tailored to audience interests.

D. Graphical User Interfaces

The Social Recommendation & Personalization tool provides a Graphical User Interface (GUI) in order to make it accessible to users willing to use the standalone version of the tool. In the integrated platform, the GUI is part of the platform in order to better exploit its potential by combining its services with that of the rest of the tools.

Since the tool needs some information about the users in order to efficiently provide its recommendations, a page where he/she can enter or alter his/her personal information is provided (Fig. 7). This information is used to initialize the user profile but will also be valuable when willing to gather

information for a specific target group. When the user enters his/her information, the data is stored in the SRP tool database.

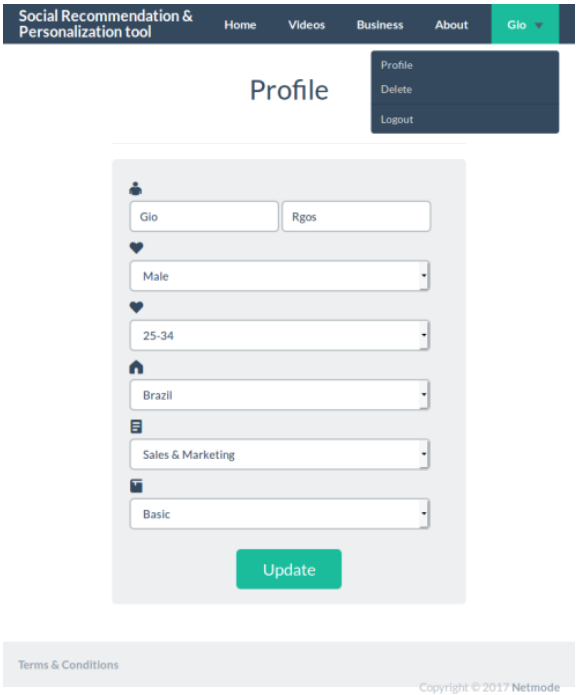


Figure 7. SRP tool login screen.

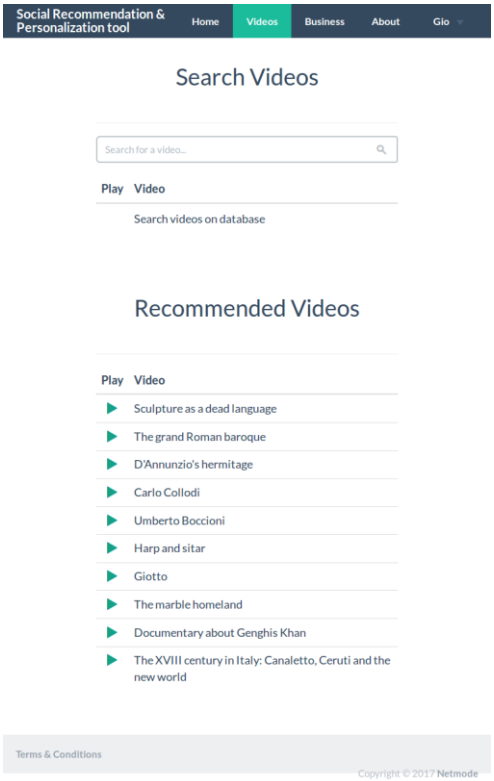


Figure 8. Recommended videos page of SRP tool.

By clicking on "Videos" from the navigation bar, a search bar for searching specific videos as well as a list of videos are presented to the user (Fig. 8). The list of the videos contains the top ten videos from the video database, ranked based on the profile of the user that requested the list by making use of the hybrid recommendation mechanism. It is thus subject to change every time the user interacts with the system, so that the top videos correspond to what the system believes are the most interesting videos for the user at any time.

The "Play Video" page contains more information about the video, as well as the video content itself (Fig. 9). From this page, the user can view the video, interact with it by sharing it to social media, like it or dislike it and watch the enrichments associated with the video. All information concerning the interactions of the user with the content is sent back to the SRP tool backend to update the profile of the user in order to be able to make more precise recommendations in the future.

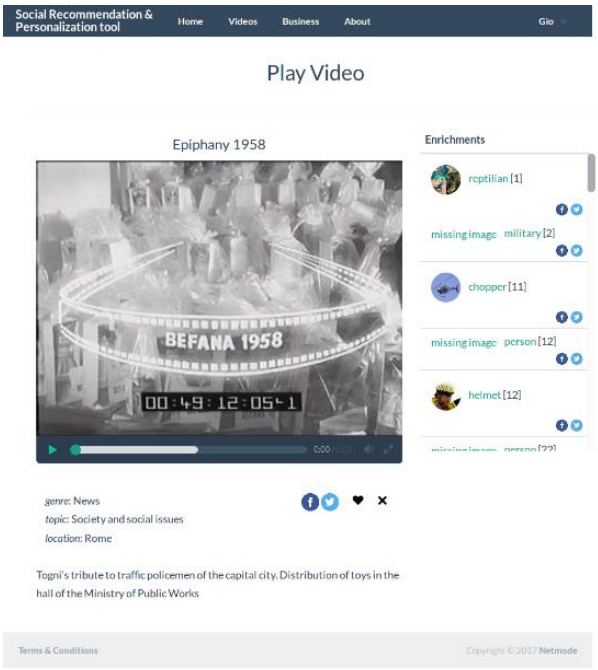


Figure 9. Play video page of SRP tool.

The last page provided by the GUI is to be used by the content providers or producers willing to use the services provided by the SRP tool (Fig. 10). The page is split in three columns. The leftmost contains a form where the user can select the audience group he/she wants to target in his/her documentary, so that the tool knows what recommendation to make. After choosing the appropriate values in the form, the user clicks on search and in the middle column, a list of the 10 most recommended videos for the target group appears. The list is ranked from most to least relevant. After selecting the appropriate video, the enrichments of the video appear on the right column. The tool gives the user the ability to select which ones of the suggested enrichments he/she finds appropriate for his/her documentary by toggling

the slider at the top right of the enrichment. After making his/her selection, the user can export his/her choices for further use in the documentary creation process. In the integrated platform, the exported data could be used by the rest of the tools of the PRODUCER platform

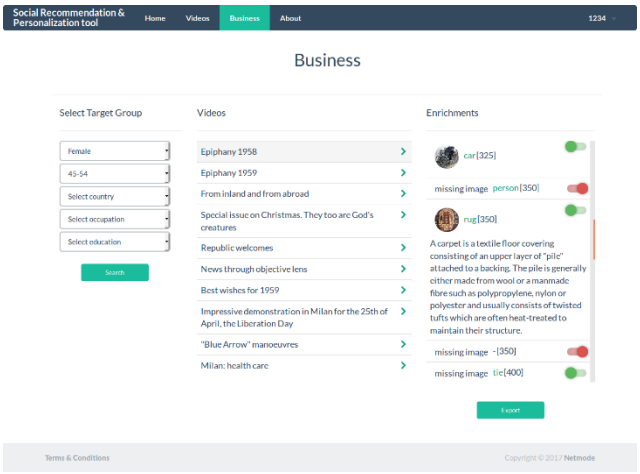


Figure 10. SRP tool page for Business users.

IV. EVALUATION & BENCHMARKING

In this section, an extensive evaluation of the two tools is presented in order to measure their performance and effectiveness on their corresponding tasks. In order to successfully evaluate the tools, both an objective benchmarking process via simulations on the underlying algorithms and a subjective benchmarking process by actual usage of the tools from real users were performed.

The reason for performing both offline and online evaluation techniques is that recommendation systems are relatively complex mechanisms and their performance cannot be holistically captured through their mathematical model representation. Offline benchmarking was used to configure the underlying algorithm and tweak the available parameters via measuring the effectiveness based on the state of the art metrics, while online experiments came as a confirmation to the above selections and captured the overall Quality of Service perceived by the users (e.g., cold start recommendations, over-specialization etc.)

A. Objective benchmarking

1) Integrated Trends Discovery Tool

The first set of evaluation actions for the ITD tool refers to the inference processes through data analytics approaches. In more details the inference algorithms were developed for: i) extracting audience's characteristics (gender) through Twitter data and ii) analyse popularity of targeted TV shows by the complementary use of Google Trends service with Twitter.

Extracting audience's characteristics

The rationale for identifying potential audiences' gender and age characteristics is that this kind of information is not freely available from social media services due to user privacy protection data policies. There are various state of the art attempts that focus on inferring user demographics though probabilistic approaches based on user related data freely available on social media (e.g., tweets content, linguistic features, followers' profile) [23][24][25][26]. With regards to the documentary preproduction phase, Twitter service proved to be the most appropriate one for extracting user profile information, as Twitter account data and content are openly available. The Facebook social media service recently updated the related data access policy and doesn't allow the access to user content if there is no direct relation with the user (e.g. friends). In a similar manner Google adwords service only provides access to user profile data strictly for mediating Google advertisements and doesn't allow the utilization of such data for other reasons to third parties.

The task of age and gender estimation is tackled by the ITD tool via the utilization of classification algorithms trained with ground-truth data sets of a number of tweeter users containing records of real Twitter profile information and the respective gender/ age. The core idea for the classification algorithm is that stylistic factors are often associated with user gender, so the Twitter profile colour that has been utilized in combination with the profile picture and the display name. The applied approach, which is presented in detail in [27], constitutes a scalable and fast gender inference mechanism, as a very limited number of features is being utilized for each user thus resulting to a low-dimensional space, in which the machine learning algorithms for gender detection operate. The core benefit of the proposed approach is that it is able to scale and process a very large dataset of Twitter users while is conclusive even in the case where only one of the three aforementioned profile fields used is specified.

The trained network is then utilized in order to generalize the training process and estimate missing information from wider networks of twitter users. The inference process is coordinated by the Trends Inference Engine. The engine uses the TwitterAPI to retrieve tweets where the keywords connected with certain topics are mentioned. Based on the respective Twitter Account ids, profile information is collected for each account. Based on profile attributes (e.g., "name", "screen_name", "profile photo", "short description", "profile_color") each user is classified to age & gender category and each classification is escorted by a confidence level.

To infer the gender of users based on their profile pictures, the Face++ Face Detection API (https://www.faceplusplus.com) is utilized. This service detects human faces within images and estimates the respective gender associated with a confidence level. To exploit the display name for determining the user's gender, a data matching technique is used comparing the names of Twitter users with the names stored in the datasets of Genderize (https://genderize.io/).

In order to exploit the theme color to infer the user gender, a hex color code has been obtained for each user via the Twitter API corresponding to the user's chosen color.

The obtained color codes have been converted to the corresponding RGB representation thus generating three features (capturing the respective Red, Green and Blue values of the theme color).

All aforementioned features were used to train three machine learning gender classifiers, namely a Photo Classifier, a Color Classifier and a Name Classifier, each exploiting the information gained from the features extracted from the corresponding field. The output of these classifiers is the inferred gender for each user, along with the respective estimation confidence level. In order to couple the outputs of all aforementioned standalone gender classifiers in a hybrid approach, three "gender numbers" have been assigned to each user, each capturing the output of one classifier.

The evaluation has been based on a public data set (https://www.kaggle.com/crowdflower/twitter-user-gender-classification) of ground truth data containing information of 10021 twitter users' profiles. The dataset contains the gender of distinct twitter users escorted by profile information.

In order to evaluate the gender inference algorithm, the initial dataset (~10000 records) has been divided into 40 parts each containing about 250 records. Each dataset part was gradually incorporated to the classifier, while the last 250 records were used for evaluation. The initial evaluation attempts did not provide high performance results. A data cleansing process was subsequently performed removing records that had the default predefined Twitter profile colors that resulted in a dataset of ~2000 records. The same evaluation process was then conducted where each of the 40 parts contained 50 records.

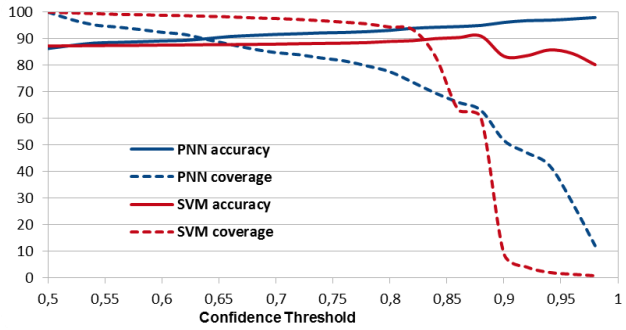


Figure 11. Accuracy and Coverage for PNN and SVM Hybrid Classifiers.

As it is presented in Fig. 11 and discussed in detail in [27], the evaluation process indicated that the utilization of two supervised learning algorithms namely the Support Vector Machines (SVMs) and Probabilistic Neural Networks (PNNs) perform excellent, resulting in ~87% accurate results. The evaluation process is planned to proceed with further testing of the proposed approach based on more datasets, originating from additional social media (not only Twitter), to compare with similar existing approaches and to incorporate additional user profile attributes, including text analysis of provided profile description and Tweets text.

Social Media and Google Trends in Support of Audience Analytics

One of the objectives of the ITD tool's inference engine is to improve the quality and reliability of the generated results by combining the outcomes of different sources of information. On the same time, there have been various research efforts aiming to investigate how social media are used to express or influence TV audiences and if possible to estimate TV ratings through the analysis of user interactions via social media. Based on the state of the art review [28], the research work conducted so far by various initiatives on this domain focuses mainly on the utilization of Twitter and Facebook. However, in certain occasions, the respective volume of information derived by these social media services is not enough resulting on low reliability outcomes. To this end, the second evaluation process of the ITD tool targets the case where the Twitter service is utilized in combination with Google Trends [29] towards the extraction of audience statistics for specific TV shows.

The analysis conducted for the Italian talent show "Amici di Maria de Filippi" that broadcasts for the last 17 years and lies among the most popular shows in Italy. The show airs annually from October until June, thus being appropriate for yearly examination of the data. In this study, data of the year 2017 have been used, split in two semesters as elaborated upon subsequently.

The keyword-hashtag that is utilized by audience is the '#amiciXX' where XX corresponds to the number of the consequent season that the show is aired. The analysis that was conducted by the ITD targeted the period January -June 2017 where the respective hashtag was '#amici16' and the period July to December 2017 where the respective hashtag was '#amici17'.

Using as keyword these hashtags and by utilizing the ITD tool, data were collected from Google Trends and Twitter. With regards to Google Trends, a time series of the relative search figures -search volume for the term divided by the total volume of the day- normalized between 0 and 100 were available by the service. Utilizing the Twitter API 882024 tweets collected for '#amici16' and 135288 for '#amici17' terms respectively. The collected data have been grouped based on date in order to acquire the daily volume.

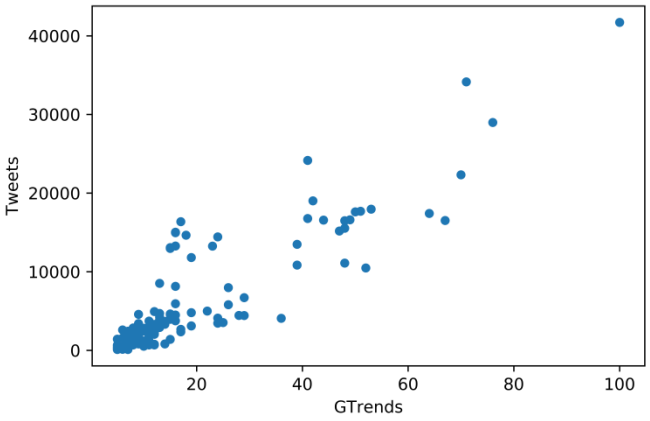


Figure 12. Correlation of Google Trends and Twitter data for the term '#amici16' targeting the first semester of 2017.

In order to verify the correlation between data originating from Google Trends and those originating from Twitter, the

Pearson correlation coefficient was utilized. The obtained results for the first semester of 2017 are illustrated in Fig. 12 and lead to coefficient of 0.893 and to significance of approximately 10-32. This indicates that the two datasets are strongly correlated, since we secured that the figures of each set are matched 1-1 and the low significance ensures that this result cannot be produced randomly. The respective outcomes for the second semester of 2017 are presented in Fig. 13 and lead to correlation coefficient of 0.816 and to significance of about 10-30. The slightly lower correlation demonstrated can be fully justified by the fact that the show does not broadcast during the summer and thus there is lower activity both on Twitter, as well as on Google, resulting in lower correlation results. Nevertheless, the findings indicate a strong relation between Twitter and Google Trends data. The aforementioned results confirm what the authors originally expected: Data obtained from Google Trends and Twitter at the same period are strongly (linearly) correlated and this of course can be further exploited in a variety of research purposes.

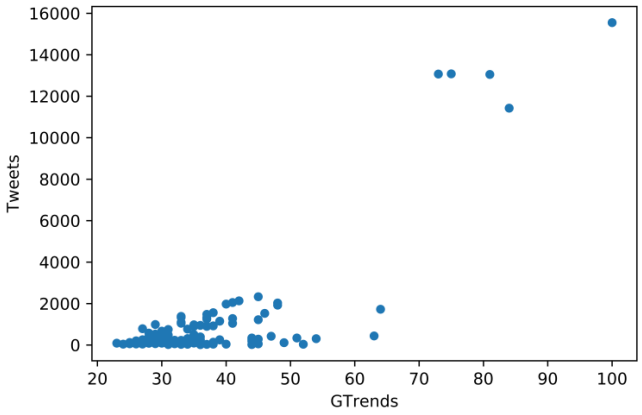


Figure 13. Correlation of Google Trends and Twitter data for the term '#amici17' targeting the second semester of 2017.

The described data homogenization and correlation evaluation mechanism has been integrated within the Inference Engine of the ITD tool allowing the dynamic deduction of whether the data from the two different information sources are converging or not for the utilized keywords that refer to the respective shows. The correlation level is then utilized as an additional value that is escorting the keyword presence volumes and presented to the end-user as an additional indication of the metrics' confidence.

The evaluation experiments conducted with regards to the overall utilization of the tool are encouraging and have allowed for the discovery of potential shortcomings early in the development phase. Such an issue is related to the volume of calls to external services. For example, Twitter API limits the allowed calls to 15 every 15 minutes per service consumer. As this issue was expected, a caching mechanism is utilized where results from each call to the Twitter API are also stored in the local database. Hence the ITD builds its own information store in order to avoid unnecessary calls. To this end, as the tool is utilized from various users, the local information store is getting richer.

2) Social Recommendation and Personalization tool

Concerning the evaluation of the Social Recommendation and Personalization tool, part of the benchmarking procedure was performed for the evaluation of the effectiveness of the algorithms used for the generation of the feature vectors of the content, that corresponds to the first process performed by our tool described in Section III, the indexing of the content in a meaningful way. In our tool, we represent the content as a vector, where each element is one of the 14 categories we have specified, and the value is the percentage to which the content is relevant to this category.

The models used in the evaluation process are four pre-trained models [30] on Wikipedia 2014 in glove representation [31] after we passed them from a transformation process to fit the Word2Vec representation, which contain a vocabulary of 400k words and 50 dimensions, a 100 dimensions, a 200 dimensions and a 300 dimensions vector representation respectively, as well as a pre-trained model on Google News with a vocabulary of 3 million words with a vector representation of 300 dimensions.

In order to test the efficiency of those models, in Section A.2.1, the default accuracy test of word2vec models questions-words [32] was performed while in A.2.2, the model was tested on the ability to effectively categorize content items on the 14 categories and a representative example from our dataset is presented. More examples can be found in [33].

Since the representation of the content is only part of the overall mechanism, an evaluation on the effectiveness of the recommendation algorithm as described in the rest of Section III was also performed. In Section A.2.3 the design of the evaluation process is described and in Section A.2.4 the state of the art metrics used for the evaluation are presented. Finally, in Section A.2.5 the results of the simulations are presented and discussed.

A.2.1. Question-words test

This test consists of 19544 sets of 4 words, and is used to test how well a generated vector model does with analogies of different kinds: For example, capital (*Athens Greece Baghdad Iraq*), currency (*Algeria dinar Angola kwanza*) etc. The idea is to predict the 4th word based on the three previous ones.

Once vectors from a corpus with sentences containing these terms is generated, the question-words file can be used to test how well the vectors do for analogy tests (assuming the corpus contains these terms). So, given an example from question-words.txt (*Athens Greece Baghdad Iraq*), the analogy test is to look at nearest neighbours for the vector

Vector(Greece) - Vector(Athens) + Vector(Baghdad)

If the nearest neighbour is the vector Iraq then that analogy test passes.

After running the question-words test for all five models, the successful and unsuccessful attempts of the algorithm

have been recorded. The respective results are presented in Table IV.

TABLE IV. MODEL EVALUATION

Model	*Correct*	*Incorrect*
Wikipedia 50d	49.69%	50.31%
Wikipedia 100d	65.49%	34.51%
Wikipedia 200d	71.98%	28.02%
Wikipedia 300d	74.05%	25.95%
GoogleNews	77.08%	22.92%

All models perform pretty good with at least once in two successfully predicting the missing word for the smaller model (Wikipedia 50d 49.69%). What we notice is that the larger the model, the better the performance. Both larger vector representations and larger vocabulary contribute to the increase in the percentage of the correct predictions, as well as the quality and length of the corpus used to train the model.

As we can see from the results, the Google News model clearly performs the best with a success rate of 77% but due to its size, it is not very practical on small infrastructures such as the one used for our prototype.

A.2.2 Examples from our database

To test the efficiency of the Word2Vec model on the actual problem of finding the relevance that the video has in each of the 14 categories, we did some evaluations on the actual data we had in our video database. The idea behind the evaluation is to provide the title together with some tags and the description of the video, and the neural network should be able to successfully deduce this relevance. The more available metadata each video has, the better the result of the algorithm is expected to be. For this evaluation process, we used the Google News model which is the best performing one, and which we expected to have the most accurate representations.

A representative video example is presented in Table V.

TABLE V. PROPERTIES OF VIDEO EXAMPLE AND RESPECTIVE INDEXING DELIVERED BY SRP TOOL.

Title						
Documentary about Leonardo da Vinci						
Description						
Learn more about the life and the achievements of the Italian Renaissance polymath Leonardo da Vinci. His areas of interest included invention, painting, sculpting, architecture, science, music, mathematics, engineering, literature, anatomy, geology, astronomy, botany, writing, history, and cartography. He has been variously called the father of palaeontology, ichnology, and architecture, and is widely considered one of the greatest painters of all time. Sometimes credited with the inventions of the parachute, helicopter and tank, he epitomized the Renaissance humanist ideal						
Tags						
Sciences, History						
Art	Business	Computer	Education	Game	Health	Home
0.438	0.205	0.250	0.366	0.206	0.253	0.225
News	Recreation	Science	Shopping	Society	Sport	Child
0.168	0.253	0.753	0.132	0.319	0.194	0.339

In this example, a documentary provided by Mediaset is analyzed that concerns the life of Leonardo da Vinci. From the description provided we can see that he was a scientist as well as an artist, and so the algorithm gives a high score to "Science" and a lesser one but still high score to "Art" categories.

More details and examples of the multimedia content indexing delivered by the SRP tool are provided in [30].

A.2.3 Recommendation algorithm evaluation via simulations

In order to evaluate the performance of the algorithm used in the Social Recommendation and Personalization Tool, we also performed some offline experiments via simulations on MATLAB in a similar way as in [21]. In order to achieve this task, sets of content items are given a scoring on the 14 categories, and sets of users with a specified behaviour are created. Based on their behaviour, the users have different probabilities on performing actions on a content item, depending on the relevance and thus the likelihood that the user is interested in the item. Although the users are artificial, we make reasonable assumptions trying to emulate a real-life user behaviour.

In our simulation we have created 50 videos, having 8 enrichments and 8 advertisements each, and a feature vector of 14 categories. Videos are assigned into 5 classes, where in each class, $\lfloor \frac{F}{m} \rfloor = 2$ elements get a higher score, corresponding to different video topics (e.g., arts and science). 30 users are created to interact with the content and are again divided in 5 classes, in a similar way as the videos. Each user class implies different interests and preferences and so users that tend to select different videos and enrichments.

The simulation consists of 200 recommendation rounds where, in each round, a list of 6 most relevant videos according to the current profile of the user is presented him, in a ranked order. As already described in Section III, the hybrid recommendation approach we are using combines the content and the collaborative recommendation approach as follows:

$$sim_{up}^{h}(i,j) = (1-\theta) sim_{up}^{cbf}(i,j) + \theta sim_{up}^{cf}(i,j)$$

where θ is the tunable parameter.

For the collaborative part of the algorithm, we randomly assign 7 users as friends of each user and we use the 5 closest ones as his/her neighbours, which are the ones whose profile vectors are used to provide the collaborative recommendations.

As far as the similarity metrics are concerned, we perform a comparative evaluation between inner product, cosine and Euclidean similarities. More information on the similarity metrics and the respective results are presented in this section.

As mentioned, user behavioural vectors are used to simulate how users interact with the video, and more specifically 5 interactions are considered:

- Percentage of video watched
- Number of clicks on enrichments
- Number of share of enrichments
- Number of click on ads
- Explicit relevance feedback

These interactions are the same as the ones used in the actual tool.

Videos are watched by the user based on the video ranking the algorithm provides, and with a probability relevant to the video's rank and the user's behavioural vector, the user performs or not the above actions. The probabilistic nature of the process is used so that not all users perform all actions, as well as to capture the realistic tendency of users following particular behaviour based on their actual interest.

After the user has finished his actions, an update procedure follows, similar to the one described in [21]. It should be noted that most of the parameters have been chosen to provide the best results based on the work presented in [21], parameters that were also used on the implementation of the Social Recommendation and Personalization tool.

In order to reduce the randomness from our results, we run the experiment 10 times and calculated the average values on our figures.

A.2.4 Evaluation Metrics

The system is evaluated based on three metrics, in order to measure its effectiveness. The metrics used are the Profile Distance, the Discounted Cumulative Gain and the R-score [34] and are defined as in [21].

- ***Profile Distance***

The Profile Distance metric, measures the difference between the generated profile score of the users from the tool and the actual predefined profile score that corresponds to the actual interests and preferences of the user. In the simulations, this corresponds to the Euclidean distance of the user profile and the user behaviour vector. From the calculation of the metric we can see if the user vector converges to the actual interests through the constant update process based on the interactions of the user with the content and from its change over time, measure how fast, given a new user with no profile, this convergence takes place.

- ***Discounted Cumulative Gain***

Another method of evaluating the system is by measuring how "correct" is the ordering of the recommendations the tool provides to the specific user. Since actually knowing the correct ordering is impossible, we approximate it by assigning a utility score to the recommendations list, which is the sum of the utility score each individual recommendation has. The utility of each recommendation is the utility of the recommended item, as a function of the explicit feedback provided by the user, discounted by a factor based on the position of the recommendation on the list. This metric assumes that the recommendations on top of the list, are more likely to be selected by the user, and thus discount more heavily towards the end of the list.

In the Discounted Cumulative Gain, the discount, as we go down the list, follows a logarithmic function and more specifically,

$$DCG = \sum_i \frac{2^{r_i} - 1}{log_2(i+1)}$$

where i is the item position in the list and r_i is the user's rating on the item i. The base of the logarithm typically takes a value between 2 and 10, but base of 2 is the most commonly used [35].

- ***R-score***

The R-score follows the same idea of evaluating the "correct" ordering of the recommendations but instead of a logarithmic discount, it uses an exponential one. Since the items towards the bottom of the list are mostly ignored from the scoring, the R-score measure is more appropriate when the user is expected to select only a few videos from the top of the list.

The equation that is used for the calculation of the R-score is the following one,

$$R = \sum_i \frac{max(r_i - d, 0)}{2^{\frac{i-1}{a-1}}}$$

where i is the item position in the list, r_i is the user's rating on the item i, d is the neutral rating denoting the indifference of the user for the item ($d = 0$ in our tool), and a is a tunable parameter that controls the exponential decline [34].

A.2.5 Simulation Results

In the first part of the evaluation, we chose as similarity metric the Euclidean similarity and tuned the θ parameter for the hybrid recommendation scheme. The θ values used on this part of the experiment are:

- $\theta = 0$ for collaborative recommendation only,
- $\theta = 1$ for content-based recommendation only,
- $\theta = 0.5$ for the hybrid approach where both content and collaborative recommendations are equally taken into account.

Even though a similar evaluation was already performed in [21], in our evaluation, the collaborative recommendation part of the approach makes use of the "friends" concept where only a subset of the users is taken into consideration on the neighbour selection process.

In Fig. 14, one can see how the Profile Distance between the generated user profile and the expected one is affected with respect to theta. The smaller the distance, the more accurate the final representation of the user is, concerning his interests and preferences. As expected, the content-based only approach is the best performing one on this metric, while the hybrid approach's performance is close, since using only his own profile, the algorithm can easier tune it towards convergence. The least successful one is the collaborative approach only with significant distance from the other two, which is expected since the algorithm tries indirectly to deduce the user's profile through the profile of his friends. Even though the hybrid approach uses both content based and collaborative methods, its performance on the metric is more than satisfactory, while making use of the

advantages provided by the collaborative method that we will discuss later on.

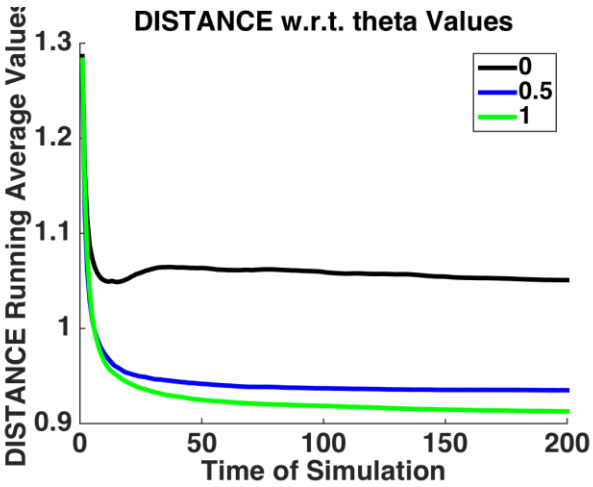


Figure 14. Average profile distance between the generated user profile and the expected user profile over simulation time for 3 different θ values.

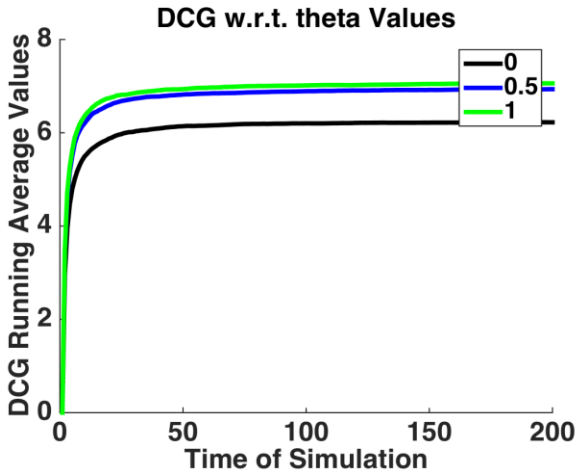


Figure 15. Average Discounted Cumulative Gain of the recommendations provided over simulation time for 3 different θ values.

Fig. 15 shows the Discounted Cumulative Gain of the recommendations provided over time. We can also see that the two best performing approaches are the content only and the hybrid approach, with the collaborative only following third. Again, the difference between the content only and the hybrid approach is not significant, validating once more the effectiveness of the hybrid approach.

Finally, in Fig. 16, we present the R-score of the recommendations list over time. The graphs follow the same pattern with the DCG, and so the hybrid approach succeeds in providing successful recommendations both on the total list and on the top recommended items.

The main disadvantage of using content-based only recommendations is the over-specialization of the algorithm on the user's choices. Collaborative filtering is important in introducing novelty and diversity in recommendations that allow the user to find interesting content that he would otherwise have missed. The element of surprise is important for a recommendation system and such diverse recommendations could lead a user in unexpected paths in his research as well as help him evolve his own taste and preferences. This fact cannot be easily captured in an offline experiment and requires online experimentation.

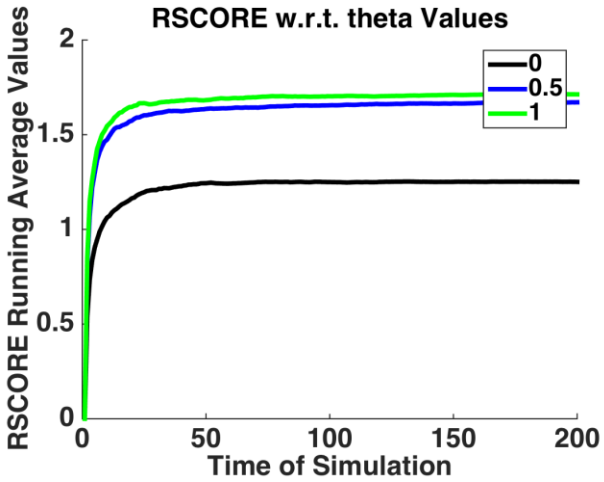


Figure 16. Average R-score of the recommendations list over simulation time for 3 different θ values.

Another problem the content-based only approach has to face is the cold start problem. When the system does not have enough information for a user, the system is basically unable to provide any meaningful recommendations. In this case, his friends network can be utilized to make use of information for users the system already has, and the recommendations provided are significantly more accurate. As a result, to overcome the problem, the collaborative approach seems effective.

From our analysis we can see that the hybrid recommendation scheme constantly achieves a smooth performance and thus successfully combines the advantages of both content and collaborative based filtering approaches.

For the next part of the evaluation, we compare the different similarity metrics used in our algorithms. In this experiment, we fix the theta parameter to $\theta = 0.5$ that corresponds to the hybrid recommendation scheme. An *input* parameter is used in our simulation to specify the similarity measure used by our algorithms and corresponds to:

1. Inner product similarity

$$similarity = X \cdot Y$$

2. Cosine similarity

$$similarity = cos(\theta) = \frac{X \cdot Y}{\|X\|\|Y\|}$$

3. Euclidean similarity

$$similarity = \frac{1}{1 + d(X,Y)}$$

$$d(X,Y) = \sqrt{\sum_i (x_i - y_i)^2}$$

where $d(X,Y)$ is the Euclidean distance of the two vectors.

In Fig. 17, we can see that the Euclidean similarity is the best performing similarity measure, achieving a slightly better score than the cosine similarity, while the inner product similarity is the worst performing. What's more, the Euclidean similarity seems conceptually more appropriate in our use case, since each user and each item can be modeled as a point in the 14-dimensional metric space and the closer they are on the space, the more similar they are.

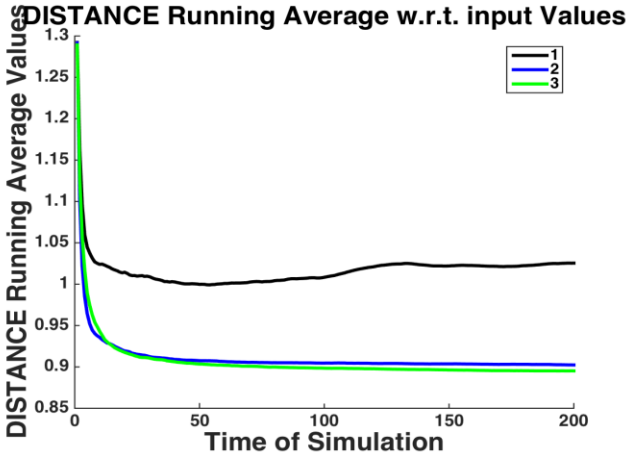


Figure 17. Average profile distance between the generated user profile and the expected user profile over simulation time for 3 different similarity metrics: 1) inner product similarity, 2) cosine similarity, 3) Euclidean similarity.

The Discounted Cumulative Gain is depicted in Fig. 18 and follows the same trend, showing that the Euclidean similarity outperforms the other two similarity measures by providing better overall recommendation lists to the user. The inner product, which is the simplest one, still performs worse than the rest.

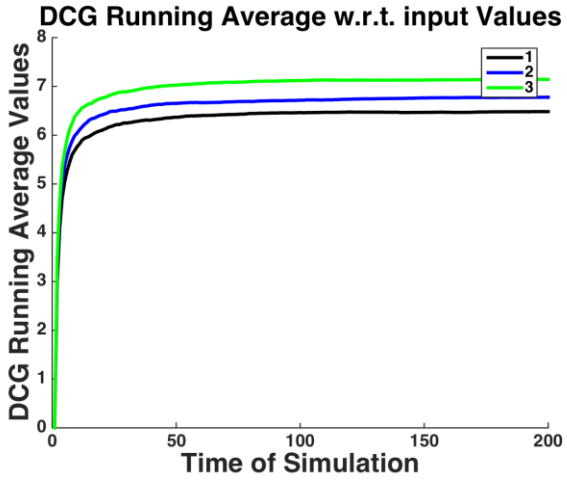


Figure 18. Average Discounted Cumulative Gain of the recommendations provided over simulation time for 3 different similarity metrics: 1) inner product similarity, 2) cosine similarity, 3) Euclidean similarity.

Finally, concerning the R-score (Fig. 19), the Euclidean and the cosine similarity achieve the highest score with minor differences, while the inner product achieves significantly lower score. The fact that the two first measures perform almost the same while in the DCG metric the Euclidean performs better, shows that the Euclidean similarity can better fine tune the lower scoring recommendations since even the lower scoring items, that the R-score ignores, are more likely to be more relevant to the user's preferences.

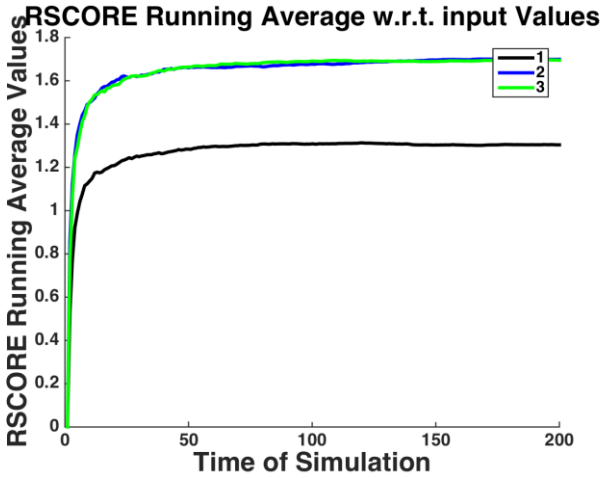


Figure 19. Average R-score of the recommendations list over simulation time for 3 different similarity metrics: 1) inner product similarity, 2) cosine similarity, 3) Euclidean similarity.

More simulations concerning the parameters used can be found in the work presented in [21].

B. *Subjective benchmarking*

1) Integrated Trends Discovery Tool

The Integrated Trends Discovery Tool was evaluated by numerous individuals that were mainly students from the National Technical University of Athens, which ICCS is affiliated with. The students were mainly coming from the Techno Economics Masters program[1], jointly offered by the Department of Industrial Management and Technology at the University of Piraeus and the National Technical University of Athens, which is a highly interdisciplinary graduate programme targeted at professionals with existing market/business/working experience. The evaluation process included the following steps:

a) A document describing the core concepts of the PRODUCER project and the core innovations of the ITD tool was initially shared with the testers.

b) After reading the document the testers watched a 10-minute video demonstrating the utilisation of the ITD tool. The video contained textual information about the internal mechanisms that contribute in generating the visualised outcome at the front end of the tool.

[1] http://mycourses.ntua.gr/course_description/index.php?cidReq=PSTGR1083

c) Finally, the testers answered an online Google Forms based questionnaire. The questionnaire is available under [36].

This process was completed by 157 individuals. In addition, another group of 20 individuals, after following steps a) and b), were requested to access a live version of the tool and to freely try the various functionalities. Then they proceeded on step c) and answered the same questionnaire as well. The results from the superset containing both user groups (177 individuals) are presented in the following figures. As depicted in Fig. 20, the ITD tool testers were mainly young persons (18-34 years old), and are in principle students and/or full-time employees. Their current occupations are mainly related to engineering, IT, and business/financial as presented in Fig. 21.

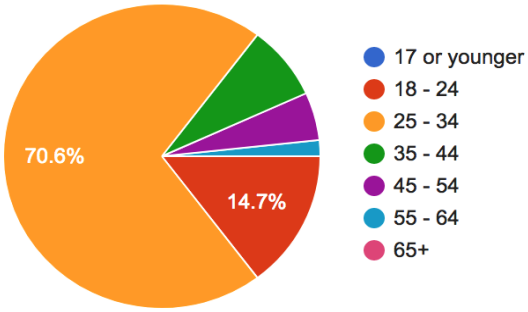


Figure 20. Ages of the user group that tested the Integrated Trends Discovery Tool.

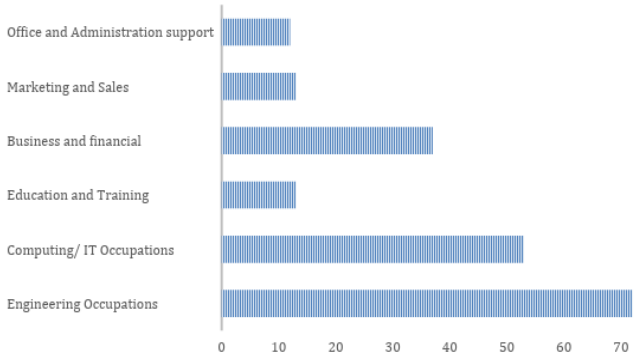


Figure 21. Occupation of the user group that tested the Integrated Trends Discovery Tool.

All testers are familiar with the concept of social media services as they utilize them for long time period (more than five years) and for 1 to 4 hours per day (Fig. 22, 23). In addition, most testers are highly interconnected with other users, having more than 100 connections (Fig. 24), and seem to prefer Facebook, LinkedIn, Google, Instagram and Twitter (Fig. 25).

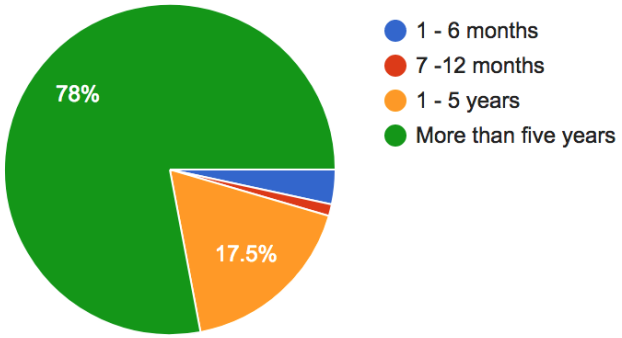


Figure 22. Time period of using Social Media Services.

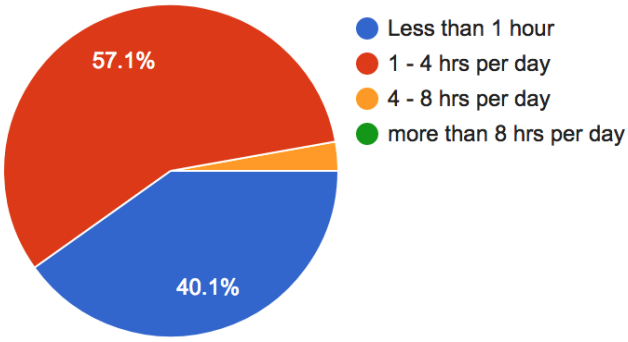


Figure 23. Time of usage per day of Social Media Services.

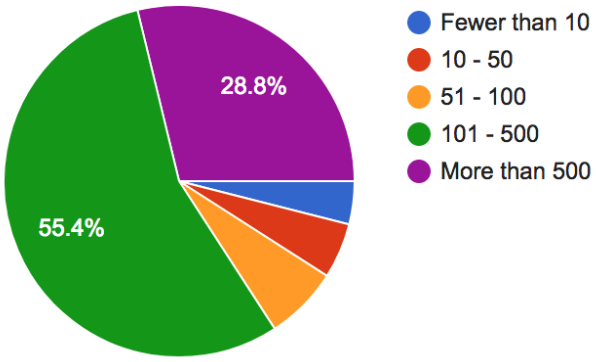


Figure 24. Number of connections each user has on his Social Media profiles.

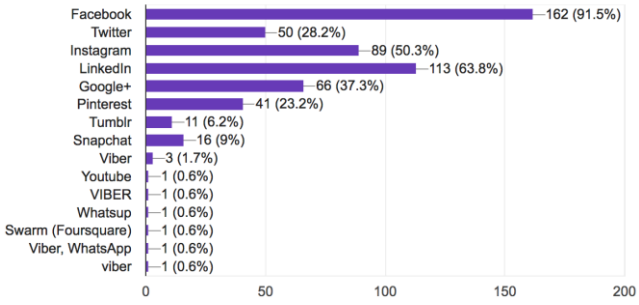


Figure 25. Social Networking Sites used by the user group.

Testers questioned about their purpose of Social media services utilization. Their replies are presented in Fig. 26. Replies such as: “To get opinions”, “To find information”, “To share your experience” are concentrating a significant amount of answers something, which is important because these views are in support of the core objectives of the ITD tool. The core concept of the ITD tool is based on the fact that it is possible to gain information about population opinions and interests through mining social media and search engines services.

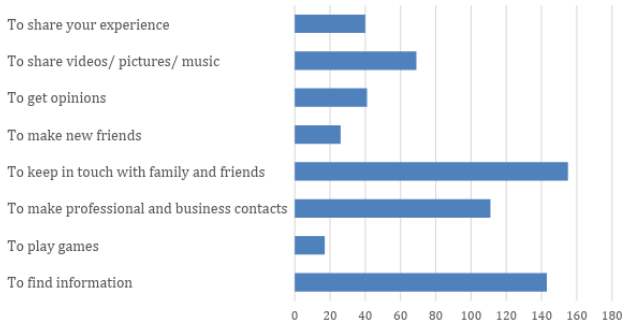


Figure 26. Purpose of using Social Media Services by the user group.

On the other hand, most testers consider that social media analytics can support the extraction of information regarding public opinion similar to the information extracted via opinion polls by survey companies (Fig. 27).

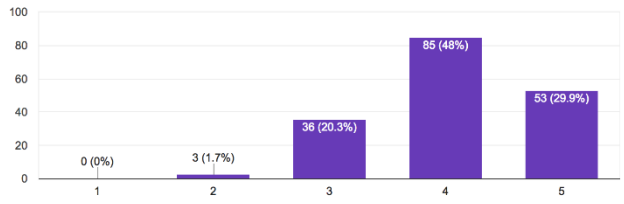


Figure 27. Do you think that Social Media analytics can support the extraction of information regarding public opinion (similar to the information extracted via opinion polls by survey companies)?.

The next question was about testers’ experience on using similar tools (Fig. 28), to which the users indicated they have limited or no experience in average.

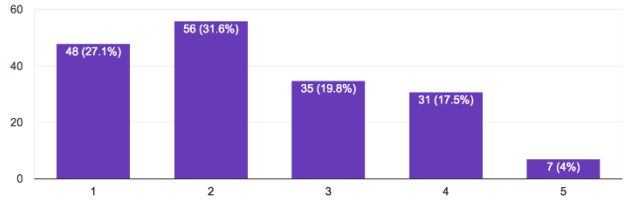


Figure 28. Evaluators’ level of experience in using tools that attempt to discover and process popularity/trends in Social Media and Search Engines.

The final question was about the ethical consequences on social media opinion mining. The actual question was: “The Integrated Trends Discovery Tool processes data that are freely available on the Internet but originate from users posts and searches. Do you consider that any ethical issues arise in this data aggregation process? Which of the following covers your opinion the most?”. Results illustrated in Fig. 29 show that most of the testers do not see any ethical issues, but a significant amount of replies considers that there are such issues. The ethical concerns of the users that appear to be significant introduce a major challenge that is further promoted by the General Data Protection Regulation (GDPR) (EU 2016/679) that took effect on May 2018 in Europe.

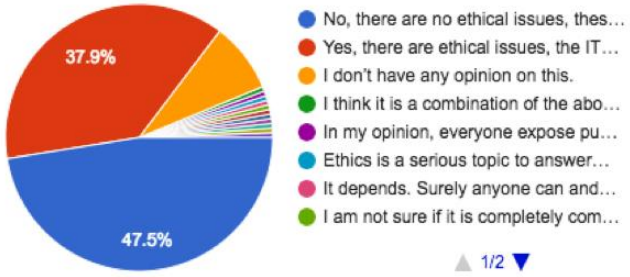


Figure 29. Ethical issues in the data aggregation process of the Integrated Trends Discovery Tool.

The next set of questions targeted directly on the tool utilization and underlying functionality. The first question was about how easy was for the testers to manage “Query Descriptions”. In order to create a new query process, users need to add the necessary information, e.g., textual description, targeted keyword, time range, targeted regions and provide parameters about inference of higher level information. Respective replies about ease of creating a new query process are presented in Fig. 30. Testers’ replies are based on a scale from 1 to 5 where 1 corresponds to “Very difficult” and 5 to “Very easy / intuitive”. Similar are the obtained findings concerning easiness with regards to managing existing Queries, as well as with respect to the generation of trend-related results.

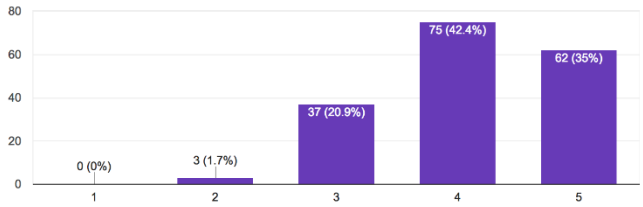


Figure 30. Ease of creating a new query at the "Add Query Parameters" page of the tool.

These findings indicate that the query configuration process was characterized as easy and/or very easy for the majority of the evaluators. The next question was about the ease of reading and understanding the results. Given that rendered results are the outcome of the integration of diverse statistical models derived from external APIs utilizing heterogeneous data models, this task was the one of the most challenging. Within the lifetime of the project we followed various iterations of design, evaluation and refinement of the

way that the trend discovery results are presented to the end user. For this reason, various intuitive graphs (times series graphs, bar charts, pie chart, node graphs) are utilized in order to make the results comprehensible to users that are not demonstrating a background in statistics or in data engineering. The outcome of this evaluation is presented in Fig. 31 and most of the tool evaluators find the results reading process relatively easy.

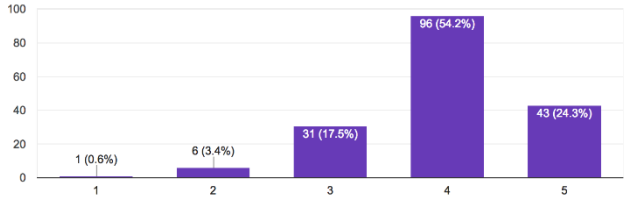


Figure 31. Ease of reading the results.

The last question related to the user interaction was "How user-friendly is the Integrated Trends Discovery Tool?" in general. The respective results are presented in Fig. 32.

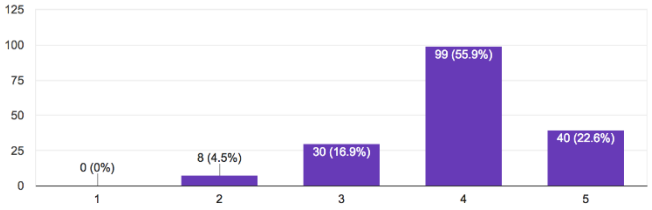


Figure 32. Overall user-friendliness of the Integrated Trends Discovery Tool.

As already described, evaluators at the first steps of the overall process had to read a textual description of the ITD tool objectives, which were also presented in the first minutes of the video describing the tool's utilization. Based on the presented list of innovations and after the demonstration and actual utilization of the tool, evaluators replied two different questions having the same target. The questions were: "*How successful is the Integrated Trends Discovery Tool in performing its intended tasks?*" and "*Meets expectations as these are defined in the innovations list presented upon video start*". Results are presented in Fig. 33 and Fig. 34.

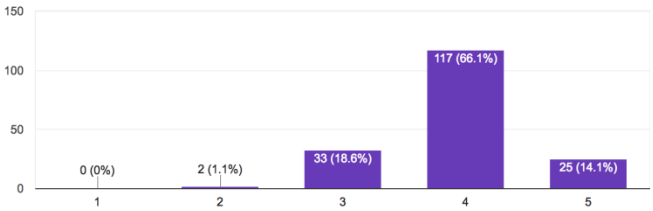


Figure 33. How successful is the Integrated Trends Discovery Tool in performing its intended tasks.

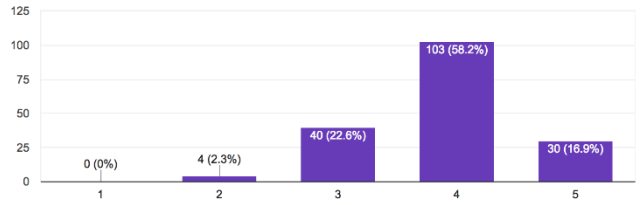


Figure 34. Meets expectations as these are defined in the innovations list presented upon video start.

The last question with regards to the actual evaluation of the tool was related to the overall software quality as this is disclosed through the execution of various tasks. Since this is a difficult question for evaluators with non-technical background, it was considered as optional and hence it was not replied by the whole set of testers. The respective results are illustrated in Fig. 35.

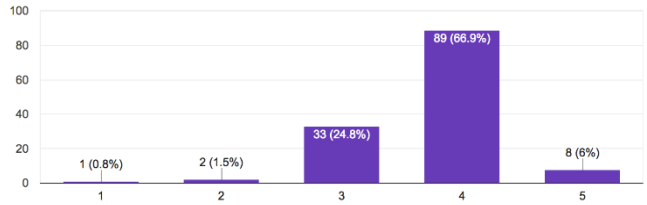


Figure 35. 65: Evaluate overall software quality.

ITD tool developers aim to continue the refinement of the service and to extend the provided functionalities. To this end, evaluators were questioned on which of the provided reports are the more useful. The responses are illustrated in Fig. 36.

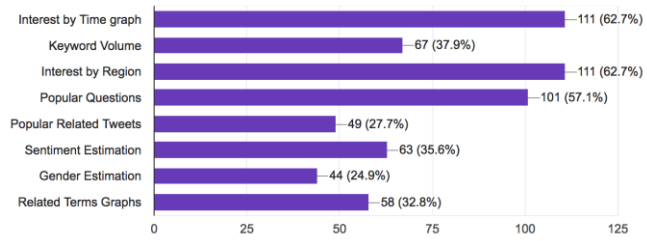


Figure 36. The Integrated Trends Discovery Tool provides various reports. Which are the more useful for you?.

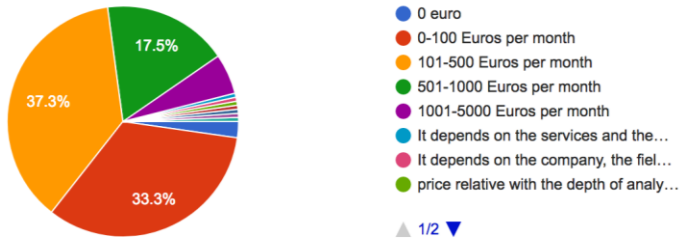


Figure 37. Estimation of cost in order to utilize ITD tool in business environment.

Finally, evaluators were questioned: “The Integrated Trends Discovery Tool currently utilizes mainly the free versions of public APIs (e.g., Google API, Twitter API, ...). Hence there are often delays and matters related to limited access to data. Do you believe that a company interested in the tool's results would be willing to purchase more advanced services (e.g., more detailed user demographics, data from larger user populations, data that span longer to the past) for an additional fee? If so, which of the following amounts do you consider as appropriate for the needs of a small company?”. The outcome of 177 responses is illustrated in Fig. 37.

2) Social Recommendation and Personalization Tool

For the evaluation of the SRP tool, 143 students from the same set of users used for the evaluation of the Integrated Trends Discovery Tool used the tool and answered the corresponding questionnaires [37]. The demographics of the aforementioned user base can be seen in Figs. 38, 39, 40.

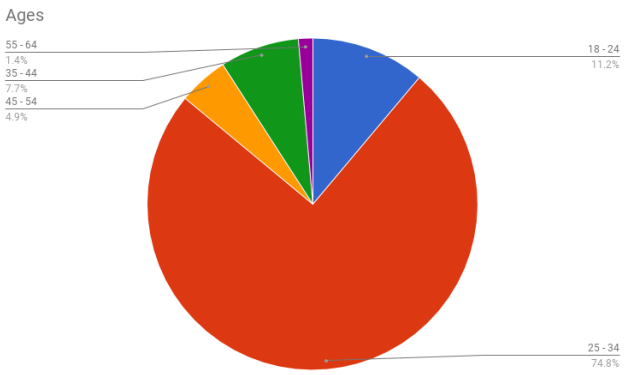
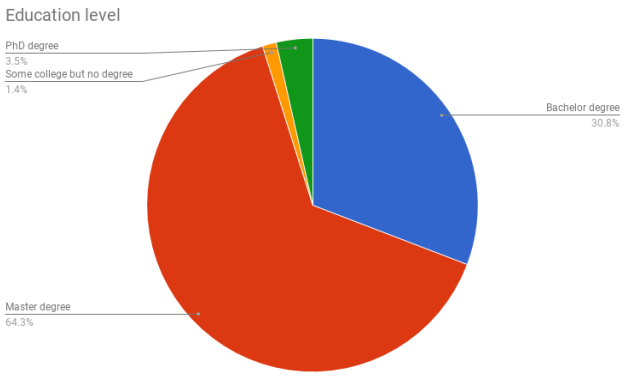


Figure 38. Ages of the user group that tested the Social Recommendation and Personalization Tool.



Education level of the user group that tested the Social Recommendation and Personalization Tool.A short video showing the functionalities of the tool and the expected interaction from the users was shown to the users and they were expected to use the tool on their own via its standalone GUI. After exposing themselves to the tool and using it until they were satisfied that they had formed an opinion on its capabilities, they were asked to respond to the corresponding questionnaire.

The experience of the users that participated in the process on recommender systems is shown in Fig. 41, confirming that a reasonable user diversity was well achieved.

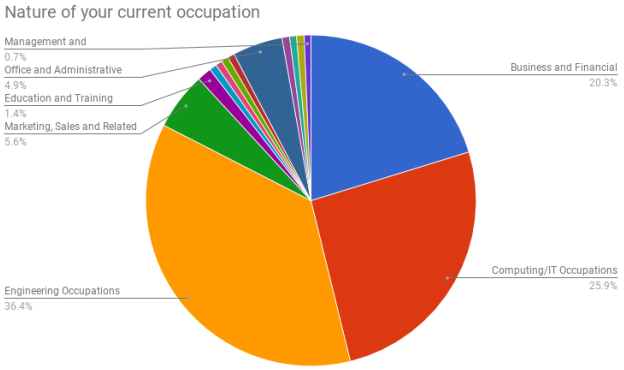


Figure 39. Occupation of the user group that tested the Social Recommendation and Personalization Tool

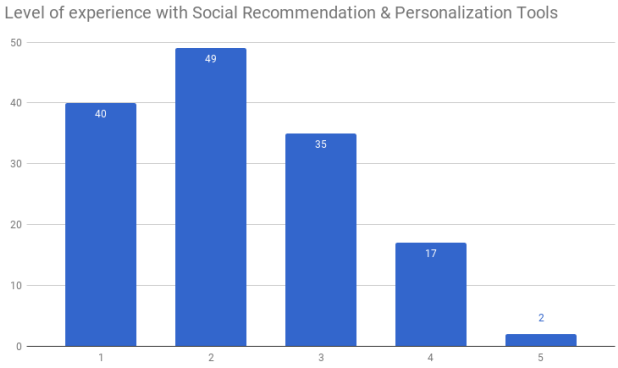


Figure 40. Level of experience with Social Recommendation and Personalization Tools (1: no experience, 5: much experience).

Users were asked to create an account on the tool inserting their information in order to create the basic profile. The information required are certain demographics (age, country etc.) and some personal information (name, email etc.) as well as a username and a password. The information required to be manually inserted by the users were limited, as can be confirmed by the responses of the users (Figs. 42, 43).

After creating his/her account, he/she continued to explore the actual functionalities of the tool. By clicking on the “Videos” tab, two options were available. On the one hand, the user could see the recommended videos that the tool suggests based on the profile the tool has created until now. In the beginning, the profile was created based on the demographics chosen by the user, so that content relevant to similar users was presented. On the other hand, a search functionality was available, where the user could search the database of the SRP tool of more than 2600 videos by providing text relevant to what he/she was searching for. The concept was to use the search functionality together with the

recommended videos and based on the interaction the user had on the videos, the tool should be able to deduce the user's profile and suggest relevant videos to his/her interests.

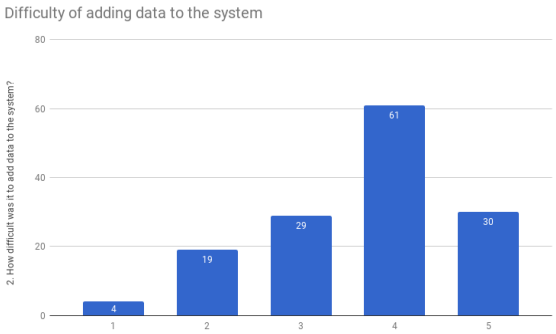


Figure 41. Difficulty of adding data to the system (1: very difficult, 5: very easy).

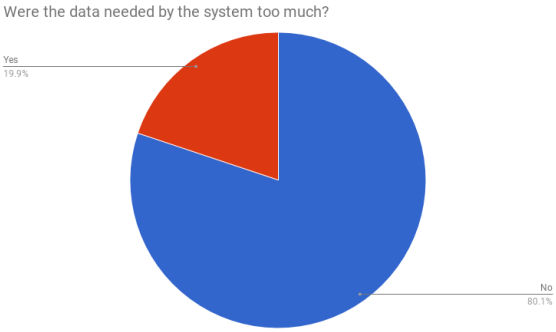
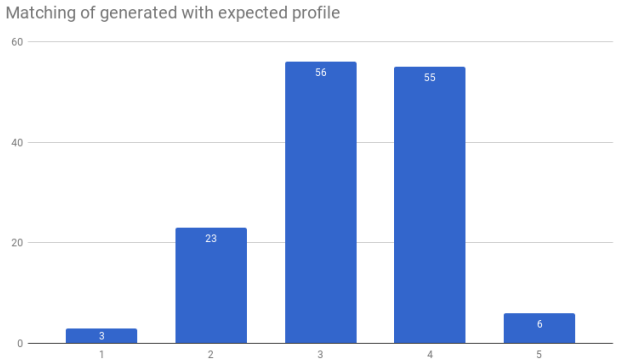


Figure 42. Were the data needed by the system too much?.

After some iterations of using the tool, the users had to rate the relevance of the recommended content and the user's interest in each of the 14 categories presented. The results of the procedure can be seen in Fig. 44 and Fig. 45.



Matching of the generated with the expected user's profile (1: unacceptable, 5: excellent).In both Fig. 44 and Fig. 45, we see that the majority of the users rate the tools performance as more than satisfactory. In Fig. 44, 39% of the users rated the profile matching generated by the tool and the one they had in mind while using the tool with 3 starts while 38% rated it with 4 stars. On the other hand, in Fig. 45, the matching of the recommended videos to the user's expectations shows again that the majority was satisfied, with a rating of 3 stars for the 39% and of 4 stars for the 36%. It is important to note that many times, the actual content of the video was rated by the users, something that is not important to the functionality of the tool, and so there could be some misinterpretation of the actual question. The limited availability of content could also play an important role in the results of the above questions.

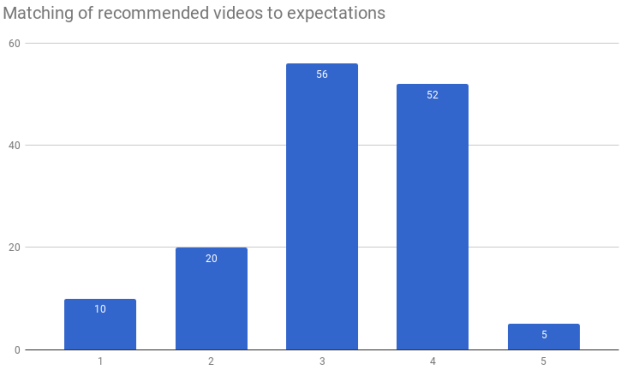


Figure 43. Matching of the recommended videos to the user's expectations (1: unacceptable, 5: excellent).

When asked about the overall Quality of Experience they had while using the tool, 49% of users rated the system with more than 4 stars (4 or 5 stars) stating that the Quality of Experience was more than satisfactory (Fig. 46).

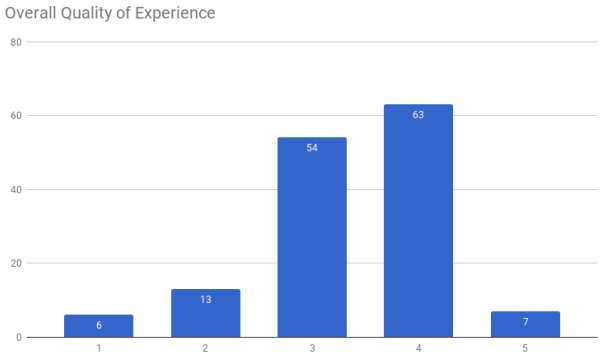


Figure 44. Overall Quality of Experience (1: unacceptable, 5: excellent).

One very interesting result coming from the questionnaires, is the importance the users give on such recommendation systems on a documentary content provider platform such as the PRODUCER platform (Fig. 47, Fig. 48). According to the graph, the Social Recommendation and Personalization tool provides a highly appreciated feature of the platform that definitely increases the Quality of Experience of the user, while helping him achieve tasks faster and more efficiently.

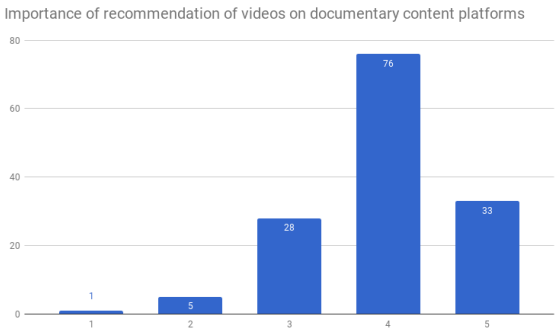


Figure 45. Importance of recommendations on videos (1: not essential, 5: absolutely essential).

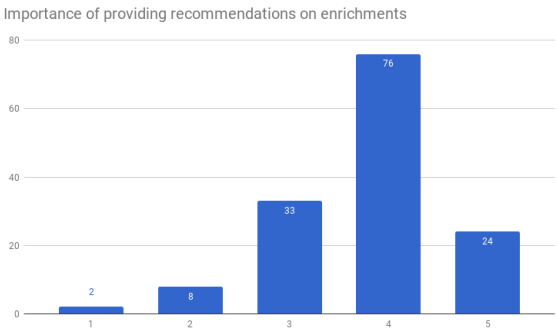


Figure 46. Importance of recommendations on enrichments (1: not essential, 5: absolutely essential).

Finally, users were asked about the relation that they expect between the video content and the enrichments that are recommended to the user by the tool. As we can see from Fig. 49, the majority has responded that they would like a balance between being relevant to the video content and the user profile, which shows that they are open to having recommendations that are more loosely tied to the content itself.

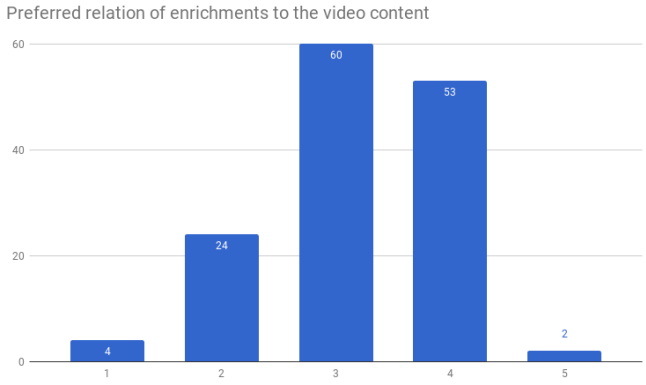


Figure 47. Preferred relation of enrichments to the video content (1: Tightly related to video content, 5: Tightly related to user profile).

Recommending something slightly out of context as far as it is of interest to the user seems to be an option opening some interesting research topics for future exploration. Adding the capability to tune that relation based on user's actions or the nature of the content could seem appropriate.

V. CONCLUSIONS

This paper analyses two software tools that aim to modernize the documentary creation methods. Initially the ITD tool is presented, which focuses on the targeted audience interests, identification and satisfaction. The ITD tool allows the identification of the most engaging topics to specified target audiences in order to facilitate professional users in the documentary preproduction phase. The SRP tool significantly improves the viewers' perceived experience via the provision of tailored enriched documentaries that address their personal interests, requirements and preferences. The core innovations of these tools and the delta from previously published work of the authors can be summarized as follows. First, both tools are used to reduce cost for the documentary production by filtering the content provided on both pre-production and post-production phases. Second, the ITD tool supports the reorientation of the documentary early on the preproduction phase based on the interests of potential audiences, thus targeting topics likely to attract larger audiences. Third, the ITD tool is designed to couple the knowledge extracted from several social media networks to investigate the audience's interests and identify the respective trends. This has already been tested over Twitter and Google Trends. Fourth, the ITD tool is also used to extract information regarding the user demographics, based on their interactions with social media. Evaluation results concerning the discovery of user gender have been presented. Fifth, the SRP tool exploits a different indexing method to classify the content on the 14 categories using NLP and the Word2Vec model instead of a naïve tf-idf algorithm. This has not been investigated before and it proves to be quite efficient in terms of performance. Sixth, the SRP tool supports collaborative filtering making use of the friends' network of the user instead of the entire user database, which enhances the performance of the proposed approach. Seventh, the evaluation of the SRP tool was performed based on different similarity metrics resulting in favouring the Euclidean similarity over the cosine similarity. Usage of this metric further enhanced the SRP tool's performance.

The prototype implementations of these two tools have been demonstrated and evaluated over a period of 3 months by end users of varying profiles. The evaluation process provided valuable feedback for further improving the overall functionality of the tools but also for the specification of reliable exploitation channels and the identification of related business opportunities

Future plans include the tools' integration with proprietary documentary production support services and infrastructures, as well as the extension of various stand-alone features that have been identified as more interesting and useful during the evaluation process. Moreover, the integration of additional social media networks and open data repositories to enhance the accuracy of the trends and interests identified by the two tools also lies among the

authors' future plans. Finally, the authors plan to investigate the suitability of the tools for domains other than documentary production, adapt them and evaluate their performance in these domains.

ACKNOWLEDGMENT

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Rethinking Enterprise Architecture Frameworks for the Digital Age: The Digital Diamond Framework and EA Tool

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***Abstract* - Enterprise Architecture (EA) Frameworks (EAFs) have attempted to support comprehensive and cohesive modeling and documentation of the enterprise. However, these EAFs were not conceived for today's rapidly digitalized enterprises and the associated IT complexity. A digitally-centric EAF is needed, freed from the past restrictive EAF paradigms and embracing the new potential in a data-centric world. This paper proposes an alternative EAF that is digital, holistic, and digitally sustainable - the Digital Diamond Framework. D²F is designed for responsive and agile enterprises, for aligning business plans and initiatives with the actual enterprise state, and addressing the needs of EA for digitized structure, order, modeling, and documentation. The feasibility of D²F is demonstrated with a prototype implementation of an EA tool that applies its principles, showing how the framework can be practically realized, while a case study based on ArchiSurance example and an initial performance and scalability characterization provide additional insights as to its viability.**

Keywords- enterprise architecture frameworks; enterprise architecture; enterprise modeling; business architecture; digitalization.

I. INTRODUCTION

This paper contributes a digitized, holistic, hyper-model EA conceptual framework called the Digital Diamond Enterprise Framework (D²F) to provide a fundamentally digital and sustainable EA framework for a digital EA future. It extends [1] with an analysis of other EAFs and describes a prototype implementation of the Digital Diamond Enterprise Framework (D²F) to show its feasibility.

Enterprise Architecture (EA) concerns itself with comprehensively and cohesively modeling and documenting the structure and behavior of the business and IT infrastructure of an enterprise as a set of artifacts in order to communicate, implement change, and develop insights in support of strategic business planning and management science. Historically, EA emerged from a necessity to document information systems for management stakeholders. One of the most well-known EA Frameworks (EAF) is the Zachman Framework, first publicized in 1987 [2]. While one might think that after 30 years the EA area must be mature, Gartner's 2017 Hype Cycle for Enterprise Architecture [3] shows EA and EA Tools within the slope of Enlightenment - not yet in the Plateau of Productivity, and EAFs are in the Trough of Disillusionment.

Enterprises now face multiple contemporaneous challenges:

1) A major digital transformation of their industry [4]. While the digitalization rate (digital score) may vary across industries and economies, it is nevertheless impacting business strategies and necessarily EA. As big data, data analytics, business intelligence, and machine learning make inroads into enterprises, improved decision-making capabilities at all levels and across organizational entities empowers employees with new insights and assistance and additional automation.

2) Agility is restructuring internal people-centric enterprise management, processes, and projects to continuously flexible and responsive business forms, accelerating product and service delivery and improving efficiency (e.g., Scrum, DevOps, BizDevOps).

3) Service-networked and mobile software: the IT landscape is rapidly changing from large, siloed, hierarchical, and static deployments to cloud-centric, networked, and containerized micro functionality deployments. Software/data functionality becomes easily reusable and accessible via standard protocols and formats independent of programming language or platform. Its scale can be seen in various "death star"-like microservice network landscape visualizations (see Figure 1).

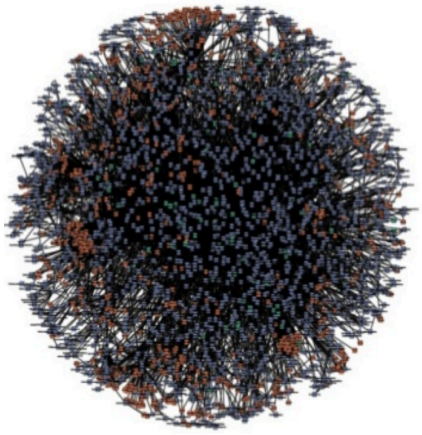


Figure 1. Visualization of microservices at Amazon [5].

Considering these major trends, the reality that EA is attempting to comprehensively model, document, and change has become much more complex than in previous decades. The era of siloed functional teams and applications is being superseded by a highly networked and integrated digitized era.

This challenges currently available EAFs, which were mostly developed before these trends swept into enterprises and typically rely on a simplified box-and-matrix paradigm.

As to the use of EAFs in industry, in 2007 Ivar Jacobson reckoned 90% of the EA initiatives he was aware of had not resulted in anything useful, stating big gaps vs. seamless relationships as a primary reason [6]. A 2008 study showed two-thirds of EA projects failing to improve IT and business alignment [7], with the most frequent explanation being that connecting EA to business elements was difficult in practice. Hence, the EAFs of the past with their associated paradigms and their models cannot continuously reflect the dynamic enterprise realities in this digital age, thus they are illusionary, ineffective, inefficient, and no longer viable.

The application of EA and an EAF typically involves some kind of EA tooling. Considering the support for EA provided by EA Management (EAM) tools, Jugel el al. [8] investigated their visual analytics capabilities and collaborative decision-making support. Their findings identified the following five challenges and needs for EAM tools:

1. *View configuration*: An easy way to configure views is needed to react to dynamic information demands.
2. *View consideration*: A method is needed to consider several views in parallel to avoid losing the overall context. Additionally, views should always be kept up to date.
3. *Interacting with views*: Stakeholders need more interaction and visual analytics capabilities to analyze and plan EAs more efficiently.
4. *Communication & collaboration*: Methods are needed to better support communication & collaboration, e.g. by adding additional knowledge to views.
5. *Stakeholder identification*: There is a need for methods to identify stakeholders that have to be involved in decision-making processes.

The following research questions guided our investigation:

RQ1: Are there obvious deficiencies in the EAF and EA tool landscape, and if so, how can these be characterized?

If a new EAF and/or EA tool appear justifiable:

RQ2: What should a digital EA framework address?

RQ3: What requirements and viewpoints should an associated digital EA tool implementation support?

RQ4: Is it feasible for a digital EAF graph-centric EA tool implementation to flexibly support the ArchiMate ArchiSurance case study examples across the various viewpoints?

RQ5: Does a graph-centric EA tool implementation appear viable based on an initial performance and scalability characterization?

This paper contributes a description of our digital EAF proposal D^{2}F. We also contribute a demonstration via case study of the feasibility of D^{2}F by describing an implementation of an EA tool prototype based on D^{2}F principles and having the following features that address the above five EAM tool challenges:

- enterprise information model agnostic,
- flexible meta-model,
- supports tagging can be used to add knowledge to elements/views,
- (re)configurable interactive dynamic (up-to-date) views,
- visual analytical capabilities,
- and cross-platform and web-centric to more easily involve and be accessible to diverse stakeholders.

This paper is organized as follows: Section II discusses background material on EA and related work. Section III describes the D^{2}F. In Section IV, we describe our prototype tool that demonstrates how D^{2}F can be implemented. Section V evaluates the implementation, and is followed by a conclusion in Section VI.

II. Background and Related Work

EA comprises the structural and behavioral aspects needed for the enterprise to function and their adaptation to align with a vision. It thus covers business (including people), information (data), and technology (IT, hardware and software). EA has been compared to city planning [9], designing in the face of many unknowns.

A. EA Frameworks (EAFs)

EAFs offer structure, associated terminology, and at times processes for EA-related work. The Zachman Framework [2] utilizes a matrix paradigm and has changed over the years, using rows (layers) to address highest level business, then logical to the most detailed technical levels, and columns for the 5W's and H (who, what, where, when, why, how). Many of these EAFs have common ancestors and historical influences. The Open Group Architecture Framework (TOGAF) [10] was first publicized in 1995 and provides a methodology for EA and a boxed architecture. The National Institute of Standards and Technology (NIST) EA Model is a five-layered reference model stemming from the 1980s and formed the basis for the Federal Enterprise Architecture Framework (FEAF) [11]. The Generic Enterprise Reference Architecture and Method (GERAM) [12] is a generalized EAF from the 1990s and focuses on enterprise integration and business process engineering.

Most EAFs use a 2D box or 3D cube paradigm when attempting to deal with the inherent complexity. Stroud and Ertas [13] developed a taxonomy for EAFs to show their interrelationships (influence, chronology, evolution). Sultanow et al. [14] classified 55 EAFs based on multidimensions (size, architectural domain scope, mutability, alignment, intention, chronology). Lim et al. [15] did a comparative study of five well-known EAFs, extracting and reifying them based on four dimensional concepts: view, perspective, scope, and time. In order to provide an impression of the extent and breadth of EAFs, Table I provides a consolidated list of acronyms and names of EAFs or architecture frameworks (AFs) and the source list used, which can be used to find more information about it. Due to space limitations, this is not intended to be a complete nor comprehensive list. Since various AFs could also be applied in the context of EA as well, no differentiation between AF and pure EAFs was attempted. The sources provided can be referred to for additional details.

TABLE I. LIST OF EAFs* AND AFs*

Acronym	Name	Source
4+1	Kruchten's 4+1 view model	[16]
AAF	Automotive AF	[16]
ADS	Architecture Description Standard von IBM	[17]
AF-EAF	Air Force EAF	[16]
AF4MgtSys	AF for Management Systems	[16]
AFIoT	IEEE P2413 AF for the Internet of Things	[16]
AGA	Australian Government Architecture Reference Models	[16]
AGATE	Atelier de Gestion de l'ArchiTecturE des Systemes d'Information et de Communication (AGATE)	[16][17]
AM	Avancier Methods	[16]
ARCHI	ArchiMate	[16][17]
ARIES	Architecting Innovative Enterprise Strategies	[16]
ARIS	Architektur integrierter Informationssysteme	[17]
AUSDAF	Australian Defence AF	[16][17]
BCA	Business Capability Architecture	[16]
BDAF	Big Data AF	[16]
BEAM	Business Enterprise Architecure Modeling	[16]
BPEAM	iteratec best-practice enterprise architecture management (EAM) method	[16]
C4IF	Connection, Communication, Consolidation, Collaboration Interoperability Framework	[17]
C4ISR		[17]
CAFCR	Customer Objectives, Application, Functional, Conceptual, and Realisation model	[16]
CAFEA	Common Approach to Federal Enterprise Architecture	[16]
Casewise	Casewise Framework	[17]
CBDI-SAE	CBDI Service Architecture & Engineering (CBDI-SAE™) for SOA	[16]
CEA	CEA Framework: A Service Oriented EAF (SOEAF)	[16]
CEAF	Commision Enterprise IT Architcture Framework (CEAF)	[16]
CIAF	Capgemini Integrated AF	[16]
CIMOSA	CIM Open System Architecture	[17]
CLEAR	Comprehensive, Landscaped, Enterprise Architecture Representation Framework	[17]
DNDAF	Department of National Defence and the Canadian Forces AF	[16][17]
DoD TRM	Technical Reference Model	[17]
DoDAF	US Department of Defense AF	[16] [17]
DRA1	Dragon1	[16]
DYA	Dynamic Architecture	[16]
e-GIF	UK e-Government Interoperability Framework	[17]
E2AF	Extended EAF	[16][17]
EAAF	OMB Enterprise Architecture Assessment Framework	[17]
EAB	Enterprise Architecture Blueprinting	[16]
EAMMF	GAO Enterprise Architecture Management Maturity Framework	[17]
EAP	Spewak's Enterprise Architecture Planning	[17]
EEAF	US OMB Enterprise Architecture Assessment Framework	[16]
EIF	European Interoperability Framework des IDABC-Programms	[17]
EPCAF	The EPCglobal AF	[16]
ESAAF	European Space Agency AF	[16]
ESSAF	Essential AF	[16]
eTOM	Business Process Framework (eTOM)	[16]
EXAF	Extreme AF	[16]
FEAF	US Federal EAF	[16][17]
FESS	Framework of Enterprise Systems and Structures	[16]
FFLV+GODS	Functions-Flows-Layers-Views + Governance-Operations-Development-Support	[16]
FMLS-ADF	FMLS Architecture Description Framework 3.0 (SE)	[16]
FSAM	Federal Segment Architecture Methodology (FSAM)	[16]
GA	Garland and Anthony	[16]
GEA-NZ	All-of-Government (AoG) Government Enterprise Architecture for New Zealand	[16]
GEAF	Gartner's EAF	[16][17]
GERA	ISO 15704 Generic Enterprise Reference Architecture	[16]
GERAM	Generalised Enterprise Reference Architecture and Methodology	[17]
GIM	GRAI Integrated Methodology	[17]
HEAF	Health EAF	[16]
HIF	Healthcare Information Framework (DIN V ENV 12443)	[17]
IADS	IBM Architecture Description Standard	[16]
IAF	Index AF	[16]
IAF	Integrated AF (Capgemini)	[17]
ICODE	iCode Security AF	[16]
IFW	IBM Information FrameWork (IFW)	[16]
IFW	Information FrameWork	[17]
IIRA	Industrial Internet Reference Architecture	[16]
ISO/IEC 42010	Recommended Practice for Architectural Description	[17]
IT City Planning	IT City Planning AF (Gartner)	[17]
JTA	DoD Joint Technical Architecture	[17]
LEAD	Leading Enterprise Architecture Development (LEAD)ing Practice	[16]
MACCIS	An Architecture Description Framework for Technical Infostructures and their Enterprise Environment	[16]
MEGAF	MEGAF	[16]
MIKE2.0	Method for an Integrated Knowledge Environment	[17]
MODAF	(UK) Ministry of Defence AF	[16][17]
NAF	NATO Architectural Framework	[16][17]
NEA	National EAF	[16]
NIH	(U.S. National Institutes of Health) EAF	[17]
NIST	(U.S. National Institute of Standards and Technology) Enterprise Architecture	[16][17]
OBASHI	ownership, business process, application, system, hardware and infrastructure framework	[17]
OIO	OIO Enterprise Architecture Method	[16]
OSSAF	Open Safety & Security AF	[16]
PEAF	Pragmatic EAF	[16]
PERA	Purdue Enterprise Reference Architecture	[17]
OSE RM	ISO/IEC TR 14252, IEEE Std 1003.0 & ISO/IEC 9945	[17]
PPOOA	Processes Pipelines in Object Oriented Architectures	[16]
PRISM	Partnership for Research in Information Systems Management	[16]
QGEAF	Queensland Government EAF	[16][17]
RASDS	Reference Architecture for Space Data Systems	[16]
RM-ODP	ISO Reference Model for Open Distributed Processing	[16][17]
RWSSA	Rozanski and Woods	[16]
S4V	Siemens 4 Views	[16]
SABSA	Sherwood Applied Business Security Architecture	[16][17]
SAGA	Standards and Architectures for eGovernment Applications	[17]
SAP EAF	SAP EAF	[17]
SASSY	Self-Architecting Software SYstems	[16]
SGCAF	Smart Grid Conceptual AF	[16]
SQUID	Specification Quality In DevOps	[16]

Acronym	Name	Source
t-eam	toolbox for enterprise architecture management	[17]
TAFIM	Technical Architectural Framework for Information Management	[17]
TEAF	(US) Treasury EAF	[16]
TEAF	Treasury EAF	[17]
TISAF	Treasury Information AF	[17]
TOGAF	The Open Group AF	[16][17]
TRAK	The Rail AF	[16][17]
UADF	Universal Architecture Description Framework	[16]
VERAM	Virtual Enterprise Reference Architecture and Methodology	[17]
xAF	Extensible AF	[16][17]
XAF	eXtreme Enterprise Architecture Framework	[17]
ZF	Zachman Framework	[16][17]

*AF = Architecture Framework; EAF=Enterprise AF

Considering that Gartner's 2011 global EA survey showed more than 60 EA frameworks in use, with the most popular being blended followed by homemade [18], it is indicative that the current state of EAFs is deficient, fragmented, and in need of rethinking from its core. To the author's knowledge, none of the EAFs in Table I meet all three essentials requirements: 1) conceived as purely digital in their essence for a digitized enterprise, are 2) domain and intention agnostic to be widely applicable for EA, and 3) provide the necessary visualization and tooling for digitized modeling and EA-centric data integration.

B. Enterprise Modeling

Modeling abstracts and simplifies an area of interest while maintaining certain its essential characteristics. Consequently reality is more complex than our models. We model in order to reason or understand within our cognitive limitations and to convey insights to others. Different domains and enterprises have different weightings and expectations as to what and how much, if any, modeling and its associated overhead should occur. The modeling spectrum can span from nothing for small organizations to modeling everything, but usually it is in the area between (see Figure 2). Something is inherently absent and models are imperfect, and manual adjustments may be necessary if the reality changes.

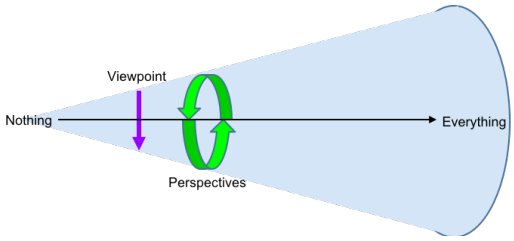


Figure 2. Modeling spectrum.

An international standard for enterprise modelling (EM) and enterprise integration is ISO 19439:2006, which based on GERAM and Computer Integrated Manufacturing Open System Architecture (CIMOSA). It uses a cube paradigm with model phase, model view, and genericity on each axis. As to business modeling, Meertens et al. [19] argue that there is hardly any agreement or standardization in the area as yet.

The reality is enterprise models for dynamic enterprises can become extremely complex and perhaps difficult to maintain, as illustrated in Figure 3 with a CHOOSE semantic meta-model [20] for an SME (small-to-medium enterprise).

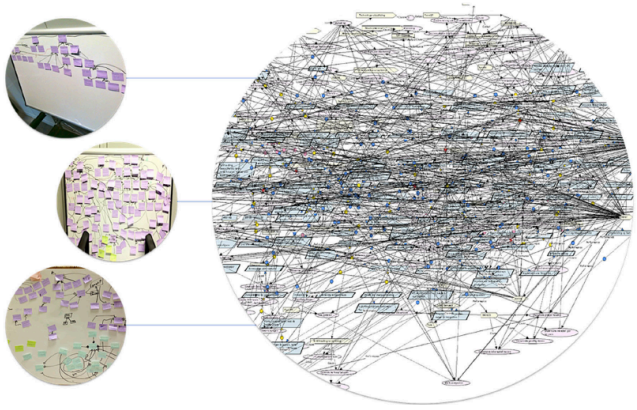


Figure 3. An example CHOOSE enterprise model for an SME, from [20].

C. EA Tool Landscape

As enterprises consist of a complex set of systems, processes, resources, organizational structures, and technologies with various interdependencies, EA Management (EAM) attempts to provide an integrated view of these various aspects to enable alignment of the business with IT capabilities and support change and optimization. In order to assist with and provide insight for EAM, EA tools typically provide various visualization capabilities.

Matthes et al. [21] evaluated nine EA tools in detail, while Matthes et al. [22] evaluated four additional EA tools using the same criteria. A scenario-based approach with a consistent information model of a fictitious organization was used. The first part deals with specific functionality such as adapting the information model, supporting multiple users and collaborative work, visualizing the application landscape, or usability. The second part assesses the EAM support of the tools, e.g. landscape management, demand management, project portfolio management, synchronization management, strategies and goals management, business object management, IT architecture and infrastructure management, and service-oriented architecture (SOA) transformation.

Sultanow et al. [23] studied and compared 34 EA tools, basing their comparison criteria on that of Matthes et al. [21] and Filss [24]. They found that a complete evaluation and in-depth look at each tool is both difficult and time-consuming. This is due to the fact that the tools are advertised and described with relatively little detailed technical depth and a lack of transparency. Many of the tools do not offer a test version for trying out and comparing them. The authors were able to use questionnaires and direct contact with the vendors to gather certain information. One of the conclusions of the study is that the tools in the EA segment do include a basic set of capabilities, but these vary considerably in scope. Most tools can be customized to the customer's needs. The organization of and access to EA data is similar, and most support TOGAF, Zachman, and/or ArchiMate. Some tools are

quite flexible and offer additional visualizations that the other tools do not offer. The comparison criteria categories and subcategories used in the study were:

- Management functions: infrastructure, IT architecture, business/object, goal, strategy, synchronization, project portfolio, demand, landscape, and SOA transformation
- Visualization types: 3D, bubble charts, business model canvas, EPC, ERD, Cluster Card, dashboard, line charts, pie charts, timeline, tree view, matrix, geographic map, flow diagram, UML, BPMN
- Layout: manual, semi-automatic, or fully automatic
- Programming paradigms: structured, modular, object-oriented, component, scrum
- Automation: manual, formatting, consistency checks, generating, inter-productive

The Enterprise Architecture Visualization Tool Survey by Roth et al. [25] surveyed 18 EA tool vendors (over 50 invited) and 109 EA experts (out of 1200 invitations). Here is an excerpt of some of their findings, and our view on possible implications considering D²F:

- The reported tools EA experts use most frequently are Visio (87%), Powerpoint (86%), Excel (74%), then to a much smaller degree Enterprise Architect (33%), ARIS (25%), iteraplan (23%), and Archi (20%) followed by the rest. Our interpretation of this is that most of the participants (mostly enterprise architects) were not using comprehensive EA tools, nor were most using EA tools with a direct access to IT infrastructure (digitally integrated).
- Less than 20% were dissatisfied with their current EA tools (16% dissatisfied and 3% very dissatisfied), 49% were neutral, 24% satisfied, and only 9% were very satisfied. Considering the non-EA-centric tools mentioned above (like Microsoft Office), we interpret this as an indication that the EA digitalization challenges described in our paper had not yet fully materialized for the participants involved at the time of this study. Since 69% were neutral or dissatisfied with their currently available EA tools, it indicates that the EA tool market still has significant growth potential towards clear EA-specific tool market leaders that show high adoption and high satisfaction rates for EA architects (the go-to EA tool for them).
- The visualization update frequency required by enterprise architects was reported as primarily quarterly (22%), monthly (20%), weekly (17%), daily (13%), and semi-annually, annually, and other were 10% or less. Thus, we see that the pace of digitalization and the degree of change with which they needed to cope was relatively slow. When we compare this to the number of deployments of software between 2014 and 2019, we also see that the reported software deployment frequency in the 2017 State of DevOps Report [26] for high performers jumped from about 200 to 1600 annually between 2015 and 2016. In turn, we can speculate that today's enterprise architect must also deal with much faster software-centric change cycles and associated information models.

The above EA tool surveys show a large set of different capability profiles among vendors (as can be seen by the Kiviat diagram profiles in the Matthes et al. studies [21] 22]), a high degree of market fragmentation, high degrees of organizational customization, and a relatively low EA-centric tool adoption rate by enterprise architects. This is indicative that none of the current EA tools appears completely satisfactory.

D. Summary

As to one of the more well-known EAFs, John Zachman admitted in 2004 "if you ask who is successfully implementing the whole framework, the answer is nobody that we know of yet" [27]. And considering Gartner's 2011 global EA survey showing more than 60 EA frameworks in use, and the most popular being blended followed by homemade [18], it indicates that none of the current EAFs suffice for enterprise needs, and many were not designed for the new digital enterprise era and lack the ability to leverage its capabilities. The EAFs and methods mentioned above typically use some layer-and-column matrix and most aspects related to models and views land in a box. This the clean-box paradigm (or syndrome depending on your view). Everything appears nicely modeled, complete, consistent, traceable, and semantically precise. But this apparent harmony is an illusion, the grey areas that cross boundaries or are cross-cutting concerns are not explicitly dealt with. E.g., automation, notification, policies, common vs. specific services, testing, staging, DevOps, etc.

Considering the EA tool popularity, satisfaction, and update rates, and the issues found when assessing the EA tools in detail, there is potential for the EAF landscape to offer a purely digital EAF and supportive EA tooling.

Thus, EAFs currently lack an integrated digitalized and data-centric concept from the ground up. They fail to provide real-time dynamic updates and thus reflect stale, inaccurate, or inconsistent data. They also require additional manual labor to maintain independent artifact consistency with a changing enterprise reality.

III. The Digital Diamond EA Framework

The depth and breadth of the digital impact and the deep integration of complex IT into all aspects of the enterprise calls for a new and digitally sustainable 'boxless' EA framework paradigm for this new era that can deal with digitalization, ambiguity, further IT complexity, and further automation. In the following subsections, the key areas, activities, principles, integrative aspects (potentially applicable when applying D²F), maturity levels, and roadmap to D²F are portrayed.

A. D²F Key Areas

Key Areas cluster related *facets* (concepts or elements) and provide a focus for human thought. In contrast to boxes/levels, here boundaries are intentionally absent, reflecting the lack of boundaries in the digital world, wherein facets can relate to multiple areas. Mind maps can be seen as a useful analogy.

Figure 4 shows key areas involved in D²F, with cross-cutting areas shown angled on the left and right.

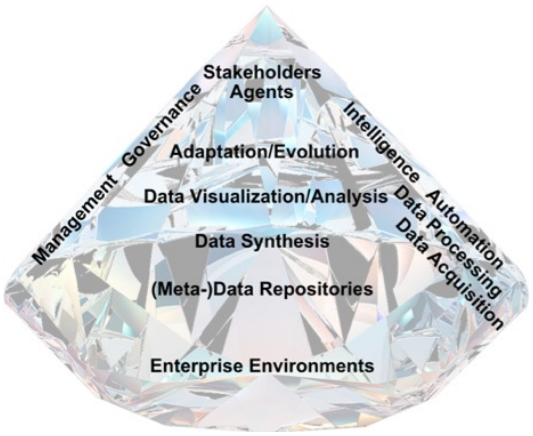


Figure 4. Key areas D²F.

The key areas are:

1) Enterprise Environments: comprises all actual human, business, infrastructural, and IT operational objects.

2) (Meta-)Data Repositories: includes all (meta-)data concept repositories in the enterprise from a logical standpoint, reflecting *Enterprise Environments* in a data-centric way in support of higher-level data-centric analyses. While such repositories also reside in an *Enterprise Environment*, the focus is support for data acquisition, data processing, and other data-centric higher-level activities.

3) Data Acquisition: involves collecting data and meta-data into *Data Repositories* and making these accessible.

4) Data Processing: includes characterizing, filtering, preparing (e.g., deriving), transforming (e.g., between formats, sorting), and cleansing data, the outputs of which are also stored in *Data Repositories* and hence available to other areas (e.g., automation, synthesis, analysis).

5) Data Synthesis: involves aggregating, clustering, and correlating related or unrelated enterprise data, e.g., for digital key performance indicators (KPIs), dashboards, model conformance, etc. While this area overlaps the previous one, its focus is on determining and structuring aggregates.

6) Data Visualization/Data Analysis: provides data-centric analysis and visualization of data, models, and other EA artefacts for understanding, exploration, and insights.

7) Adaptation/Evolution: includes taking action, responding to issues or concerns, stimulating or commissioning adaptive changes to fix or optimize the enterprise, and creating new initiatives and capabilities that let the enterprise evolve to a new state.

8) Stakeholders/Agents: stakeholders can be viewed as anyone with an interest in the enterprise, and they may have conflicting and overlapping interests and (informational) needs. Agents (human or software) are able to directly effect changes within the enterprise.

9) Automation and Intelligence: automation will increasingly support digital enterprise processes and will leverage data to improve efficiency and effectiveness and is thus explicitly considered. Beyond automation, intelligence utilizes data analysis and machines learning capabilities to assist humans in forming decisions or, via intelligent software agents, directly supporting autonomic decisions in given areas. For instance, automatic real-time adjustment of business product prices based on market movements or IT forecasting of required cloud infrastructure capacities.

10) Management and Governance: involves managing and directing enterprise resources to reach enterprise goals as well as the enterprise governance including controlling, compliance, and assessments at various enterprise levels.

Note that *Key Areas* can overlap (a data or meta-data repository will likely reside in an enterprise environment) and thus may appear redundant or inconsistent, yet this is not problematic and one strength of the D²F paradigm. *Key Areas* may be tailored for a specific enterprise. A prerequisite to a complete implementation of D²F presumes digitalization of EA-relevant areas for any given enterprise. As to scaling, the concept of a connected *D²F Chain (Diamond Necklace)* can be considered for applying D²F within various entities (e.g., divisions) but tied into a larger enterprise organization.

B. D²F Key Principles and Qualities

Key principles and resulting qualities of D²F include:

1) Digitized (digital and networked): data and artifacts are acquired or transformed into a digital and network-accessible form, open and transparent within the enterprise (to the degree feasible from a security standpoint), and preferably retained in some version-controlled repository (database or configuration-management database (CMDB) such as git). Internet-of-Everything and concepts such as digital twins can be used for physical entities to mimic real properties. Standards for data formats and interface access are considered for the enterprise.

2) Meta (self-describing): all (data) elements including artefacts, entities, services, etc. should, as far as feasible, provide (its own) metadata (properties and semantic meaning) that can be integrated in metadata repositories (e.g., federated CMDBs) or searched via metadata networks (e.g., LinkedData), and which can be utilized by data processing and data synthesis. Various technologies such as semantic data graphs, RESTful services, JSON-LD, etc. can be used.

3) Linked: Related networked data and meta-data are (semantically) linked in such a way that related data to some element or concept can be discovered and accessed.

4) Dynamicity: In an adapting and evolving digital enterprise, all artefacts and enterprise elements (or the digital twins thereof) as well as their relationships are assumed to be dynamic, and configurations are used to "snapshot" a set of element states that can be used in some analysis or communication. Models can be based on functions that

transition from simulated to real data rather than static structures detached from external values.

5) Holistic: bottom-up and top-down deep integration of applicable enterprise facets, such that various concepts (e.g., business models, business strategies, policies, architectures) can be tied to various related artefacts, models, operational data, and actual enterprise entities and thus be holistically analyzed across various factors.

6) Hyper-models: embraces many coexistent and co-evolving intertwined models (domain, business, process, software, IT architectures, context), perspectives, viewpoints, and views (not necessarily consistent) supported by data processing. Automation will also affect how EA models are generated (manual vs automatic), thus we must adapt our tooling and methods towards sustainable integrative modeling. Humans desire simplicity and computers can better deal with complexity and massive data volume; thus, a symbiotic relationship should be pursued.

7) Actuality processing (real/continuous/resilient/fuzzy): ongoing data acquisition and processing should be able to continuously access and adjust the data picture to the real live enterprise truth. To have resilient processing (vs. expecting consistency or exact values), data processing should embrace data ranges and the inconsistencies that will occur between data, models (inter- and intra-), reality, etc., and develop (automated) strategies and methods for detecting and working with exceptions, ranges, and thresholds and escalating more serious issues. That may include automated discrepancy monitoring and analysis and criticality weightings based on thresholds, risks, and potential impacts. While data cleansing can remove some of the dirt, rather expect issues to occur and have measures and thresholds in place to detect and govern these and processing that can work with ambiguity such as semantic imprecision [28].

8) Analytics: data forms the basis for EA decisions. Data-centric processing and analysis capabilities are available for the present, past, and planned enterprise states to determine alignment to expectations. Digital KPIs, dashboards, reports, and visual data analytics enable investigation and exploration of EA-related views, perspectives, viewpoints, and any other factor of interest (X-Factors) to contribute to understanding and insights on various EA factors of interest to a stakeholder.

9) Actionable: data is leveraged to support decisions and governance, enabling responsive and predictive adaptation and evolution of the enterprise to a futures state.

10) Automation/Intelligence: Data is leveraged for automation to reduce sources of error and improve effectiveness and efficiency. For example, business process management systems and business and IT rules can be utilized. Intelligence via data-centric machine learning is integrated where possible to improve, support, or automate (human and software agent) decision making.

11) Traceability and Logging: mistakes will happen, and people and the enterprise can learn from mistakes. To embrace this fact, changes to data, elements, artefacts, and all actions with their associated agents are tracked (and versioned if appropriate), logged, and traced in order to be able to investigate and resolve potential issues that might arise.

C. D^2F Key Activities

Various (ongoing) human and IT activities are involved to apply and maintain D^2F. We use the term activities instead of processes, as processes have a clearly-defined goal and workflow and can be documented with specified artifacts, whereas activities can be agile and integrated where and when needed in whatever agile method is currently being used and done in any order deemed appropriate. They can be recurring and continuous to maintain D^2F capabilities.

Figure 5. Digital Diamond Framework (D^2F) activities.

As shown in Figure 5, key D^2F activities include:

1) Data Acquisition: ensures necessary and desired (meta-)data is collected, characterized, and accessible.

2) Data Processing: ensures data is cleansed, filtered, prepared, and transformed into expected (standard) formats.

3) Data Synthesis: aggregates and correlates data from various repositories for a specific purpose, such as providing data needed for a certain viewpoint or dashboard.

4) Data Analysis, Visualization, & Exploration: involves agents (human or software) exploring, forming questions or hypotheses, utilizing various data and visualization analysis techniques from certain perspectives and viewpoints to address the concerns of various stakeholders, developing solutions, detecting opportunities and develop insights.

5) Adapting & Evolving: directing and commissioning change, usually involving the previous activity (4), be it adjustments to align or to evolve the enterprise, its EA, or its supporting infrastructure. It may utilize effectors available in the enterprise environments and/or human efforts via initiating projects or enacting processes.

6) Modeling & Configuring: involves creating and maintaining (hyper) business, operational, architectural, product and other models (which can be logical in nature) and provide some simplification of some structure of interest and associated properties. These can be for a pre-development, development, or operational stage. While maintaining models is burdensome, incorrect models are worse, thus the basis for models should be tied into current enterprise data. Configuring involves (re)arranging enterprise elements in various ways to optimize certain desired properties.

7) Testing & Simulating: involves testing and/or simulating hypotheses and models with potential real or generated data on virtual or real staged or production elements. The goal is to develop an improved basis for decisions affecting elements of the EA, and might include concepts such as a delivery pipeline. These activities become more important as the systems increase in complexity. Without the data from these activities, decision making at the higher levels can be hampered.

8) Management & Governance: includes setting the vision and goals for the enterprise, perceiving and acting on opportunities and risk, planning, organizing, directing, and managing enterprise resources, making decisions, performing assessments, determining compliance with policies and alignment with expectations, supporting the development and application of strategies, best practices, policies, and guidelines, and making this information available to the enterprise. It is both top-down and bottom-up in its approach. It includes a feedback loop for continuous improvement or adjustment, enabling the enterprise to learn from mistakes and to optimize its future state. It ensures that logging and traceability of the data used for decisions, the decisions made, and the resulting actions are accessible.

9) Intelligence & Automation: involves developing, maintaining, and optimizing automation processes in the enterprise, including EA analysis activity. Activity to support intelligence builds on automation and includes decision assistance for humans and software agents.

D. D²F Enterprise Facets

Any enterprise concept or element can be a *facet*. To provide further detail on which enterprise facets might be of interest for an enterprise when using D²F, Figure 6 clusters facets (referred to below in italics), near *Key Areas*. Its intent is not to portray every possible facet, or by neglect thereof or apparent inconsistency to negate the entire approach. Rather, it shows that grey or inconsistent areas with which matrix approaches struggle are not as problematic with D²F, since it embraces these types of relations, be they local or holistic in nature. A short explanation of selected facets follows:

Enterprise Environments can involve a *Business* in a *Market* with *Customers*, involving *Projects*, *Processes* (business, development, agile, IT Infrastructure Library), *Products*, and *Services* (business, IT) together with *Actors* organized in *Teams* utilizing *Infrastructure*, *IT* (cloud, microservices, mobile), *Resources*, *Tools*, and *Technologies*. *Entities* can be organizational units or any other enterprise element not already covered by other facets. *Sensors* permit data about changes in the enterprise state to be acquired, while *Effectors* permit desired changes to be applied. *IT Rules* and *Biz* (Business) *Rules* support automation or escalation.

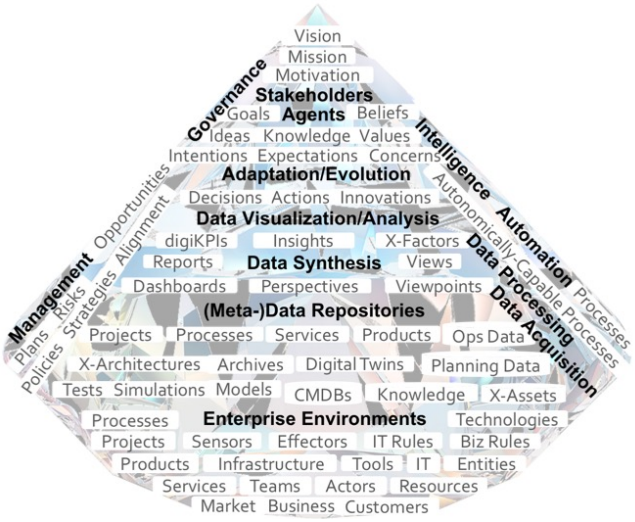


Figure 6. Illustrative enterprise facets when applying D²F.

(*Meta-)Data Repositories* includes data and metadata about *Projects*, *Processes*, *Products*, and *Services* as well as *Planning Data* and *Ops* (Operational) *Data*. *CMDBs* provide data and metadata about the *IT* landscape, *X-Assets* are repositories for data and metadata about other enterprise assets (e.g., program code). *Knowledge* repositories may be used. Archives provide historical data. *Digital Twins* provide a digital representation of real enterprise elements not covered by the above. *X-Architectures* stands for any (enterprise, business, software, IT) architecture, describing the goals and representation of some structure and its properties and involving principles, rules, abstractions, and views. *Models* (conceptual, mathematical, business, data, etc.) are a partial representation of some reality.

Data Synthesis, *Data Visualization*, and *Data Analysis* can be used to develop Insights and can include *digiKPIs* (digital KPIs), *Dashboards*, and *Reports*. *Perspectives* address a particular quality property and have an implicit goal or intention. *Views* (partially) address some concern. *Viewpoints* are a class of views to address associated concerns. *X-Factors* can be qualities, capabilities, properties, aspects, etc. otherwise not addressed by the above.

Adaptation/Evolution includes *Decisions* and *Actions* to respond to disruptions, support change such as enterprise element lifecycle adjustments (acquire, prepare, operate, maintain, retire) as well as discovering and utilizing Innovations and instigating digital transformation initiatives.

Stakeholders/Agents are driven by some *Motivation*, have *Knowledge*, *Values* (what they hold to be good), and *Beliefs* (what they hold to be true), develop *Ideas*, and have future-oriented *Goals* and present-oriented *Intentions* with *Expectations* and *Concerns* they would like addressed,

including a (common) *Vision* (future desired state) for the enterprise and some *Mission* (purpose) it intends to fulfill.

Automation involves *Processes*. In an intelligent enterprise, *Autonomically-Capable Processes* (ACPs) [29] will increasingly be desired and expected. These ACPs can be completely autonomic, involve human interaction, or assist human operators in some fashion. These intelligent ACPs are much more complex than normal business processes.

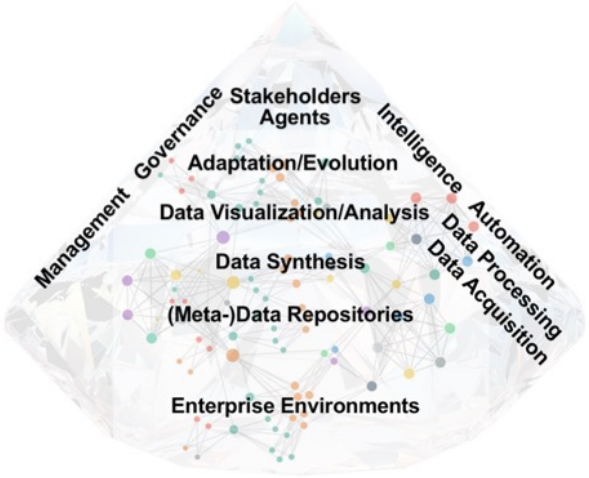


Figure 7. Colored graph showing possible linked facet instantiations.

The random colored node graph superimposed in Figure 7 conceptually illustrates how facet instantiations (data) across various areas could be linked via graph relations (lines in Figure 7) to provide various insights addressing stakeholder concerns. Consequently, queries can be used to find or determine relations that may otherwise not be apparent or would be ignored.

E. D²F Maturity Levels

Because D²F is a digital EAF, to achieve and apply all D²F principles across all levels of any existing large enterprise will require a transformation and enterprises will be in different states of digital transformation. The following Maturity Levels shown in Table II can be helpful to guide and ensure that requisite capabilities are addressed before focusing on higher level capabilities. Each level subsumes the one below.

TABLE II. D²F MATURITY LEVELS

Level	Label	D²F Qualities	Data Perspective
0	Arbitrary	-	-
1	Digitized	Digitized Meta	Data Acquisition
2	Linked	Dynamicity Linked	Data Processing
3	Analytical	Hyper-models Analytics Actuality processing	Data Synthesis Data Analysis Data Visualization
4	Adaptive	Holistic Actionable Traceability/Logging	Effectors
5	Autonomic /Intelligent	Automation Intelligence	Automation Intelligence

F. D²F Roadmap

Each enterprise and its IT infrastructure are unique. The digital nature of D²F requires access to (semantically annotated) data repositories and software functionality. Various methods and best practices related to enterprise application integration (EAI), EA and other IT tools, protocol standards and formats (JSON/REST), and data visualization techniques can be leveraged to realize D²F in an enterprise.

IV. D²F EA TOOL IMPLEMENTATION

This section describes a D²F EA tool prototype we developed. In contrast to the professional EA tools discussed in the prior section, this tool is not intended to be a professional EA tool nor to provide or compete with any of their features. Rather, the focus and point of this prototype is to demonstrate the practical feasibility of the D²F approach and to show one possible implementation approach. D²F approach is independent of any specific EA tool, and any EA tool could incorporate D²F or some subset thereof. ArchiSurance data is used here to help illustrate the implementation.

A. D²F EA Tool Requirements

To develop our D2F EA tool and show its feasibility, we solicited our requirements from sources in the literature to ensure we use a sufficiently generalized set of requirements.

1) EA visual requirements: Naranjo et al. [30] describe general visual requirements for EA tools summarized in Table III. We oriented our implementation on these EA tool visual requirements.

TABLE III. EA TOOL VISUAL REQUIREMENTS

ID	Name
MVE	Maximize Visual Economy
EVE	Enhance Visual Expressiveness
MN	Minimize the Noise
NI	Navigate and Interact
KC	Keep the Context
DNI	Derive New Insights
GSC	Guarantee Semantic Correspondence

2) EA analysis requirements: Naranjo et al. [30] describe general analysis requirements that EA tools should support, and is summarized in Table IV. We oriented our implementation on these EA tool analysis requirements.

TABLE IV. EA TOOL ANALYSIS REQUIREMENTS

ID	Name
IRD	Identify and Relate Domains
EKE	Emphasize Key Elements
OFI	Offer a Focus of Interest
FSD	Facilitate Structural Diagnosis
DSC	Display Semantic Characteristics
UAQ	Uncover Architectural Qualities
PFM	Provide a Flexible Metamodel

TABLE V. IMPLEMENTED EA VIEWPOINTS AND ASSOCIATED STAKEHOLDER CONCERNS FROM [31]

ID	Name	Concerns
V-107	Business application technical or business status	See subviewpoint
V-107.1	Complexity of business applications	C-124 Reduce application landscape complexity
V-108	Physical component status	See subviewpoint
V-108.2	Evaluate potential removal candidates	C-129 Remove monolithic applications
V-108.4	Increase transparency of application landscape	C-34 Look of long-term application landscape C-62 Determine business capabilities of application landscape C-119 Definition of target application landscape C-157 Detection of consolidation potential
V-109	Transparency about which physical components are used by which business applications	C-41 Determine used infrastructure for applications C-147 Merge two different application landscapes C-169 Architectural assessment of change requests
V-111	Business application status within a specific business capability	See subviewpoint
V-111.1	Use of business applications	C-62 Determine business capabilities of application landscape C-142 Map business applications to business capabilities
V-111.2	Relation between business capability and business application	C-147 Merge two different application landscapes C-157 Detection of consolidation potentials
V-113	Technical or business status of business application	See subviewpoint
V-113.1	Complexity of business applications	C-124 Reduce application landscape complexity
V-114	Layer diagram to visualize IT landscape status	C-98 Determine shutdown impact of infrastructure component
V-119	Number of infrastructure components used by a business application	C-120 Measure changes in application landscape C-124 Reduce application landscape complexity C-141 Get transparency about IT costs

.

the configurable mapping of EA data to visualization types and a filtering capability. For determining initial viewpoints to consider implementing in our prototype and prove the feasibility of D²F, we used Khosroshahi et al. [31] as a reference. It provides a best-practice Enterprise Architecture Management Pattern Catalog (EAMPC) that describes concern-specific viewpoints (V-Patterns), which can be used as best-pattern reusable building blocks to tailor an organization-specific EAM approach. These viewpoint patterns (V-patterns) were analyzed, and due to project time and resource constraints we limited our initial support to the subset shown in Table V. This in no way indicates an inherent limit of D²F nor the EA tool to not support the other viewpoints, but rather this set is sufficient to demonstrate key viewpoint capabilities and show that D²F can be practically applied. Those not initially implemented due to time and resource constraints for the prototype are:

- V-110 Business application usage
- V-112 Application costs
- V-115 Number of interfaces per business application
- V-116 Number of redundant business functions per business application
- V-117 Number of business applications used within a functional domain
- V-118 Standard conformity of business applications
- V-120 Functional scope of a business application

4) D²F-based requirements: Requirements based on the D²F principles and qualities described in Section III.B and listed in Table V should be shown to be feasible or supported and P:Trc (shown in italics) were not specified or yet implemented for the prototype due to time and resource constraints.

TABLE VI. D²F SUPPORT REQUIREMENTS

Acronym	Principles and Qualities
P:Dig	Digitized
P:Meta	Meta (self-describing)
P:Lnkd	Linked
P:Dyn	Dynamicity
P:Hol	Holistic
P:Hyp	Hyper-models
P:ActProc	*Actuality processing*
P:Anyltcs	Analytics
P:Act	*Actionable*
P:AI	*Automation/Intelligence*
P:Trc	*Traceability/Logging*

5) EA data model requirements: the tool should support the import of common EA information models and flexible information schemas. In particular, the popular ArchiMate [32] EA modeling language, which can model the motivation, structures, and behavior related to strategy, business, application, technology, physical, and implementation aspects for business organizations, and BPMN, which can model business processes at a technical detailed level.

B. D²F EA Tool Architecture

The following architectural principles, based on the expected features and functionality and in consideration of the requirements mentioned above in Section IV.A, played a significant role in structuring the implementation solution:

- AP:enterprise information model agnostic
  - Supports EA information model data interchange.

- Supports flexible meta-models or schemas.
- AP:flexible metadata relation and tagging capabilities
  - Enables additional knowledge to be flexibly joined to any elements/views.
- AP:flexible visualization
  - Support various visual types and parameterization.
  - Support the configuration and mapping of EA data to visualization types and filtering.
  - Provide interactive and dynamic visual analytical capabilities.
- AP: client web-centric cross-platform access
  - Supports access and involvement of diverse stakeholders from anywhere on any platform.
- AP: cloud data/service backend access
  - All data needed for EA tool is accessible and integratable, to minimize the inconsistency and redundancy issues resulting from locally-installed applications or isolated data.
- AP:internal common simple data format (JSON)
  - All data can be converted to/from this format.
- AP: graph database
  - Supports flexible (re)structuring of data dependencies between elements via a graph structure.

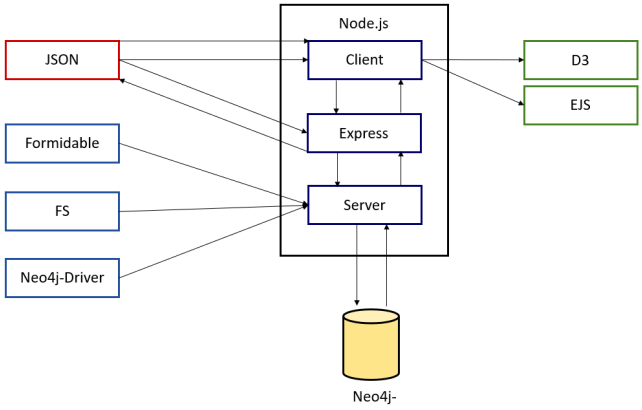


Figure 8. D²F EA Tool Architecture.

As shown in the diagram in Figure 8, the following technologies were chosen:

- Node.js was chosen as a runtime environment due to its popularity and to maintain front and backend in JavaScript.
- Neo4j: graph database that supports the Cypher Query Language (CQL). Neo4j was chosen due to its popularity as a graph database.
- D3: JavaScript library for dynamic and interactive data visualizations, chosen due to its popularity and the available functionality.
- EJS: embedded JavaScript templating engine.
- Express: Node.js web application server framework handling GET/POST requests from the client.
- Formidable: Node.js module for parsing form data
- FS: Node.js file system module

C. D²F EA Tool Implementation

On the main page when loaded by a browser, the following four main tabs as shown in Figure 17 are provided:

- *Load data*: provides the ability to import data from various sources.
- *Connection*: provides the ability to manage and connect data with metadata
- *Analysis*: provides pre-defined EA Viewpoints and filtering options.
- *Visualization*: provides a flexible visualization option to provide custom search and filtering options

Information about an element can be retrieved by clicking on its ID within a table or in a visualization. A new view is opened which shows the ID, Name, and Creation timestamp as shown in Figure 18.

The following Cypher statement supports data retrieval for this view:

```
MATCH (n{id:{idParam}})
RETURN n
```

1) Load data tab. This tab supports importing metadata, infrastructure data, BPMN diagrams, and ArchiMate data in JSON format (see Figures 17 and 9). Any other formats such as XML must be converted beforehand and any special characters in keys or values (such as punctuation symbols) removed. Metadata can be imported as well from schema.org (e.g., we utilized PhysicalComponent and BusinessProcess) or similar sites. Since some of the metadata may not be applicable (since they may cover various domains or branches of industry), we provide a whitelist and blacklist in config.json in order to exclude inapplicable elements and thus reduce metadata clutter. The whitelist is for explicit inclusion with the assumption that the rest is not applicable, whereas the blacklist specifies elements to remove and allowing the rest.


```
{
    "archimatemodel":{
        "xmlns:xsi":"http://www.w3.org/2001/XMLSchema-instance",
        "xmlns:archimate":"http://www.archimatetool.com/archimate",
        "name":"Archisurance",
        "id":"11f5304f",
        "version":"3.1.1",
        "folder":[
            {
                "name":"Business",
                "id":"8c90fdfa",
                "type":"business",
                "folder":[
                    {
                        "name":"Actors",
                        "id":"fa63373b",
                        "element":[
                            {
                                "xsitype":"archimateBusinessInterface",
                                "id":"1544",
                                "name":"mail"
                            },
                            {
                                "xsitype":"archimateBusinessInterface",
                                "id":"1540",
                                "name":"phone"
                            },
                            {
                                "xsitype":"archimateBusinessInterface",
                                "id":"1542",
                                "name":"GIM"
                            },
                            {
                                "xsitype":"archimateBusinessInterface",
                                "id":"1538",
                                "name":"e-mail"
                            },
```


Figure 9. Example ArchiMate data.

Each element has a name, creation date, and a unique id to avoid inconsistencies. Metadata should also provide the subclass, type, description, and layer.

ArchiMate data involved additional folders and subfolders analogous to its layers: Business, Application, Technology, Motivation, Implementation and Migration, Relations and Views. While software to transform an ArchiMate model to a Neo4j database model exist, we were not satisfied with the conversion results using an Archi plugin [33]. The resulting structure differed from the original model while relations were converted into nodes. We thus chose to do our own mapping. The information about ArchiMate layers are stored via a property in the Neo4j database. One challenge was to find the individual elements in the various subfolders. The following Cypher statement is used to import ArchiMate data:

```
CREATE (node:Archi
{foldername:{folderNameParam}, folderid:
{folderidParam}, foldertype: {foldertypeparam},
instancename:{instanceNameParam},
instancenid:{instanceIdParam}, id: {nameParam},
identifier:{idParam}, name:{xsitetypeParam},
time:{timeParam}})
```

2) Connection tab. Metadata can be added or changed as seen on the right side of the screenshot shown in Figure 19. Once one of the fields is active, applicable context-specific recommendations are provided. A single node can be associated with metadata by providing a node ID in the top field, providing a Meta field, and then pressing the upper "Create metaconnection" button. Similarly, to associate a set of nodes, the bottom Name field provides a category to select the set of nodes, and the bottom Meta field specifies the metadata node to which it should be associated.

```
MATCH (a {id: {originalIdParam}})
SET a.meta = {metaParam}
RETURN a, {originalIdParam: nodeMetaId,
metaParam: metaMetaId}
```

As seen to the left in Figure 20, metadata associations are visualized with data elements as blue squares and metadata as green triangles. The following Cypher statement supports this visualization:

```
MATCH (n)
WHERE EXISTS (n.meta) AND NOT ((n:Meta) OR
(n.meta = "To be specified"))
RETURN (n)
```

3) Analysis tab. This tab provides those predefined EA viewpoints listed in Table V. In our implementation of these viewpoints, options for filtering the elements by "IT Infrastructure", ArchiMate, or All are provided via the respective "Show" buttons in the upper left of the view in Figure 21.

a) V-107 Business application status. In this viewpoint business applications are clustered by organizational unit and can be allocated multiple times, while color is used to visualize some status such as complexity that can be based on various metrics. Variants include architectural fit or architectural health.

V-107.1 Complexity of business applications was implemented (see screenshot in Figure 21), which deals with the following stakeholder concern:

- C-124 Reduce application landscape complexity

In our implementation, the complexity is based on the metric of the number of associations between architectural elements. These colors are associated with complexity: green (low), yellow (medium), red (high), white (unknown). In config.json the thresholds can be adjusted.

To realize this viewpoint, the following Cypher statement is used to find all applications `a` and their associated business unit(s) `b`:

```
MATCH (a) -[] ->(b)
WHERE ((a.name ="Application") OR
(a.name="BusinessService") OR
(a.name="ApplicationFunction") OR
(a.name="ApplicationService") OR
(a.name="SystemSoftware") OR
(a.name="InfraStructureService"))
AND ((b.name ="BusinessActor") OR
(b.name="BusinessObject") OR
(b.name="BusinessProcess") OR
(b.name="Project"))
RETURN a, b, labels(a), labels(b) ORDER BY b
ASC)
```

The following Cypher statement finds applications that are only indirectly associated via some other node. Due to the time needed to execute, it is limited to the first 500:

```
MATCH (a) - [] ->(c) - [] -> (b)
WHERE ((a.name ="Application" OR a.meta
="SoftwareApplication" OR a.meta
="MobileApplication" OR a.meta =
"WebApplication") AND b.name ="Project")
RETURN a, b, labels(a), labels(b) ORDER BY b ASC
LIMIT 500')
```

The following Cypher statement then counts the number of relations for each found node:

```
MATCH (c {id:{idparam}})-[r]-()
RETURN count(r)
```

b) V-108 Physical Component Status. In this viewpoint business applications are clustered by business capability, and physical components can be assigned to a business application. Color is then used to convey the technical status of a physical component.

V-108.2 Evaluate potential removal candidates was implemented (see screenshot in Figure 22), which deals with the following stakeholder concern:

- C-129 Remove monolithic applications

Via the respective "Show" buttons at upper left, the elements can be filtered by "IT Infrastructure", ArchiMate, or All.

In contrast to [33], in our implementation of this viewpoint we show all elements that are isolated and that are not Metadata, and for this we use the Cypher statement:

```
MATCH (a)
WHERE NOT(a)-[]-() AND NOT a: Meta
RETURN DISTINCT a, labels(a)
```

V-108.4 Increase transparency of application landscape was implemented (see screenshot in Figure 23), which deals with the following stakeholder concerns:

- C-34 Look of long-term application landscape

- C-62 Determine business capabilities of application landscape
- C-119 Definition of target application landscape
- C-157 Detection of consolidation potential

The following Cypher statement finds infrastructure components based on metatags `b` which are associated with capability `c`:

```
MATCH (n) - [] - (b) - [] - (c)
WHERE (b.meta = 'SoftwareApplication' OR b.meta
= 'MobileApplication' OR b.meta =
'WebApplication' OR b.foldername = 'Application'
OR b.name = 'Software ' OR b.name =
'Application') AND (n.foldername = 'Technolo-
gy' OR n.name = 'PhysicalComponent' OR n.meta =
'PhysicalComponent') AND (c.meta = 'Capability'
OR c.foldername = 'Business' OR c.name =
'Capability')
RETURN n, b, c, labels(n), labels(b), labels(c)
ORDER BY c ASC
```

4) V-109 Transparency about used physical components for business applications. In this viewpoint, which physical components are used by which business applications are shown (see screenshot in Figure 24). Since multiple relations can exist between elements, we chose to use graphs using the D3 forced graph layout. Green triangles are used for physical components and yellow crosses for applications. The viewpoint deals with the following stakeholder concerns:

- C-41 Determine used infrastructure for applications
- C-147 Merge two different application landscapes
- C-169 Architectural assessment of change requests

To realize this viewpoint, the following Cypher statement is used:

```
MATCH (n) - [r] - (b)
WHERE ((n.name ="Application" OR n.foldername
="Application" OR n.name ="Software" OR n.meta
="SoftwareApplication" OR n.meta
="MobileApplication" OR n.meta =
"WebApplication") AND (b.name =
"PhysicalComponent" OR
b.meta="PhysicalComponent" OR b.foldername
="Technology"))
RETURN n, r, b, labels(n), labels(b)
```

5) V-111 Business application status within a specific business capability. In this viewpoint, a matrix is used to depict business capabilities as rows and business applications as columns, while a business or technical status is depicted at their intersection.

Viewpoint 111.1 Use of business applications was implemented (see screenshot in Figure 25), which deals with the following stakeholder concerns:

- C-62 Determine business capabilities of application landscape
- C-142 Map business applications to business capabilities

To realize this viewpoint, the following Cypher statement is used:

```
MATCH (n) -[r]- (b)
WHERE (n.foldername = "Business" OR n.meta
="Capability" OR n.name = "Capab-ility") AND
(b.name = "Application" OR b.foldername =
"Application" OR b.meta = "SoftwareApplication"
OR b.meta = "MobileApplication" OR b.meta =
"WebApplication")
RETURN n, r, b, labels(n), labels(b)
```

V-111.2 Relation between business capability and business application was implemented (see screenshot in Figure 26), which deals with the following stakeholder concerns:

- C-147 Merge two different application landscapes
- C-157 Detection of consolidation potentials

6) V-113 Status of business application. In this viewpoint business applications are listed in a tabular format with a column that indicates a business or technical status.

Viewpoint 113.1 Complexity of business applications was implemented (see screenshot in Figure 27), with the number of relations used as a metric for depicting the complexity of a business application. These colors are associated with complexity: green (low), yellow (medium), red (high), white (unknown). In config.json the thresholds can be adjusted. The viewpoint deals with the following stakeholder concern:

- C-124 Reduce application landscape complexity

To realize this viewpoint, the following Cypher statement is used:

```
MATCH (a)-[c]-()
WITH a, count(c) as relation
WHERE (a.meta ="SoftwareApplication" OR a.meta
="MobileApplication" OR a.meta =
"WebApplication" OR a.name="Application" OR
a.name="Software" OR a.foldername
="Application") AND NOT a: Meta
RETURN a, relation, labels(a)
```

7) V-114 Layer diagram to visualize IT landscape status. In this viewpoint, business processes are depicted in the top layer, supported by various business applications in the middle layer, and the required physical components are visualized in the bottom layer (see screenshot in Figure 28). In contrast to Khosroshahi et al. [31], we chose to use colors and symbols instead of spatially separate layers to differentiate the layers, using green triangles for physical components, yellow crosses for applications, and red circles for business processes. The arrows in the relations show the direction of information flow. The viewpoint deals with the following stakeholder concerns:

- C-98 Determine shutdown impact of infrastructure Component

To realize this viewpoint, the following Cypher statement is used:

```
MATCH (n) - [] -(b) - [] - () - [] - (c)
WHERE ((n.meta ="PhysicalComponent" OR n.name
="PhysicalComponent" OR n.foldername
="Technology") AND' (b.foldername ="Application"
OR b.name ="Software" OR b.meta
="SoftwareApplication" OR b.meta
="MobileApplication" OR b.name =
"WebApplication") AND (c.foldername = "Business"
AND c.instancename = "Processes"))
RETURN n, b, c
```

8) V-119 Number of infrastructure components used by business application. This viewpoint depicts the number of infrastructure components used by a specific business application (see screenshot in Figure 29), using the number and variety of components as a measure. It can be sorted by clicking on a column header. The viewpoint deals with the following stakeholder concerns:

- C-120 Measure changes in application landscape
- C-124 Reduce application landscape complexity
- C-141 Get transparency about IT costs

To realize this viewpoint, the following Cypher statement is used to find all physical components or applications that are used by a business application:

```
MATCH (n) - [] - (b)
WHERE ((n.meta ="PhysicalComponent" OR n.name
="PhysicalComponent" OR n.foldername
="Technology") AND (b.foldername ="Application"
OR b.name ="Software" OR b.meta
="SoftwareApplication" OR b.meta
="MobileApplication" OR b.meta =
"WebApplication" OR b.name="Application"))
RETURN b.id
```

Then using the application ID, all components and applications associated with it are counted:

```
MATCH (b {id: {idparam}}) - [r]- (n)
WHERE (n.name ="PhysicalComponent" OR
n.foldername ="Technology")
RETURN b.id, count(r), labels(b)', {idparam:
record._fields[0] }
```

9) Visualization tab. The fourth and final tab provides customizable graph-based visualization as shown in the screenshot in Figure 30, supporting analysis and exploring. Elements are differentiated by both color and shape. Initially only the first 200 nodes are loaded to limit the response time, since initially one is unclear about the actual interest of the user.

The Cypher statement used to support this visualization is:

```
MATCH (n) - [r] - (b)
WHERE NOT n:Meta
RETURN n, r, b, labels(n), labels(b) LIMIT 200
```

The resulting JSON is then processed by the D3 JavaScript library using forced layout, and an SVG is created. Each node supports mouseover, mousedown, mouseup, and mouseout events. The interface supports zoom. Search is supported in the upper right of the visualization tab, and supports any Cypher query, while past queries are shown in a dropdown list (see Figure 10). Pressing search sends a POST to app.js.

Filtering is provided to support users who are not familiar with Cypher. It supports element labels, names, and IDs via checkboxes, while metadata is not supported. First a label from the list of possible labels is selected as shown in Figure 11.

The Cypher statement used to support filtering is:

```
MATCH (n)
WHERE NOT n:Meta
RETURN DISTINCT labels(n)
```

After a label is selected, a name selection dialog as shown in Figure 12 is displayed. Then a list of matching IDs is offered as shown in Figure 13.

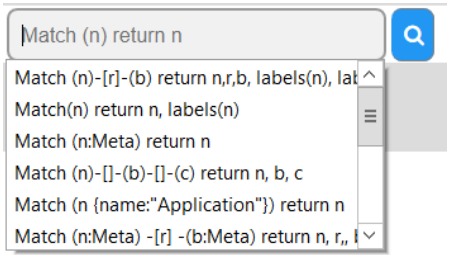


Figure 10. Search functionality.

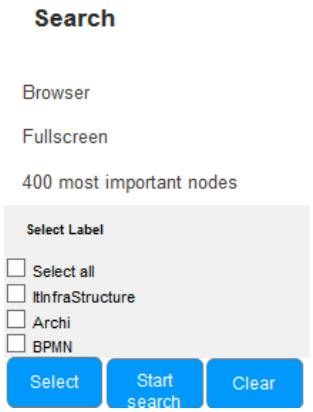


Figure 11. Filtering label selection dialog.

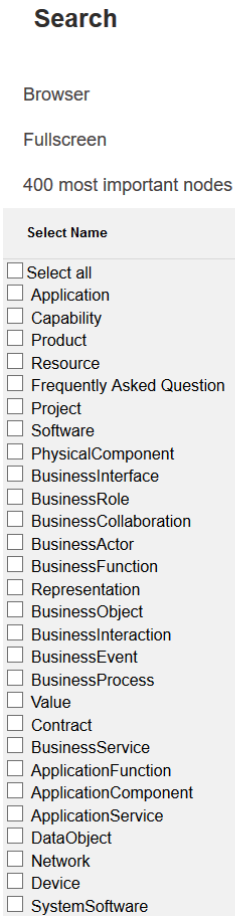


Figure 12. Filtering name selection dialog.

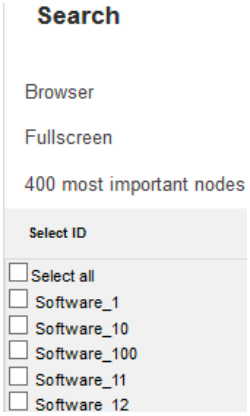


Figure 13. Filtering ID selection dialog.

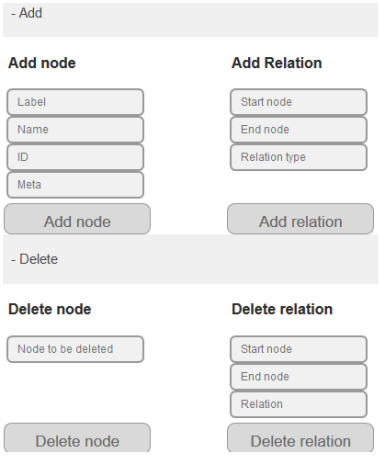


Figure 14. Dialog for manually adding or deleting a node or relation.

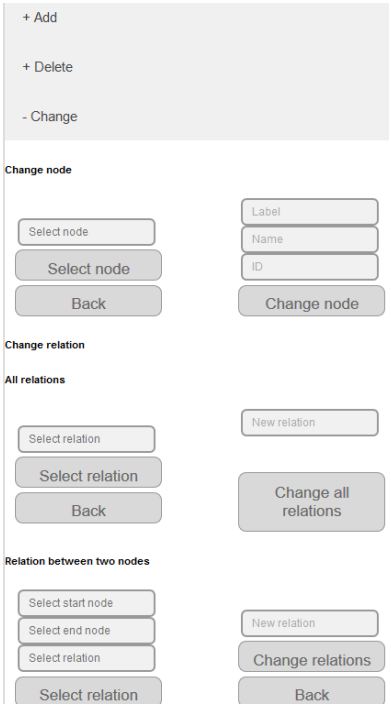


Figure 15. Dialog for manually changing a node or relation.

Adding or deleting a node or relation is also supported via the dialog shown in Figure 14, while changing a node or relation is supported with the dialog shown in Figure 15.

D. D²F EA Tool Validation

To validate the implementation against requirements, we refer to the requirements described in Section IV.A. As to EA visual requirements (see Table III):

- Maximize Visual Economy (MVE): the implementation was able to demonstrate that concepts can be differentiated with a concrete syntax for specific concepts, e.g., with colors and shapes in V-109 (Figure 24) and V-114 (Figure 28).
- Enhance Visual Expressiveness (EVE): multiple visual attributes can be used together to assist with differentiating concepts, e.g., both colors and shapes were used in V-109 (Figure 24) and V-114 (Figure 28) to differentiate the same concepts. ´
- Minimize the Noise (MN): only a single ID was used to identify an element visually, minimizing irrelevant information (Figure 20).
- Navigate and Interact (NI): various common user navigation techniques support analysis.
- Keep the Context (KC): we applied self-organizing layouts to deal with placement and relatedness issues in large models (Figure 20).
- Derive New Insights (DNI): our implementation supports new insights via ad-hoc queries, e.g. via Cypher statements (Figure 10).
- Guarantee Semantic Correspondence (GSC): legends are provided to support graphic and conceptual correspondence (e.g., as in Figure 23).

As to EA analysis requirements (Table IV):

- Identify and Relate Domains (IRD): multiple domains, such as BPMN for process and ArchiMate for EA models can be differentiated and related (see Figure 28).
- Emphasize Key Elements (EKE): visual emphasis or distinction for elements of high structural or semantic importance is provided, for instance by interactive support via node selection (emphasizing relations of a node to its neighbors) or by color (green, yellow, red) as in Figure 21.
- Offer a Focus of Interest (OFI): spatial proximity is used to tie or cluster similar elements (e.g., Figure 24).
- Facilitate Structural Diagnosis (FSD): the visualization tab provides various structural diagnosis opportunities (e.g., Figures 23 and 28).
- Display Semantic Characteristics (DSC): semantic characteristics can be displayed that are not directly in the model, as the viewpoints showed with the relational complexity metrics (Figure 27).
- Uncover Architectural Qualities (UAQ): various supported viewpoints can be helpful in uncovering architectural qualities, such as frequency of use, isolation, etc. (Figure 21).

- Provide a Flexible Metamodel (PFM): our visual model and mapping is decoupled from the conceptual models, allowing for flexible visualization opportunities (Figure 19).

Various EA viewpoints from EAMPC as listed in Table V were demonstrated to be supported, and the rest appear supportable with additional effort, indicating the flexibility of the D²F approach and the EA tool implementation architecture.

Various D²F principles and qualities are shown to be supported, namely digitized data and models, support for flexible metadata (self-describing), the elements are easily linked, dynamicity is supported should an element change, the various models are holistically viewed, hyper-models are supported, and analytics are shown.

In summary, the D²F EA tool was able to fulfill the given requirements with this prototype and show the feasibility and practicality of implementing the Digital Diamond Framework principles in an EA tool. The supported viewpoints showed the diversity of viewpoints and stakeholder concerns that could be addressed with the approach.

V. EVALUATION

A case study and performance measurements provide initial insights into the practicality of our solution. Because of security concerns, it is difficult to receive permission to access company internal IT infrastructure data and be able to publish any related visualization and evaluation data. We thus chose to use fictional data for our evaluation case study.

A. Case Study with ArchiSurance

The Open Group created the ArchiSurance case study [34] as a fictitious example to illustrate the realistic use of the ArchiMate enterprise modeling language. It is considered in the context of the Open Group's TOGAF Framework, which is a method for EA. In this case study, we ignore the TOGAF method aspects and instead focus on the use of the ArchiSurance data. It is modeled using ArchiMate 3 and incorporates EA elements from the baseline and target business, application architecture, data architecture, and technology architecture. The fictitious ArchiSurance is the result of a merger of three previously independent insurance companies:

• Home & Away, specializing in homeowners' insurance and travel insurance

• PRO-FIT, specializing in auto insurance

• Legally Yours, specializing in legal expense insurance

The data consists of 120 elements and 176 relations and is available in an XML data format. We converted the data format to JSON, removing special characters present in the keys. The following screenshot in Figure 31 shows the actor cooperation view for ArchiSurance in the tool ArchiMate.

A sample subset of stakeholder concerns from Khosroshahi et al. [31] as shown in Table VII will be used in conjunction with the Viewpoints of Table IV to show how the ArchiSurance data can be analyzed with the D²F prototype.

TABLE VII. CONCERNS

ID	Name
C-41	Determine used infrastructure for applications
C-62	Determine business capabilities of application landscape
C-98	Determine shut-down impact of infrastructure component
C-124	Reduce application landscape complexity
C-129	Remove monolithic applications

1) Determine used infrastructure for applications (C-41): V-109 can be used as shown with ArchiSurance data in Figure 32 to show what infrastructure is used by which applications.

2) Determine business capabilities of application landscape (C-62): to show the business capabilities of the business applications, V-111 can be used as shown with ArchiSurance data in Figure 33.

3) Determine shut-down impact of infrastructure component (C-98): to show the shutdown impact of an infrastructure component, V-114 can be used as shown with ArchiSurance data in Figure 28.

4) Reduce application landscape complexity (C-124): to reduce the application landscape complexity, the following viewpoints shown with ArchiSurance data can be used to provide insights: V-107.1 (see Figure 34) complexity of business applications, V-113.1 (see Figure 35) complexity of business applications in tabular form by business application, and V-119 (see Figure 35) number of infrastructure components used by a business application.

5) Remove monolithic applications (C-129): V-108.2 Evaluate potential removal candidates provides information useful for this concern. E.g., in Figure 22, the Unix Server 1059 has no relation to any other element, and is thus a possible candidate for removal.

B. Performance and Scalability of Graph Database

An initial characterization of the performance and scalability of our prototype implementation used an Acer Aspire X3-710 notebook with a i5-6400@2.7GHz CPU, 4GB RAM, Win10x64, Firefox, and Neo4j Community Edition (note that the Enterprise Edition this is intended for scalable commercial deployments). Thus, this is not an ideal or typical cloud deployment server setup, but rather a setup to investigate our implementation and characterize how the graph database behaves as we increase nodes. For any serious evaluation, real enterprise data and equivalent cloud and enterprise versions of components and databases should be used.

We measured the latency, CPU utilization, and RAM utilization based on this Cypher query to find all elements with relations as we increased the number of nodes:

```
MATCH (n) - [r] - (b)
RETURN n, r, b, labels(n), labels(b)
```

The resulting measurements are shown in Table VIII and plotted in Figure 16. We note that the latency did not automatically go up as the number of nodes increased from 250 to 1750. As the nodes increase from 250 to 2500, the latency goes from 32 to 79 seconds. Between 1250 to 1500

nodes we note significant changes in CPU utilization, between 1750 and 2000 nodes significant changes in latency, and between 2250 and 2500 nodes significant changes in RAM.

TABLE VIII. QUERY LATENCY (IN MILLISECONDS), CPU UTILIZATION (IN %), AND RAM (IN MIB) AS THE NUMBER OF NODES INCREASES.

Nodes	CPU	RAM (MiB)	Latency (ms)
250	38%	47	32650
500	25%	50	35812
750	26%	57	34000
1000	38%	56	35479
1250	55%	59	34000
1500	82%	63	44495
1750	79%	65	36186
2000	85%	69	60832
2250	87%	72	66644
2500	73%	123	78580

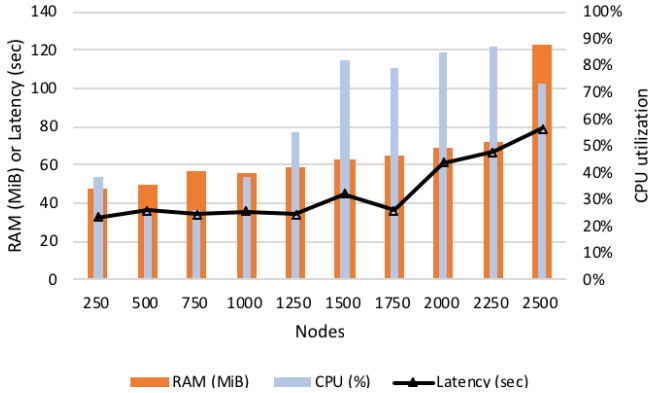


Figure 16. RAM (MiB), Latency (seconds), and CPU (%) vs. number of nodes.

This indicates that especially as CPU utilization increases beyond 50%, performance impacts may become noticeable; thus, deployment planning should consider the maximum number of expected nodes and plan sufficient CPU and RAM with appropriate load-balancing techniques, or attempt to use the Enterprise Edition of Neo4j. On a positive note, below these thresholds increasing the number of nodes does not automatically have an equivalent impact on query latency.

C. D²F Assessment

In summary, the D²F prototype shows that D²F can be supported by any EA tool willing to adopt the D²F principles. Specifically, our prototype furthermore supports the Jugel el al. [8] visual EAM analytic tool findings mentioned in Section I, namely:

View configuration: views can be easily configured to react to dynamic information demands. Furthermore, complete flexibility and interaction for queries is provided.

View consideration: a method is provided via multiple browser tabs, such that several views can be considered in parallel to avoid losing the overall context. Additionally, the views can be kept up to date since they are based on a datastore that can extract, transform, and load enterprise data.

Interacting with views: additional interaction and visual analytics capabilities are provided to help analyze and plan EAs more efficiently.

Communication & collaboration: to better support communication & collaboration, additional knowledge can be added to views via its flexible (meta)tagging capability.

Stakeholder identification: by providing enhanced visual analytic capabilities with real EA data, actual stakeholders that have to be involved in decision-making processes can more readily be identified.

Other EA tool implementations could be implemented to support the D²F, our prototype implementation and performance characterization shown here is primarily intended to show that it is feasible and that graph-based implementation approaches can also work.

VI. CONCLUSION

A sustainable EAF is needed that can embrace the digitized enterprise era. This paper described the Digital Diamond Framework (D²F) to support digitized enterprises with structure, order, modeling, documentation, and analysis to enable more responsive and agile enterprises with better alignment of business plans and initiatives with the actual enterprise state. Key areas, principles, activities, facets, and maturity levels were elucidated.

The D²F EA tool prototype showed the feasibility of D²F, and that an EA tool based on D²F can support important features for enterprises in the digital age: enterprise information model agnostic, flexible meta-models, tagging for adding knowledge to elements/views, easily create and (re)configure interactive dynamic views, support visual analytical capabilities, and via a web-centric implementation diverse stakeholders can be incorporated. The implementation also demonstrated the power of graph databases for accessing and conveying facets in a very flexible manner. Furthermore, hyper- models were demonstrated, incorporating BPMN and ArchiMate models in one repository.

To be of significant value for enterprises in the digital age, integration and customization of EA tools to each specific enterprise is required. Future work includes studying the D²F EA tool prototype in industrial case studies.

APPENDIX

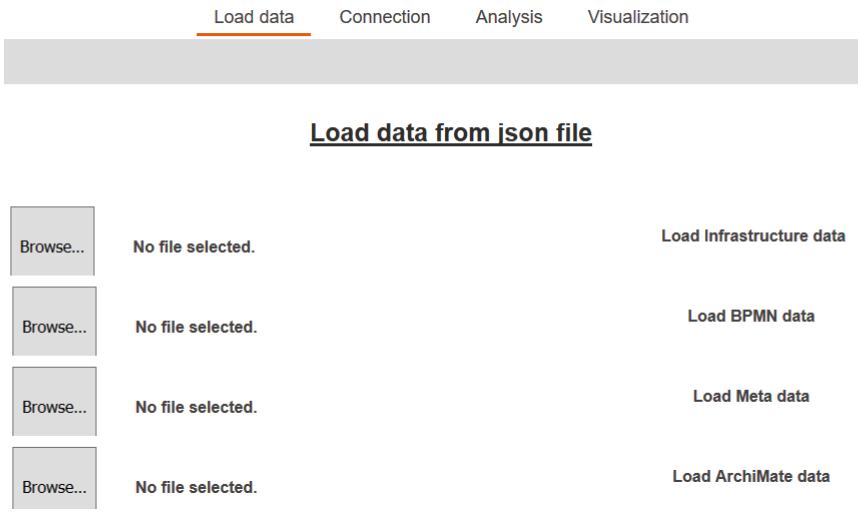


Figure 17. Load data tab and other tabs.

ID	Name	
Unix Server	Device	2018-10-30 16:18:07

Figure 18. Additional element information.

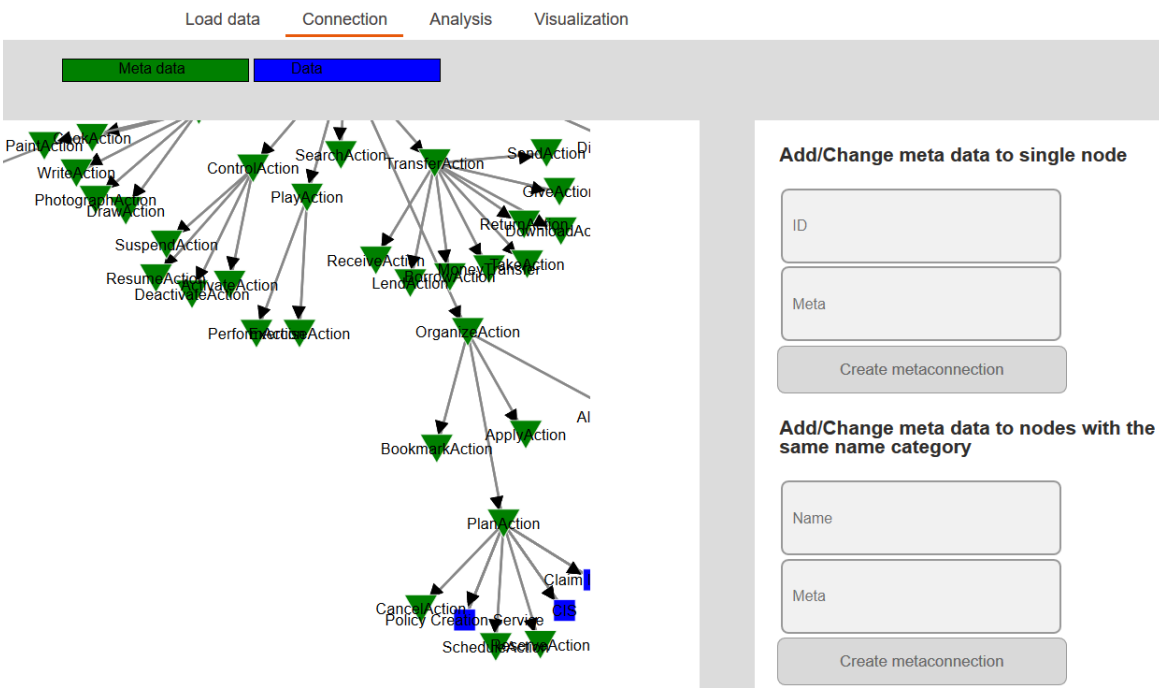


Figure 19. Metadata to data association screen.

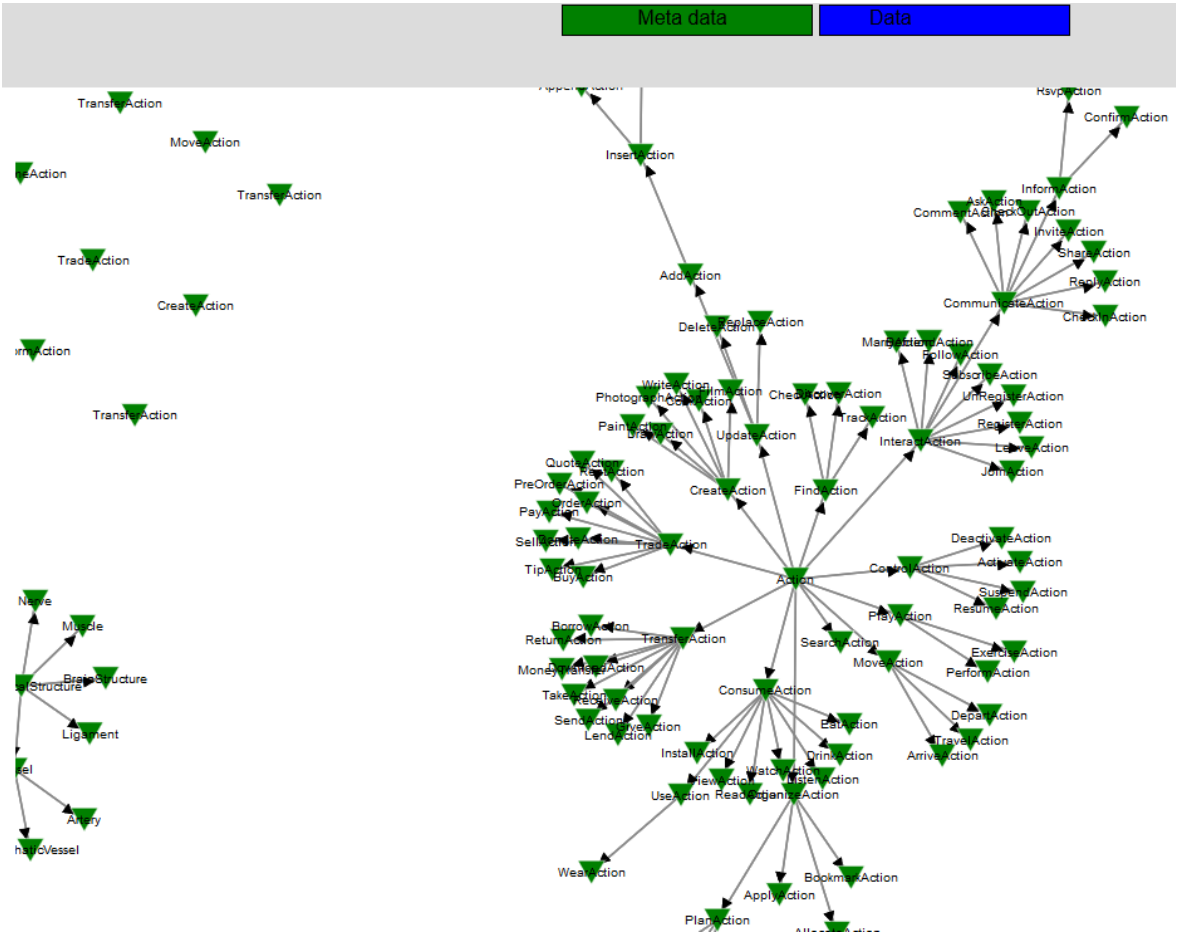


Figure 20. Metadata association visualization.

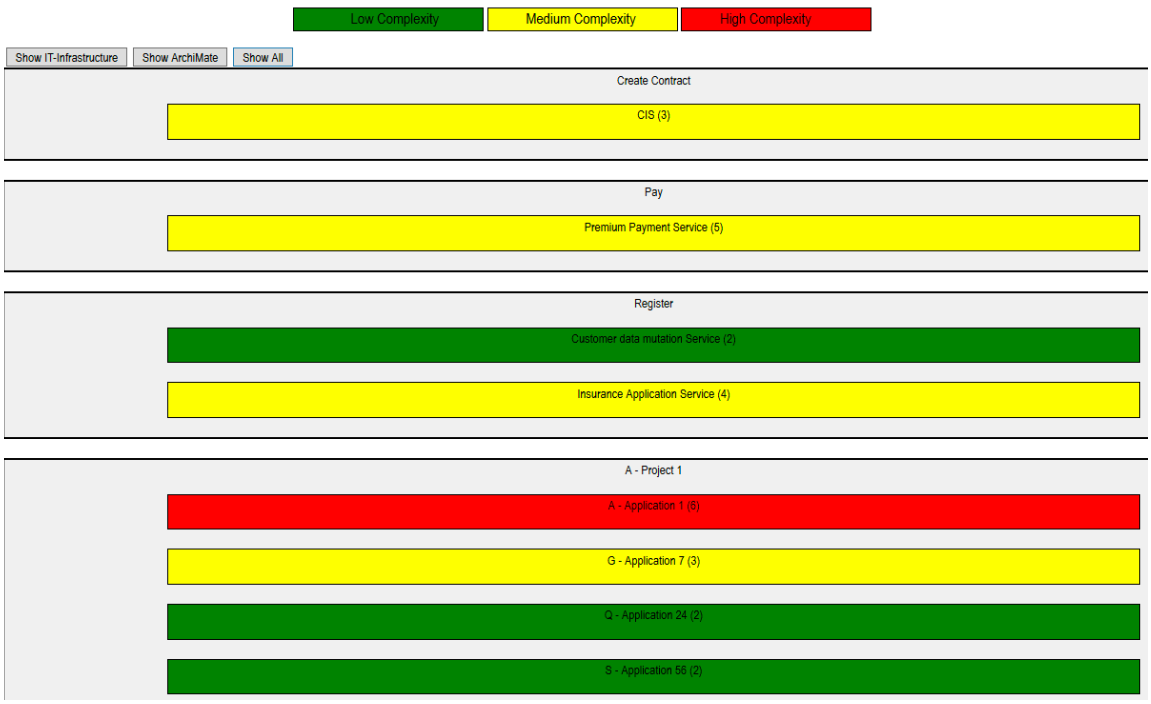
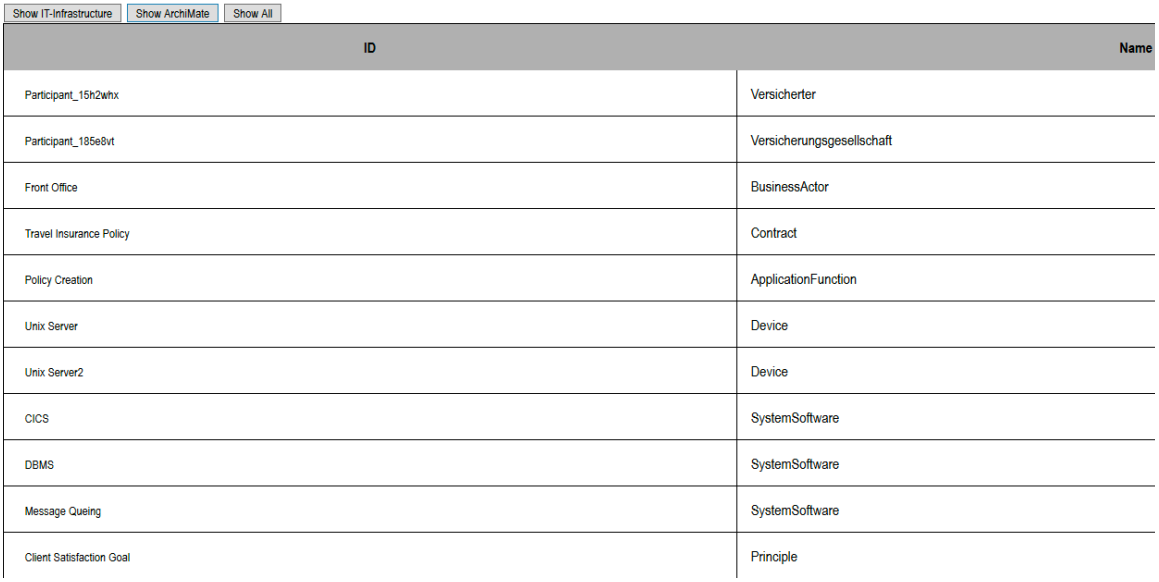


Figure 21. V-107.1 Complexity of business applications.



ID	Name
Participant_15h2whx	Versicherter
Participant_185e8vt	Versicherungsgesellschaft
Front Office	BusinessActor
Travel Insurance Policy	Contract
Policy Creation	ApplicationFunction
Unix Server	Device
Unix Server2	Device
CICS	SystemSoftware
DBMS	SystemSoftware
Message Queing	SystemSoftware
Client Satisfaction Goal	Principle

Figure 22. V-108.2 Evaluate potential removal candidates.

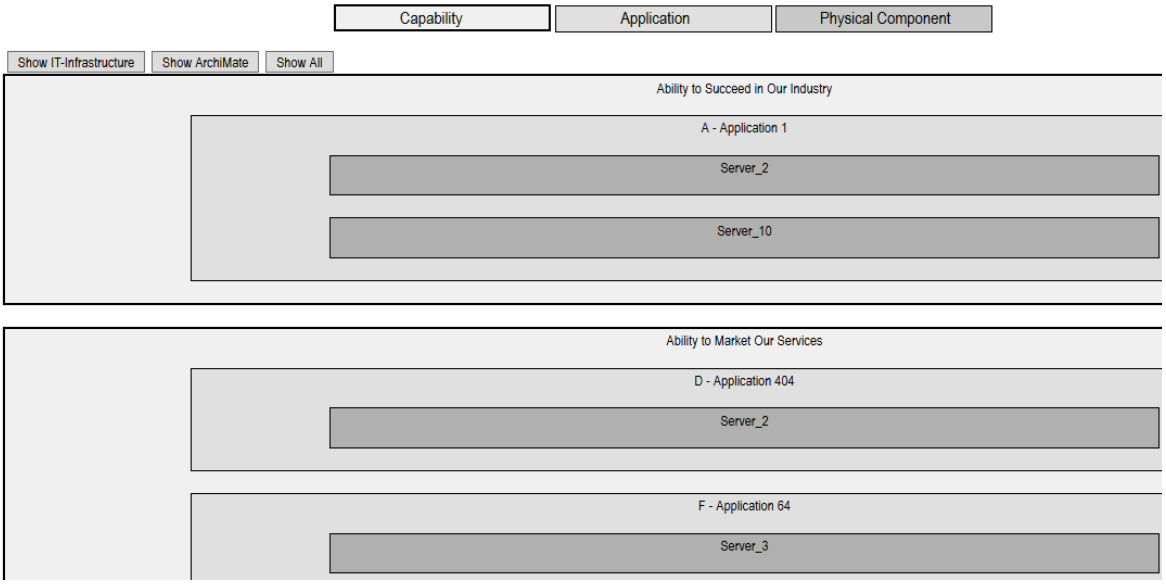


Figure 23. V-108.4 Increase transparency of application landscape.

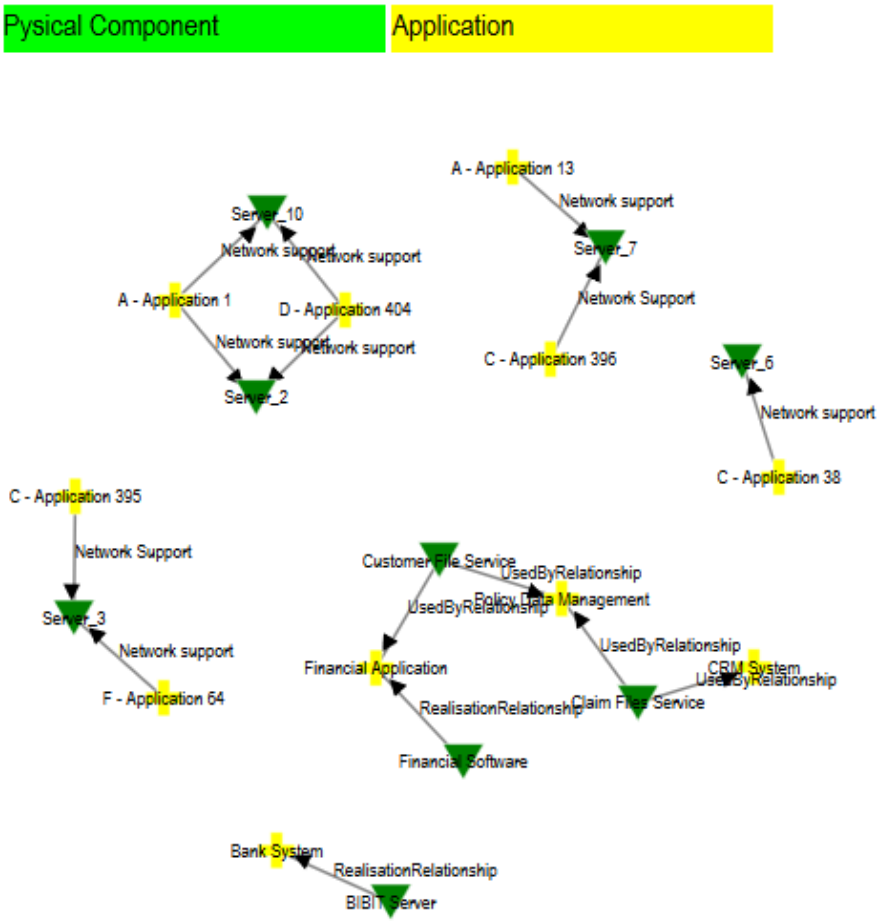


Figure 24. V-109 Transparency about used physical components for business applications.

Show IT-Infrastructure | Show Archi | Show All

Business capability Business application	Insurance Policy Data	Insurance Request Data	Customer File Data	Damage Claim Data	Policy Creation Service	Claim InfoServ	CIS
Legal aid Insurance Policy	X						
Insurance Request		X					
Liability Insurance Policy	X						
Customer File			X				
Damage Claim				X			

Figure 25. V-111.1 Use of business applications.

Show IT-Infrastructure | Show Archi | Show All

Business capability / Business application	Y - Application 722	W - Application 528	U - Application 321	T - Application 225	S - Application 129	R - Application 914	Q - Application 818	I - Application 978
Ability to Succeed in Our Industry	X	X	X	X	X	X	X	X
Ability to Sell Our Products to Public Sector								
Ability to Market Our Products to Public Sector			X			X		X
Ability to Design Services								

Figure 26. V-111.2 Relation between business capability and business application.

Low Complexity | Medium Complexity | High Complexity

Show IT-Infrastructure | Show ArchiMate | Show All

Business Application	Instance	Number of relations
Policy Data Management	ApplicationComponent	7
Insurance Policy Data	DataObject	7
Financial Application	ApplicationComponent	6
Customer Data Access	ApplicationComponent	4
CRM System	ApplicationComponent	4
LAN	Network	4
Home and Away Policy Administration	ApplicationComponent	4
Mainframe	Node	3
Claim InfoServ	ApplicationService	3
Customer File Service	InfrastructureService	3
CIS	ApplicationService	3
Firewall2	Node	3

Figure 27. V-113.1 Complexity of business applications.

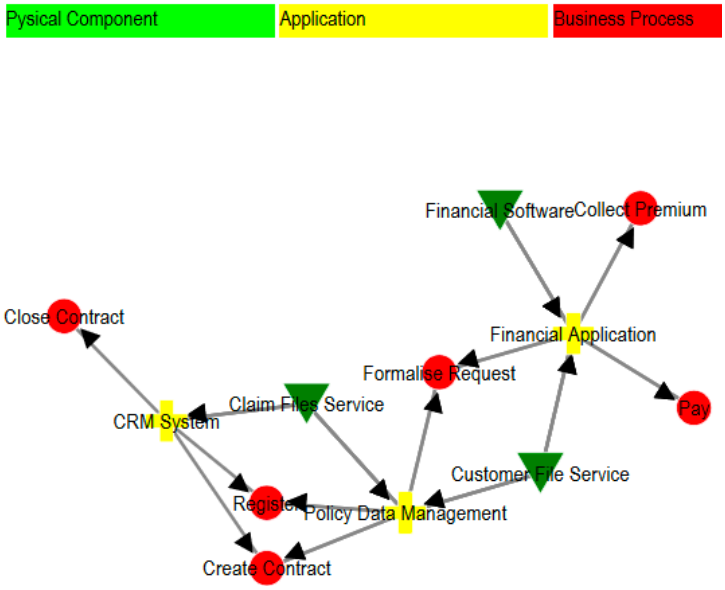


Figure 28. V-114 Layer diagram to visualize IT landscape status.

Show IT-Infrastructure | Show Archi | Show All

ID	Number of relations
Bank System	1
Financial Application	2
Policy Data Management	2
CRM System	1
D - Application 404	2
A - Application 1	2
C - Application 395	1
F - Application 64	1
C - Application 38	1
C - Application 396	1
A - Application 13	1

Figure 29. V-119 Number of infrastructure components used by business application.

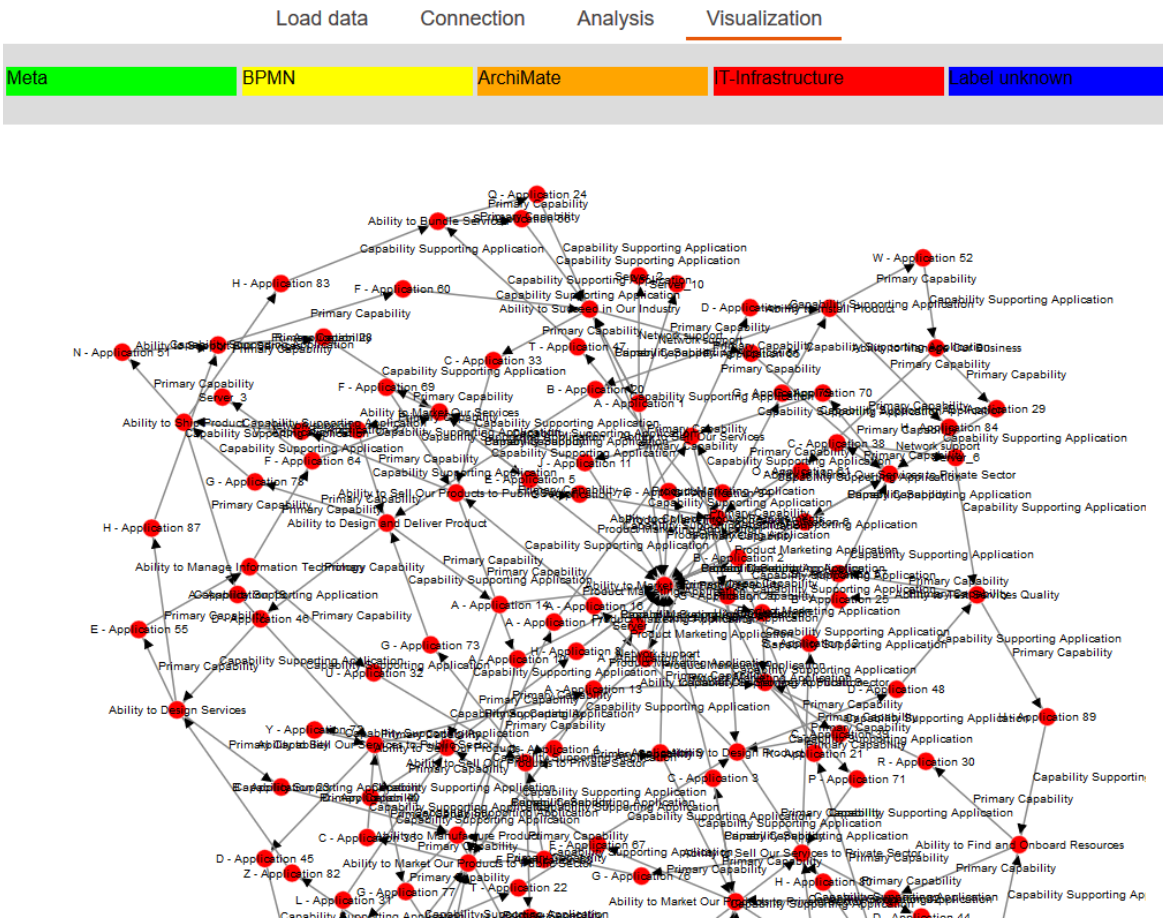


Figure 30. Visualization tab.

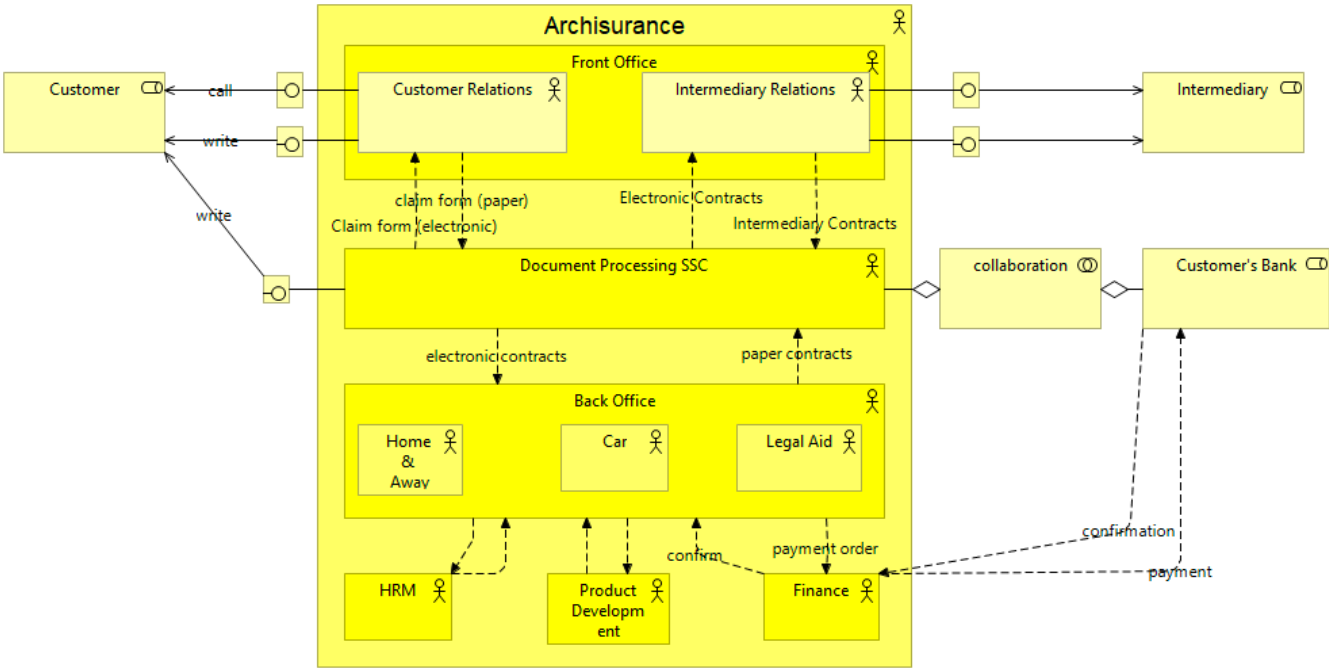


Figure 31. ArchiSurance Actor Cooperation View.

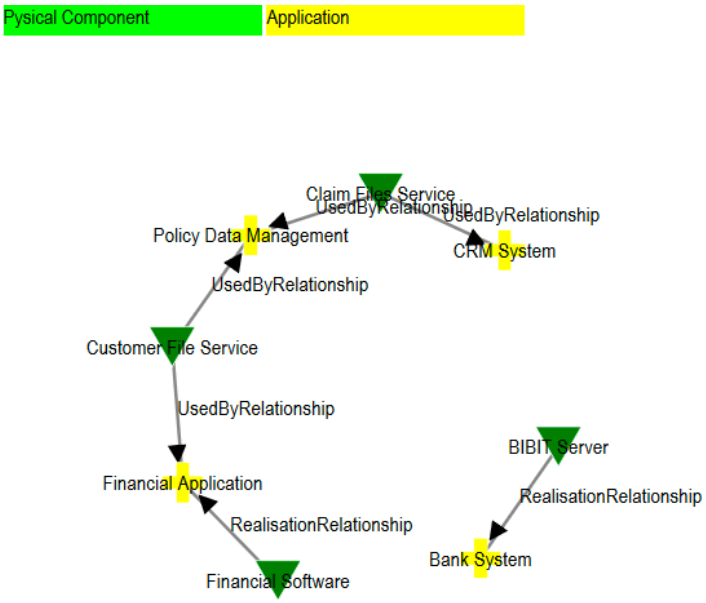


Figure 32. V-109 with ArchiSurance data.

Business capability **Business application**	Legal aid Insurance Policy	Insurance Request	Liability Insurance Policy	Customer File	Damage Claim	Travel Insurance Policy	Car Insurance Policy	Home Insurance Policy	Check and Sign Contract
Insurance Policy Data	X		X			X	X	X	
Insurance Request Data		X							
Customer File Data				X					
Damage Claim Data					X				
Policy Creation Service									X
Claim InfoServ									
CIS									
Financial Application									
CRM System									
Policy Data Management									

Figure 33. V-111 with ArchiSurance data.

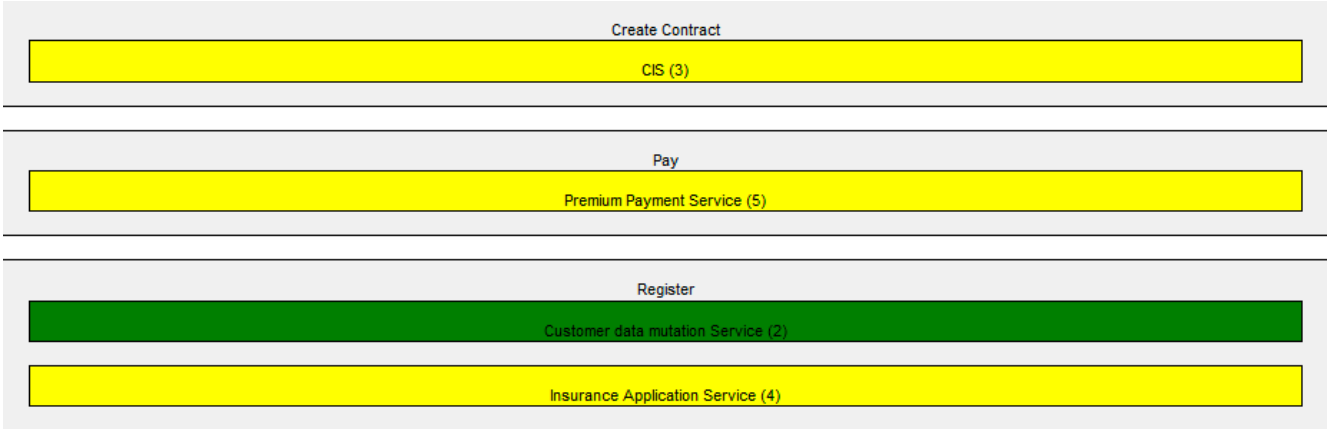


Figure 34. V-107.1 with ArchiSurance data.

Business Application	Instance	Number of relations
Call center application	ApplicationComponent	2
CRM System	ApplicationComponent	4
Customer Data Access	ApplicationComponent	4
Home and Away Policy Administration	ApplicationComponent	4
Claim Data Management	ApplicationComponent	1
Financial Application	ApplicationComponent	6
Bank System	ApplicationComponent	2
Policy Data Management	ApplicationComponent	7
Risk Assessment	ApplicationComponent	2
Web portal	ApplicationComponent	3
Calculate Premium	ApplicationFunction	2

Figure 35. V-111 with ArchiSurance data.

ID	Number of relations
Bank System	1
Financial Application	2
Policy Data Management	2
CRM System	1

Figure 36. V-119 with ArchiSurance data.

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Model-centric and Phase-spanning Software Architecture for Surveys

Report on the Tool *Coast* and Lessons Learned

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***Abstract*—Surveys are used in empirical sciences to answer research questions. Such surveys can be separated into five phases (e. g., planning and data collection), where each phase shares information with each other. Since the interdependencies between the phases are sometimes complex, it is helpful to have a software system, which supports each phase of a survey. There already exist such systems, which cover all of the phases. However, the implementations of the phases have usually strong limits; a more individual handling of the phases has to be done in external tools. But an external handling of the information would disrupt the links between the phases. The merging of the phases become a cumbersome task. This was one reason to build the new survey and report tool *Coast*. This paper presents a realization of the advanced requirements on this new survey system. The system keeps the links between the phases intact and is able to distribute surveys on different devices, e. g., paper and web. The focus on the meta-model of surveys makes that possible. The model is derived as a mathematical and as a data model. The data model builds a domain-specific language in order to construct the necessary parts of a survey. The architecture with its components and services is built around this language. Mainly, the architecture describes how the model of surveys is transferred and compiled. Its benefits and disadvantages provide lessons learned for other researchers and developers.**

Keywords–Survey; Architecture; Model; Coast; Tools.

I. Introduction

Surveys are prevalent in the empirical sciences (for example in psychology and sociology) [1]. In many cases, it is profitable to use surveys to reach a large and locally dispersed sample (e. g., [2]).

A survey can be separated in different phases: (1) Planning, design, and implementation, (2) data collection, (3) data preparation, (4) data analysis, and (5) reporting [3]. Each of the phases is interwoven with the others. For example, the reporting phase needs the specific questions asked in the survey as well as the different variables and scales from the implementation phase. In turn, the collected data can only be interpreted by knowing the scales and variables they belong to. So, it is beneficial to have a software system, which supports each of the phases of a survey and which is phase-spanning.

Such software tools are available on the market, e. g., *EvaSys* [4], *KwikSurveys* [5], *LimeSurvey* [6], *SurveyMonkey* [7], and *Unipark* [8]. Most of them cover all phases of a survey. They provide predefined or simple data analyses and reports. However, the data analysis and reporting phases are very individual processes and can become quite complex. For further analyses (e. g., multivariate analyses, machine learning) exceeding the standard repertoire, these tools offer the download of the raw data. This separation from the tool, unfortunately, disrupts the link between the data and the other phases of a survey — the individual data analysis in an external tool becomes a time consuming and cumbersome task.

This fact was one of the main reasons for the *Course Evaluation Center* at the Friedrich Schiller University Jena in the year 2009 to build its own survey and report tool, called *Coast*. It focuses on the integration of the analysis and report phases for advanced analyses. Although it is in successful use for the course evaluation of the university, the first version of *Coast* had its disadvantages. The disadvantages resulted from varying requirements, wrong design decisions, and surveys, which got more complicated than the architecture could handle. A monolithic architecture emerged, which made it hard and risky to implement changes in business logic. Although monolithic architectures are profitable in early-stage development [9], such architectures become more confusing during growth. That makes the architecture difficult to maintain and hard to understand [10][11].

As the questionnaires handled by *Coast* became more complex, the usage of the first version of *Coast* was not possible anymore. However, like a tool comparison in Section II-C will show, the currently available tools do not fulfil all our requirements. Usage of those tools cannot happen without significant changes on the questionnaires (and questions asked in the survey). Since we use longitudinal analyses [12] (which require equal questionnaires during each data collection), it is necessary to keep the existing structure intact. The overhead to change the questionnaires and to build workarounds to solve the requirements is high. Therefore, it is *not* possible without high efforts to use a different survey tool. This high effort made it necessary to transfer our tool *Coast* into a different architecture.

As a result, a new version of the *Coast* application is currently under development. This new version deals with the disadvantages of the first version by clarifying the architecture and modules as well as the model of ques-

tionnaires and reports. The architecture is build up around this model, which should offer a familiar development of questionnaires and reports. The model formulates a *Domain-Specific Language* (DSL) to handle the context-specific interaction between humans and machines. Our domain covers all phases of a survey and the model. In other words, one goal of *Coast* is to provide a DSL for surveys, which allows the construction of questionnaires and reports in a language that everyone understands who has knowledge in the domain.

This paper deals with our research question about the realization of a survey system that keeps links between the phases of surveys intact. We define requirements on such a system, especially those being not fulfilled by existing systems. A detailed presentation of the relationships and information of surveys and reports is done mathematically and as a data model. The data model builds a DSL for the construction of all the parts belonging to a survey. Based on this DSL, we examine the necessary components and services for the different phases of a survey and discuss them in terms of our software architecture. Benefits and disadvantages of our approach provide experiences for other researchers who have to realize similar research questions.

This paper is structured as follows: Subsequent to this introduction, the reader finds an overview about related work, our advanced requirements on a survey system, and a comparison of existing survey systems regarding those requirements (Section II). Section III describes the meta-model as a DSL, especially for questionnaires. This description is done (1) mathematically to provide an overview of the different information and relationships and (2) as a data model which gives more detailed information. Based on this data model, Section IV explains the architecture of our survey system with a high focus on the interactions between the phases of a survey. The benefits and problems of the proposed solution are shown afterwards in Section V. This paper concludes with a short outlook into future work in Section VI.

II. Related Work and Requirements

This section explains the five phases of surveys and defines our requirements on a survey system. An overview of existing solutions for creating, carrying out, and analysing surveys makes it further possible to compare the requirements for those solutions, subsequently.

A. Phases of an Electronic Survey

A survey can be separated into five phases [3]:

1) Planning, design, and implementation,
2) Data collection,
3) Data preparation,
4) Data analysis, and
5) Reporting.

The first phase (*planning, design, and implementation*) includes *planning* on the research questions you want to answer, *deciding* what survey questions are necessary to answer these research questions, and *specifying* who will be surveyed (the *population*). Furthermore, the survey will be implemented. As a result, there is a paper or web link that can be distributed to a sample of the population.

The population is surveyed with the implementation of the survey in the second phase. This phase is called *data collection* where the answers of the respondents for the questions are stored in a data set (for example in a database).

The third phase *data preparation* is necessary, because the collected data may contain malformed, incomplete, or wrong records. Sometimes, there are faults in the implementation or conception of the questionnaire, which have to be corrected. If other data sources are combined with the collected data, some data may have to be recoded. Summarized, the data has to be cleaned and prepared to be used in a *data analysis*, the fourth phase, afterwards.

In the analysis phase, the collected data are analysed in order to answer the research questions from the first phase. The results of the analysis, as well as general information about the survey, are finally summarized in detail in a report. The report is the outcome of the last phase, *reporting*.

B. Requirements

The primary requirement of a survey tool is its coverage of all mentioned phases of a survey. Besides this basic requirement, a tool in our context should fulfil the following functional requirements:

- DEV A questionnaire and report model should be usable for different **dev**ices (paper, web, smartphone, etc.).
- QAD New kinds of **q**uestion visualizations can be **ad**ded (sliders, timetables, etc.).
- AAD New kinds of **a**nalyses can be **ad**ded (group comparisons, regressions, etc.).
- MUL **Mul**tiple surveys should be analysed together in a single report.
- ADA Questionnaires and reports should allow **ada**ptivity, i. e., conditional branches.
- DIS The survey conduction should be **dis**tributed on other systems than the construction of surveys.
- PRI The survey conduction should be distributed also on **pri**vate systems.

Furthermore, it should fulfil the following two non-functional requirements:

- FLE The creation of questionnaires and reports should be **fle**xible.
- SCA All the phases should be **sca**lable.

C. Other Survey Tools and Their Comparison

Coast is not the only survey tool available on the market supporting the phases of a survey. There are well-established tools like *EvaSys* [4], *KwikSurveys* [5], *LimeSurvey* [6], *SurveyMonkey* [7], and *Unipark* [8]. All of them cover the previously introduced five phases of surveys. Almost all tools allow the creation of a questionnaire via drag and drop of the questions. The resulting questionnaire can be used for the data collection subsequently.

The tools are compared in Table I. The table compares licensing, type of operation, types of questionnaires, analysis tools, export of results, individualization of the layout, as well as extensibility of question types and data analysis algorithms. Concerning licensing, all tools offer a commercial license, which is usually accompanied by a managed

Table I. Survey tool comparison for license types, hosting, and devices for questionnaires, as well as export options for data and modifications to layout, question types, and analysis algorithms. The compared aspects were assigned to the requirements.

	Requirements	EvaSys	Unipark	LimeSurvey	KwikSurvey	SurveyMonkey
Commercial	-	✓	✓	✓	✓	✓
Open Source	-	✗	✗	✓	✗	✗
Free Version	-	(✓)	✗	✗	✓	✓
SaaS	DIS, PRI, SCA	✓	✓	✓	✓	✓
Self Hosting	DEV, PRI, SCA	✓	✗	✓	✗	✗
Web Questionnaire	DEV, PRI, DIS	✓	✓	✓	✓	✓
Paper Questionnaire	DEV	✓	✗	✗	✗	✗
Hybrid Questionnaire	DEV	✓	✗	✗	✗	✗
Analysis Tools	FLE	✓	✓	✓	✓	✓
HTML Export	FLE	✓	✓	✓	✓	✓
PDF Export	FLE	✓	✓	(✗)	✓	✓
Spreadsheet Export	FLE	✗	✓	✓	✓	✓
Raw Data Export	FLE	✓	✓	✓	✓	✓
Add. Question Types	QAD	✗	✗	✓	✗	✗
Add. Analysis Algorithms	AAD	✗	✗	✓	✗	✗
Individualization	FLE, ADA	✓	✓	✓	✗	✓
Multi-Survey-Report	MUL	✗	✗	(✓)	✗	✗

hosting and therefore a minimum of installation effort. Such a Software-as-a-Service (SaaS) offer is an advantage, especially with regard to the SCA, PRI, and DIS requirements. Some systems offer free test phases; others offer a permanent free use of the system with limited functionality. A hybrid concept (use of paper and web surveys) in relation to the DEV requirement can only be realized with the EvaSys tool. The realization of new question types and new analysis algorithms is only possible in the case of the open source application LimeSurvey through independent hosting and individual adaptation.

In conclusion, none of the tools considered would fully meet the intended requirements. In particular, the MUL requirement does not seem to be possible in any tool. The phases of data preparation, data analysis, and reporting are not separated in most of the tools and, therefore, merge smoothly. All the tools have the possibility to export the collected data for further research in external tools (e. g., *IBM SPSS* [13], *Excel* [14], or *R* [15]). Furthermore, they provide standardized reports, which include the questions of the questionnaires, frequencies, significance tests, and mean values, among other parameters. However, with all tools, the link between phases is lost in the case of individual analyses and the accompanying export of the collected data.

III. A Domain-Specific Language

The tools mentioned in the previous section have a focus on the development of the survey instead of a fine-granular and sophisticated data analysis and reporting. As mentioned before, a new focus on the data analysis and reporting was one reason to build an own survey tool *Coast*. Another main reason to build *Coast* was the missing coverage of our requirements of the existing survey tools.

As mentioned in Section II-A, conducting a survey is an almost well-defined process. The same holds true for the development of questionnaires (used to survey the population) and reports. It is our goal for *Coast* to offer a controlled and realistic modelling and development of them: We want to provide a DSL as a possible way to handle the interaction between humans and machines in a specific context. Our context contains all phases of a survey as well as how questionnaires, analyses, and reports are structured. In other words, the DSL can be used to model such questionnaires, analyses, and reports. In this paper, the DSL focuses on the description of the questionnaires to avoid repetition, since the description of the reports is quite similar.

Since the DSL should be used to define questionnaires in a language that everyone understands who has knowledge about questionnaires, the focus lies on *how* a questionnaire is structured and what kind of information is important. More concrete, the DSL describes the *meta-model* of the questionnaire. That means an instance of that meta-model is a description of one questionnaire. The instance of this description is one physical questionnaire, which can be answered by one respondent. The *meta-model* of questionnaires makes it possible to derive different kinds of surveys from the same model: For example, surveys represented online on PC, on paper, or on smartphones.

It is useful to inspect the structures of questionnaires from a mathematical perspective to get a general and compact model. Therefore, we considered questionnaire models and descriptions in the literature [16], interviewed psychologists in our department, and derived the following mathematical questionnaire *meta-model*.

A. Mathematically

One way to picture questionnaires is to consider them as computer programs: Questionnaires have a starting point and the respondent follows the questionnaire on a "path" question by question. Sometimes a path can branch out depending on previous answers and a respondent follows one or another. That means, the questionnaire forks — it allows *adaptivity*. In other places in the questionnaire, different paths join each other. It is like a program with branches. In other words, a questionnaire can be described as a (control flow) *graph* (definitions of graphs and paths can be found in [17, pp. 432] and [18, p. 1180]).

Before it is possible to define a questionnaire based on graphs, it has to be examined what the nodes of the graphs mean in this context. For this reason, we have to introduce some concepts of measurement theory.

1) Codomains and Variables: The theory of psychological measurements aims to study the properties of objects, especially of humans [19, p. 8]. In reality, the (psychological) properties, e. g., intelligence or motivation, are too complex and varied in such that the measurement has to coarsen and discretise them. Therefore, each measurement describes the mapping from the *true* domain to a set of discrete values [20, p. 22]. This set of discrete values is called the *codomain*.

Stevens describes four different kinds of codomains named *levels of measurement* [21]. Depending on the level of measurement of a codomain, it can be decided, which statistical analyses can be applied. The levels are *nominal*, *ordinal*, *interval*, and *ratio*. Starting from the *ordinal* level, the codomains are called *scales*. More information about the different levels can be found in [21].

It is necessary to decide carefully which level of measurement is suited for a specific measurement since it is difficult or impossible to transform the values of a low-level to a higher level measurement.

A property of an object obj is measured with the help of the values of a codomain $\mathcal{D}$. A measure assigns a value $val \in \mathcal{D}$ to obj and can be described as a pair (obj, val). If the same property is measured for the set of all objects $\mathcal{O}$ in a sample, it results in a mapping from those objects to the codomain $\mathcal{D}$. This mapping is called a *variable* [20, p. 22]:

Definition 1 (Variable): A variable V is a left total mapping from a sample set of all objects $\mathcal{O}$ to a codomain $\mathcal{D}$, $V\colon \mathcal{O} \mapsto \mathcal{D}$. The codomain of V is described with $\mathcal{D}(V)$.

A variable describes the characteristics of *one* property for different objects [22, p. 19]. However, in questionnaires, many of such properties should be measured. Therefore, there is a variable for each of the properties to measure.

2) Items, Pages, and Questionnaires: The measurement in questionnaires is done by asking the object (the *respondent*) with a set of instructions and questions — *items* [22, p. 19][23]. An item is a concrete question or request, which measures one or more variables.

Definition 2 (Item): An *item* I consists of an *instruction* and a set of enquired *variables*.

In almost all questionnaires, more than one item is presented to the respondent at the same time. They are grouped thematically on *pages*:

Definition 3 (Page): A *page* is a finite set of items.

Not each page has to appear for each respondent. For example, if a respondent has never done a job, a page with items about jobs is not suitable. In questionnaires, the exclusion of pages and items depends on previous answers of the respondent. There could be a previous item with the question "Do you ever had a job?" as an example whose answer includes or excludes the page about jobs. Questionnaires with conditional pages are called being *adaptive*. In adaptive questionnaires, *conditions* are allowing the control of the path a respondent follows:

Definition 4 (Condition): A *condition* on the variables $V_1, \ldots, V_m$, $m \geq 1$, is a left-total mapping from the Cartesian product of the codomains of the variables to the boolean set $\{true, false\}$:

$$\mathcal{D}(V_0) \times \cdots \times \mathcal{D}(V_m) \mapsto \{true, false\}$$

It is known from research that the structure of a questionnaire can influence the measurement results [24, S. 68 ff.]. The structure of a questionnaire seems to be important. For this reason, a questionnaire should not only be defined by an unordered set of pages and conditions. There has to be an order of the pages and items [25]. Sometimes, this order is described as the *item flow* and *sequence of questions* [26]. As mentioned before, it is promising to describe the structure of a questionnaire as a control flow graph, in our case as an acyclic, connected digraph [27, S. 547] (also proposed by Bethlehem [16]).

Definition 5 (Questionnaire): A *questionnaire* Q is a triple $(\mathbb{P}, \mathbb{E}, Cond)$. It consists of an acyclic, connected digraph $(\mathbb{P}, \mathbb{E})$ with a set of pages $\mathbb{P}$ and a set of *edges* $\mathbb{E}$; and a left-total mapping, $Cond$, which assigns a condition to each edge.

3) Measurement Methods and Surveys: A questionnaire can be used as a *measurement method*. A measurement method is applied for a single obj and a set of variables. For each of these variables var a pair (obj, var) is determined, $val \in \mathcal{D}(var)$. Assume the variables in a specific order within the measurement method. Then it is a mapping from the set of all objects of the sample to the Cartesian product of all codomains collected in the measurement method.

Definition 6 (Measurement Method): A *measurement method* $\mathcal{M}$ is a mapping from the set of objects $\mathcal{O}$ to the Cartesian product of all codomains of all measured variables $\mathcal{V}$:

$$\mathcal{M}\colon \mathcal{O} \mapsto \prod_{v \in \mathcal{V}} \mathcal{D}(v)$$

Remark 1: A questionnaire is a specific measurement method. The set of objects is the set of respondents. The set of all measured variables contains the variables in the questionnaire. Therefore, a questionnaire is also a mapping from an $object$ (respondent) to a set of values (the answers).

Since a questionnaire is a measurement method, a *survey* is a special *elicitation* in our context using a questionnaire [22, p. 18]. Elicitation is the application of a measurement method to a set of objects.

Definition 7 (Survey): A *survey* $\mathcal{S}$ contains a questionnaire Q and a set of *respondents* $\mathcal{O}$, $\mathcal{S} = (Q, \mathcal{O})$. The union of all measurements of all objects builds the results $\mathcal{R}$ of the survey $\mathcal{S}$:

$$\mathcal{R}(\mathcal{S}) = \bigcup_{o \in \mathcal{O}} Q(o)$$

B. Data Model

There are some mathematical structures, which are not trivial to implement, e. g., conditions. Some other structures are too unspecific yet to be used in software. An example is a codomain, which is an arbitrary accurate set in a mathematical sense. However, such a set cannot be implemented for discrete computers. For these reasons, the mathematical model has to be made concrete as a data model.

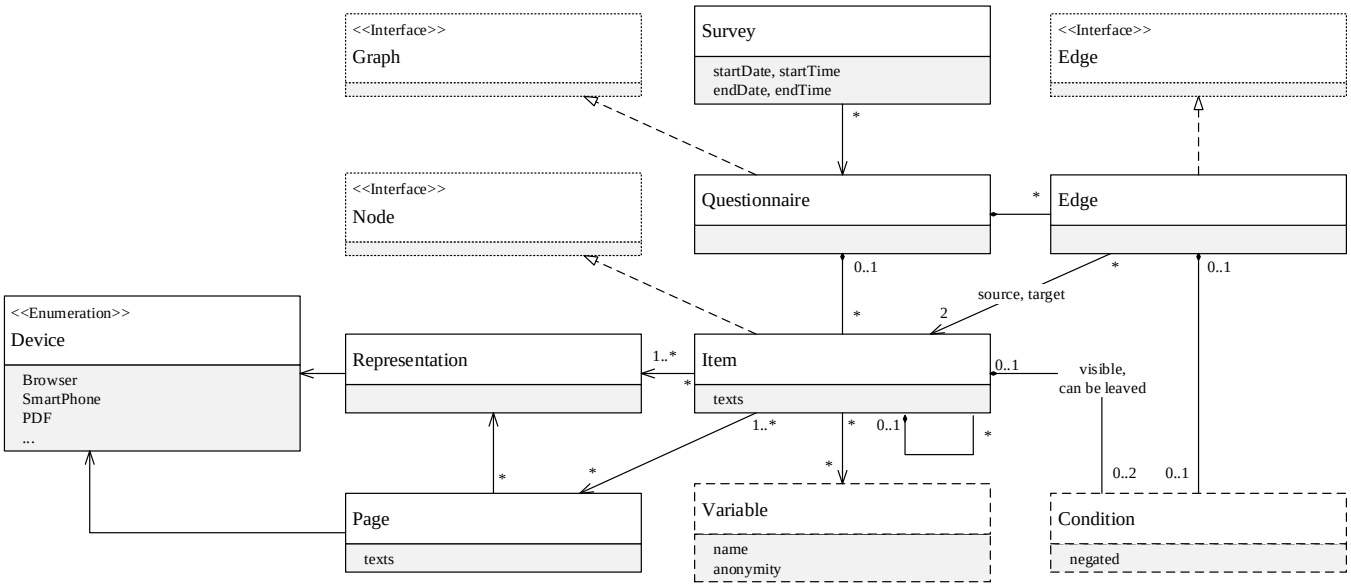

Figure 1. The questionnaire classes.

1) Questionnaires, Items, and Pages: Figure 1 shows the classes belonging to questionnaires and surveys. Classes with dashed lines have at least one association with a class in the current diagram but will be explained later.

The class *Survey* represents an elicitation using a questionnaire. Besides the questionnaire, a survey has a start and end date as well as a start and end time in the data model. The respondents (see Definition 7) are not illustrated in the class diagram since they are not of interest in this context of the data model and architecture yet.

Regarding Definition 5, a questionnaire is a graph consisting of pages and edges, where each edge has an assigned condition. A questionnaire is represented by the class *Questionnaire* in the class diagram. It implements an interface *Graph* giving it rudiment graph functionalities like getting the nodes and edges. That makes it also possible to apply general graph algorithms to questionnaires, e. g., topological ordering, data-flow analyses, etc.

Instead of referring to pages, the questionnaire has *Item*s as nodes in our data model. That infringes the mathematical formulations for reasons of generalization: Each questionnaire should contain the same items independently from the device, e. g., a browser, a smartphone application, or a PDF. The number of items, which should be displayed on the same page, varies for different devices because of display sizes. Therefore, the pages should be defined dependent on the device. For example, a smartphone display may be too small to show more than two items on a single page. A desktop device, however, enables at least five items per page. The items are the same for both devices, but the pages differ.

For these reasons, the questionnaire in the data model refers to items, where each item refers to a set of pages. Each item can only have up to one page per device as otherwise, it would be uncertain, which page should be used. A *Page* has a link to the *Device* enumeration in the class diagram. Since the page depends on the device, the items can be grouped differently on pages for diverging devices.

The *Item* in Figure 1 has a reflexive aggregation. Since items can become very complex, such complex items can be decomposed into *sub*items in the model, i. e., complex structures can be reduced to more simple ones. Although this is not explained in the mathematical model, this design decision supports reusing of structures. A battery of rating items (a set of questions with usually five or seven different, distinct answer possibilities) is a prominent example of such a complex item (cf. Figure 2). In our model, a rating battery with five different questions would be separated into an item representing the whole rating battery (in the example of Figure 2 the box with the header “Some questions”) and five subitems representing the five different questions.

As it can be seen in this example, the master item should have a different visualization than the subitems — it should group the subitems in a table-like form, where each row represents one subitem with the actual question. Although the visualization of the items is not part of the mathematical questionnaire model, there is a need for it in practice. For this reason, an item has at least one representation (the association to the class *Representation* in the diagram of Figure 1). Similar to a page, a representation is defined for a specific device since an item could be represented differently for example on a web or a paper survey. There is a restriction that each item has up to one representation for a specific device. Like the diagram shows, a page has different representations too since it must also be visualized.

Items and pages contain *texts*, which define, e. g., questions, instructions, and headers, corresponding to the mathematical model (Definition 2). The different texts should be stored language-separated such that a questionnaire can be used in different languages.

As a further extension to the mathematical model, each

Statements						
(*1=strongly disagree ... 3=neutral ... 5=strongly agree*)	*1*	*2*	*3*	*4*	*5*	*no answer*
1 The instructor creates a stimulating work atmosphere.	○	○	○	○	○	○
2 The course stimulated my interest in this topic.	○	○	○	○	○	○
3 The subject matters fit my level of knowledge.	○	○	○	○	○	○
4 Most of the participants attend the course regularly.	○	○	○	○	○	○
5 Overall, I am satisfied with the general conditions of this course.	○	○	○	○	○	○

Figure 2. Example of a battery of rating items.

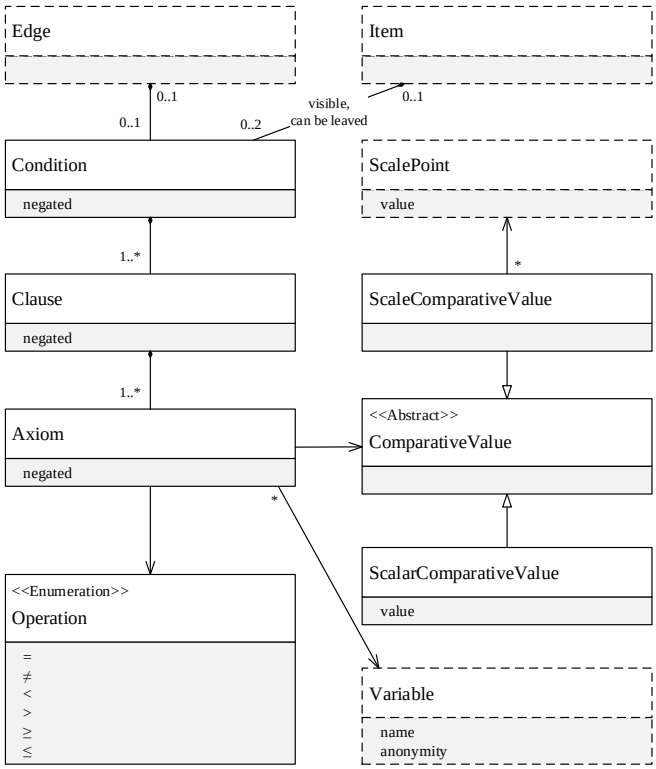

Figure 3. The condition classes.

item may have two conditions: (1) A condition whether the item is *visible* to the participant, and (2) a condition whether the participant *can leave* the item. The latter condition is practically necessary to avoid the reaching of the next page by a participant if some questions are required to answer. The former condition is an extension to the adaptivity of the questionnaire: Items can be visible on a page to specific groups of participants only.

Conditions are also used by the edges of the questionnaire following the mathematical model. In the class diagram of Figure 1, the questionnaire consists of edges beside the items. The class *Edge* implements an interface *Edge* and has a *source* item, where the edge starts, and a *target* item, where the edge ends. As a restriction, an edge cannot start or end in a subitem.

2) Conditions: As mentioned before, adaptivity can be realized by multiple outgoing edges of an item. This adaptivity is based on conditions following the mathematical model. If the condition holds true for an edge, then this edge of the questionnaire is subsequently followed. Mathematically, such a condition is easy to describe. However, the conditions in the data model should be interpretable or executable for a computer program. Therefore, it has to be described as a term (string) or as a parse-tree [28, pp. 45] in the data model. We decided to describe a condition as a parse-tree in disjunctive normal form (DNF). The advantages of using the DNF are that (1) each logical formula can be described in DNF and that (2) the resulting tree of clauses and axioms (the parse tree) has always the depth of 3. The latter makes it possible (a) to generate a simple UI for adding and describing new conditions, (b) to avoid parsing of terms in string format, and (c) to transform it to source code very fast. The disadvantages are obvious, (i) the possible bigger size of such conditions and (ii) the expected knowledge about logical equations in DNF and its transformations. However, the advantages prevail the disadvantages.

The class *Condition* in the class diagram of Figure 3 represents a condition in DNF. As an addition to the DNF, a condition can be *negated*. Each condition consists of at least one *Clause*, where each clause can be *negated* again and all clauses are connected by a logical OR ($clause_1 \vee \ldots \vee clause_n$, $n \geq 1$). A clause object connects different *Axiom*s with a logical AND, $axiom_1 \wedge \ldots \wedge axiom_n$, $n \geq 1$.

In our model, each axiom is a simple expression $(variable\ \ operator\ \ value)$. $variable$ is a reference to a variable (cf. class *Variable*), $operator$ is a relational operator, i. e., $=, \neq, <, >, \geq, \leq$, realized by the enumeration *Operation*. Eventually, $value$ is a comparative value. Since the comparative values can have different data types, e. g., a string, an integer, or a reference, they are realized as abstract class *ComparativeValue*. In the class diagram, two specializations are illustrated: A *ScalarComparativeValue*, which represents an integer, real, or string value, and a *ScaleComparativeValue*, which is associated with a specific scale point. Scale points are explained later. It is possible to add other specializations of the *ComparativeValue* class, e. g., one for handling complex macros.

3) Variables: The classes *Axiom* and *Item* are associated with the class *Variable* of the class diagram in Figure 4. It represents a variable of the mathematical model (Defini-

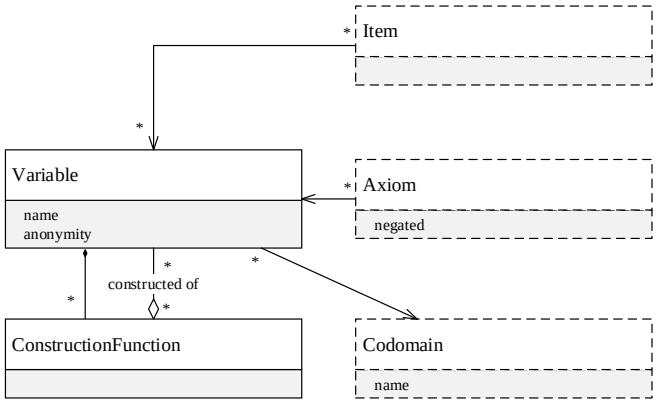

Figure 4. The classes of variables.

tion 1) and has a unique name and a rank of anonymity. The latter is technically important due for reasons of data security and anonymous surveys. For example, if there is a variable representing email addresses, the addresses should not be stored in the same context as other anonymous variables. Otherwise, the variables would lose their anonymity.

Another addition to the mathematical model is the possibility to define construction functions for variables. A construction function is a formula (e. g., source code), which describes the deriving of values for the variable based on the values of other variables. Each variable may have different *ConstructionFunction*s. A construction function again uses variables for their constructions. Obviously, each cyclic construction of variables should be avoided, i. e., no variable should be able to be constructed of itself.

4) Codomains, Scales, and Scale Points: Each variable uses an object of class *Codomain* following Definition 1 of the mathematical model. The classes belonging to codomains are shown in Figure 5.

For codomains, several specializations represent different levels of measurement as explained before and introduced by Stevens [21]. A *NominalCodomain* is a codomain having a relation (class *Relation*) defining equivalence between two values of this codomain. An *OrdinalScale* is a nominal codomain with an additional relation, which defines a linear order on the values of this domain. The class *IntervalScale* specializes the ordinal scale with two additional relations for plus and minus operations. At last, the class *RatioScale* is an interval scale with an identity element and additional multiplication and division relations.

Based on the measurement level one can decide which analyses are possible and could be applied on the collected data. For those analyses, it is good to know all the values in the codomain. For a large portion of codomains, there is a finite and enumerable set of discrete values describing it. These values are called *scale points* in the data model.

An object of the class *ScalePoint* consists of a value from the base set of the codomain (which will be explained later). Furthermore, a scale point has texts describing the textual answer printed to the respondent. For example, in the previously shown battery of rating items in Figure 2, the scale points of each statement are “strongly disagree”, “disagree”, “neutral”, “agree”, and “strongly agree” with the values 1 to 5. Most codomains have a list of such scale points. Furthermore, they have another list of *special* scale points. Special scale points are, for example, “default” and “no answer” scale points. As an example, each statement of Figure 2 has the value of the “default” scale point if the respondent saw it but has not answered; and it has the value of the “no answer” scale point if the respondent chooses the “no answer” checkbox.

5) Base Sets: As mentioned before, the values of the scale points have to be part of the base set of the codomain. In mathematics, it is easy to describe a set D with $D \subseteq \mathbb{R}$ as part of the real numbers or with $D = [5, 10]$ as all real numbers between 5 and 10 inclusively 5 and 10. In a data model, this has to be a part of the model too.

For this reason, the mathematical model was extended, and a *BaseSet* describes the set of values a codomain is based on. It is shown in the class diagram of Figure 6.

A base set describes typical number systems in the first place, for example, integer and real numbers. If the codomain contains texts, the base set is a set of strings (words), i. e., the Kleene star on the set of all characters. Alternatively, a base set can be a set of arbitrary objects, e. g., pictures or persons.

As base sets can look different, the class *BaseSet* is abstract. Therefore, a codomain must use one of its specializations. The model defines four concrete specializations: (1) A *CharacterSet* defining arbitrary texts, (2) an *ObjectSet* for arbitrary objects, (3) *Integer* for integer values, and (4) *Real* for real values. The latter both classes *Integer* and *Real* are specializations of the class *NumberSet*. Each number set represents a number systems and may define an interval between *from* and *to*. The interval has a specific distance between all the values (*stepsize*). The *NumberSet* is abstract with only two specializations *Integer* and *Real*.

With the description of the base sets, the mathematical model was transferred to a data model. As the reader can check, the data model differs from the mathematical model mostly for reasons of generalization in the resulting architecture and for more details and simplifications of mathematical terms.

6) Reports: The report model is similar to the questionnaire model, however, the model will not be introduced in detail in the context of this paper. Instead, the following explains the report model in short.

The class *Report* is a graph like a questionnaire. It consists of different *Parts* (pendants of items in questionnaires) and *ReportEdge*s. The edges of a report use conditions again. This allows the creation of individual reports based on a single report model. Report edges connect the parts in the report. Each part has different *ComputationalRepresentation*s, up to one for each *OutputDevice*. There could be different output devices, e. g., for online or paper reports. The representations contain information about the visualization of a part and define *Calculation*s. A calculation illustrates a function performed on the collected data of the part. For doing this, it has different *Parameter*s specifying the input and output information of the function. The parameters could

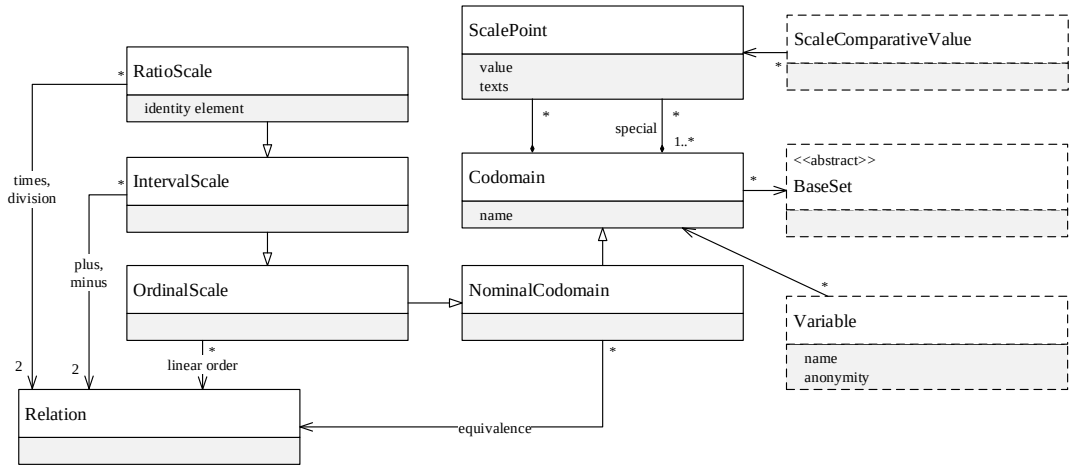

Figure 5. The codomain classes.

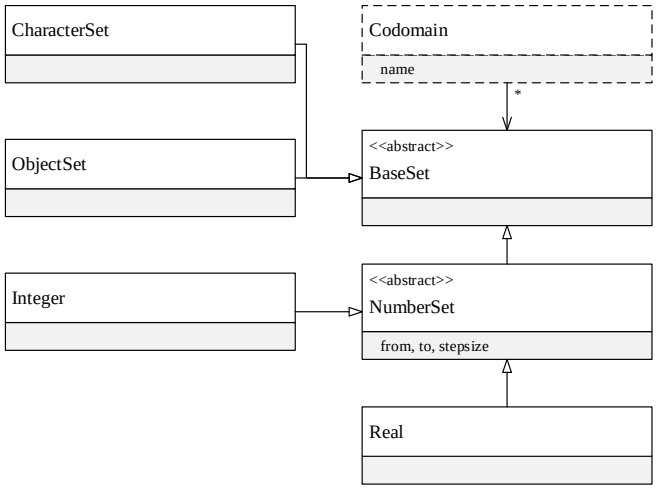

Figure 6. The base set classes.

be scalars or variables.

Besides the *Report* class, there are *EvaluationProject*s configuring the report. The evaluation projects define *DataSource*s, which specify the places of different data collections. This makes it possible to combine different data sources (also external data) in a single report. Evaluation projects also define sets of *Filter*s. Filters filtrate the data sources and create groups. For example, in a longitudinal survey, one could filtrate the data based on the year and create a group and data for each year. This allows to compare groups in the reports. Furthermore, each collection of filters ends in a single report.

IV. A System Architecture for Surveys

Our central architectural concept is to build the architecture around the questionnaire and report models. These models form the language for psychologists, sociologists, and researchers of other empirical disciplines to describe their needs. That means, the models also have to contain the processes and logics, which the researcher needs; *or* the architecture has to contain these processes and logics. Altogether, this is the *domain* of a survey: the domain covers all phases of conducting a survey and the models, processes, and logics. Since the models are part of the architecture, the architecture does finally represent the complete domain. In the topic of software engineering, this is a *Domain-driven Design* (DDD) approach [29].

The questionnaire model was derived to be a DSL to describe a questionnaire as near as possible to the daily experiences of researchers in empirical sciences (the users). For this reason, researchers can describe their questionnaires on their own without deep experiences of the system. That means, the questionnaires are developed by the domain experts and not by the developers of the system like originally done in classic DDD approaches. In other words, the users create formal models of questionnaires, which are afterwards able to be used to conduct web or paper surveys and to perform analyses and create reports. What the system has to achieve is to handle such formal models and to give an infrastructure for transformations, compilations, interpretations, executions, and other derivations.

The focus on a formal domain-specific model and its transformations into runnable code or reports as well as the focus on the infrastructure for such models make it a *model-driven engineering* (MDE) approach. MDE is the transition of DDD to software architectural decisions. In classic MDE a software is automatically derived from a formal model similar to the way our questionnaires are compiled automatically to web surveys [11]. Prominent examples of MDE are the *model-driven architecture* of the *Object Management Group* [30] and the *Eclipse Modeling Framework* [31]. Both focus on the *Unified Modeling Language* (UML) and provide an infrastructure of transformations from UML into the source code. In general, however, MDE is independent of UML and can be applied to arbitrary DSLs.

Our architecture describes the infrastructure and the transformations of the questionnaire and report model during the five phases of conducting a survey. Most parts of the

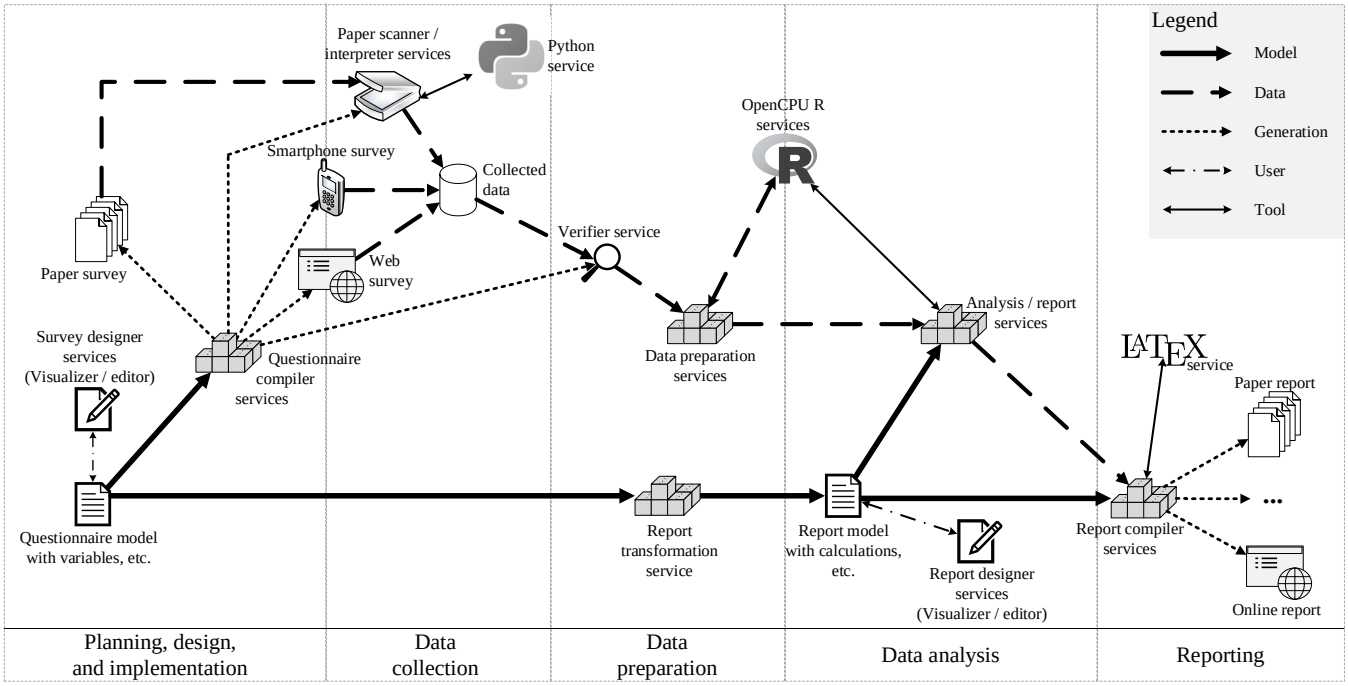

Figure 7. The architecture of the *Coast* system regarding the survey phases.

architecture use a questionnaire or report as input. For example, a questionnaire designer is a part of the architecture and receives a (possibly empty) questionnaire as input and produces a modified questionnaire as output.

Figure 7 shows our simplified architecture (infrastructure) separated into the five phases of (1) planning, design, and implementation, (2) data collection, (3) data preparation, (4) data analysis, and (5) reporting. The architecture is explained in the following.

A. Information Flows in the Architecture

The diagram contains different edges describing different flows between the phases. The most important flow is the bold one: The *model* flow. The model flow describes a questionnaire or report described in the DSL. It can be interpreted as a specification, which is sent to some algorithms or services (the term "service" will be explained later).

From the perspective of the user (the empirical researcher), the *data* flow seems to be the most important. It describes the collected data of the surveys and how it is transferred. The data flows are illustrated as dashed bold edges.

Regarding the MDE approach, the dotted edges are of interest. They show automatically generated programs, documents, etc. The primary input for those automatically generated elements are the user-generated models. Although there is more interaction between the user and the infrastructure as illustrated in Figure 7, this interaction is reduced to the UI tools named *survey* and *report designer* for reasons of clarity. The interactions between the user and the services and models are illustrated as small dashed and dotted lines. Eventually, interactions between external tools and the architecture are illustrated as small solid edges.

B. Services in the Architecture

Since the architecture covers the phases of conducting a survey, there is a natural flow from the left side of Figure 7 to the right side. The following description of the different parts of the architecture follows this flow starting in the first phase: planning, design, and implementation.

It all begins in the *Survey designer services*. These allow the user to model a questionnaire using our questionnaire DSL. The services provide a visual designer and editor for changing texts, variables, and others. They handle the creation and modification of necessary instances of the classes of the questionnaire meta-model. As a result of the designer, there is a well-specified *questionnaire model*.

If the user decides that the questionnaire is finished and should be used in a paper and web survey, for example, the model of the questionnaire is given to the *questionnaire compiler services* via the model flow. The compiler services implement the questionnaire and translate the model into a paper and web survey (illustrated as generation flows). The web survey can be accessed from the web and the results are stored directly in a data collection. This is illustrated as outgoing data flow from the web survey to the *collected data*.

In the case of a paper survey, a printable survey will be generated by the compilers. The printed questionnaires can be given to the participants. Since the survey results are not available digital, the compilers produce templates of the questionnaire based on the printable survey too. These templates can be used for scanning the printed and completed

papers in the *paper scanner* and *interpreter services*. During the scanning process, the data is extracted and the results are stored; illustrated as data flow from the scanner services to the *collected data*. The scanner service is a separate tool called *Amber Collector* and will be available as open source under this name in the future. It is built on *Python* and provides (user) interfaces for performing and checking such scans of paper surveys. The whole scanning process, web surveys, etc. are part of the phase *data collection*. The results of this phase are the collected data as data flow.

Besides the printable, web, and smartphone surveys and the templates for the paper scanner, an automatically derived *verifier* is another important result of the questionnaire compiler services. The *verifier service* uses that verifier, which belongs to the phase of data preparation. It checks the collected data for malformations and unsoundnesses. This can happen for example if during the scanning process multiple answers for a single-choice variable were identified. The application of the verifier results in a verified data.

The verified data arrive at the *data preparation services*. At this time, the user has created a questionnaire model, has implemented it by the compiler as paper and web survey, and has verified the collected data. Now, the user wants to use the data for a report. Therefore, the necessary data has to be requested. Furthermore, the user wants to delete or modify open (text) answers, which may contain profanity or misspellings. The preparation services contain functionality to request, replace, and standardize data information. Naturally, it should not be able to modify the originally collected data. Therefore, each modification is done on a copy of the data information and is logged by the system. So it is possible that other researchers can reconstruct the modifications and are able to detect potential problems in other research. The same happens during the replacement of default, no choice, and other special values by user-defined values.

The replacements and computations of the data preparation services are done with *R*, a statistical programming language which is perfect for data handling. As shown in the figure, there is a bidirectional data flow from the data preparation services to the *OpenCPU R services*. The *R* services are like a pipe in which the data is transferred, processed, and the enriched data is sent back.

The *analysis and report services* receive the prepared data from the data preparation phase. However, those services have to know which analyses should be performed. Therefore, there is another service during the data preparation phase — the *report transformation service* — which translates a questionnaire model into a report model. To derive this information from the questionnaire model, the report transformation service maps the questionnaire to a new report, e. g., the items of the questionnaire to report parts and the representations of the items to computational representations. As a result of the service, there is a full specified standard report model for the entire questionnaire model. This is illustrated as the model flow to the *report model* in the figure.

Some users want to have more powerful and specialized computations in their reports, e. g., group comparisons, geographical maps, and regressions. With the *report designer services*, it is possible to modify the report model to one's need and remove items, change variables, add computations, add report items, add group comparisons, among other things.

The report model together with the collected and prepared data are combined in the *analysis and report services* for computations. As mentioned before, the report model contains the information about necessary calculations. The collected data are then used as input for the computations. By doing this, the report model is transferred into a linear topological order and the conditions on the edges are translated into set operations in order to filter the data. Since the services need a lot of statistical calculations, *R* is used again to perform the computations. All standard calculations are collected in a *R* package, but the user can freely add new functions to the analysis and report services.

The result of the analysis and report services are the computed values. Together with the report model, these values can be combined in a report. This is done by *report compiler services* similar to the questionnaire compiler services explained before. Instead of compiling the model to surveys, the report model is translated to reports for different output devices. In this case, a *device* means the medium for which the report is generated. For example, the compiler is able to create printable paper and online reports. For the former, the compiler services use a LaTeX service. They compile the entire report model and the values into a LaTeX document, which can then be compiled into a PDF or DVI document. This is where the report is finished.

C. Service-Orientation

The architecture uses a lot of concepts of MDE as mentioned before. Especially, the questionnaire and report compiler services of Figure 7 are strictly model-driven and do not allow modifications on the result without doing it on the model. Since the models are transferred within the architecture and a lot of statistical computations are done, the architecture contains possibly long-running and computationally expensive tasks. Such tasks should, however, not affect other tasks of the architecture, for example, the data collection of a survey. In other words, the tasks should *scale* and should be physically *separable*. With *Service-oriented architectures* (SOA) [11] such a separation and scalability is easier and, therefore, a good choice.

Another reason for using SOA is that important parts of our architecture follow ongoing research in the context of psychoinformatics and compiler construction. That means that some of the tasks have to be flexible, evolutionarily growable, and replaceable. By encapsulating the tasks as services, the tasks should become loose coupled and should have high cohesion [32] — the services are almost independent of other services. Changing the services but retaining their interfaces makes them replaceable. For these reasons, each task (module) of the architecture is defined as a service with its own interface. If the functionality of the service is shared with other systems or users, it will be provided as a *RESTful* web interface. Otherwise, it is a simple system interface for reasons of performance. The flows in Figure 7 indicate how the modules interact with each other. For

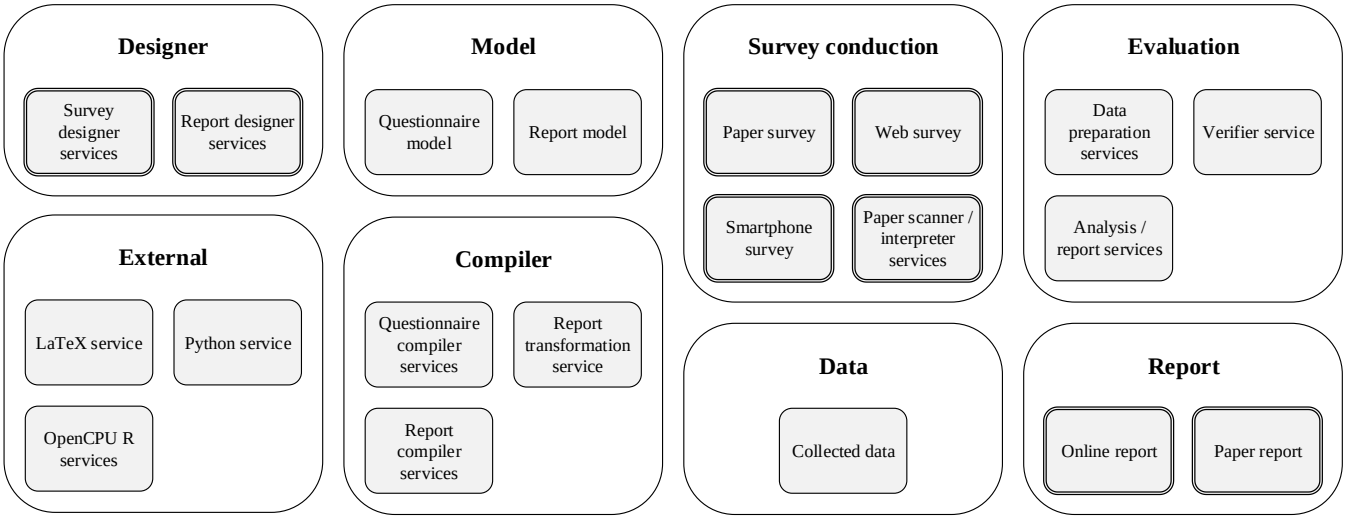

Figure 8. The integration layer of the *Coast* system.

example, to use *R* as a service, the *openCPU* [33] engine is used. OpenCPU makes it possible to use *R* as a RESTful web service.

Although the architecture is service-oriented, it is not a classic SOA. Some concepts have not been implemented in the architecture (yet). One missing component is a classic service repository. Right now, there is a repository for the different hosts where the web surveys are running. But all necessary system services are known in the architecture and do not have to be linked dynamically. Other services do not work via a network because of security and performance related issues.

Some of the services interact with the user. In order to achieve such communication, the architecture decomposes into server and client applications following a typical enterprise architecture. On the server, all the computations are done, the models are stored, the compilations are performed, and the collected data is handled. The client applications are mainly functional user interfaces allowing to talk with the server applications and to hide architectural and modelling details. Since the communication of the client to the server is done via HTTP, the whole architecture also describes a web application based on different modules.

It has become best practice during the development of the *Coast* architecture to maintain each module in separate projects and to build up the system based on them. This approach helped us to generalize modules, to define proper interfaces, to get loosely coupled functionality, and to reuse code whenever possible.

D. Integration Layer

Using services requires the *componentization* of the application into subsystems and modules (services) as described in Figure 7. In general, the architecture of *Coast* disintegrates into eight abstract layers: *designer*, *model*, *compiler*, *survey conduction*, *data*, *evaluation*, and *report* (illustrated in Figure 8). The collection of the different layers is called *integration layer* in SOA.

The *designer* contains the services belonging to the interaction with the user. Most of the business logic is configured with the designer. Therefore, it is the main application, which constructs the questionnaires and reports, starts the compilation of them, and initialize the analyses of the data. The survey and report designer services are part of the layer.

The *model* layer contains the structure of the questionnaire and report models and arranges their storing, for example, in a database.

The *compiler* layer with the compiler and report compiler/transformation services uses the model and configurations (done in the designer layer) to transform them either in other models or in documents, programs, or intermediate representations (IR). For example, the compiler produces the IR *liQuid* [34], which contains all necessary information about running a web survey. Furthermore, *liQuid* contains pre-compiled representations of each page, computed remaining pages, etc.

The *survey conduction* layer handles the data collection with the different kinds of surveys. This contains the paper, web, and smartphone surveys as well as the paper scanner and interpreter services. As part of the web surveys, there is a virtual machine (a survey engine). *liQuid* can be transferred to the survey engine, which executes it. Together, the compiler and survey conduction layers follow an old computer science principle: Compilation and execution. Since the engine can be separated from the rest of the architecture, it is possible to have multiple survey engine instances on different physical systems. As a result, the survey conduction becomes scalable.

The survey conduction produces data. The *data* layer handles the storing and processing of that data information. Furthermore, it allows the request and combination of different data sources.

The *evaluation* layer uses the report model, which offers computations, variables, and structures needed during evalu-

ation. The evaluation accesses the data layer to get the right data information. Furthermore, it stores its results back in the data layer.

There is an *external* layer in Figure 8, which contains the LaTeX, Python, and OpenCPU R services. Those services build wrappers around existing tools to integrate them into the architecture. They have exclusively functional interactions with the other layers. The services/modules with double lines in Figure 8 instead have also interactions with the user. They need user interfaces. For the paper surveys and reports the term "user interface" has a symbolic meaning. However, the web survey, online report, designers, and scanner services have high user interaction and, therefore, real user interfaces. The other services in the figure do not interact with the user. Their interfaces are functional.

V. Benefits and Problems of the Approach

The explained architecture used in our tool *Coast* is one possibility and implementation of a software architecture for surveys. In the previous sections, it was explained, *how* the data model and architecture look like and *why* both were constructed in this way. This section further describes benefits and problems emerged during implementation time, usage, and ongoing development.

The main benefit of the introduced architecture is the coverage of our requirements specified in Section II. The architecture allows the compilation of the questionnaires and reports to different devices, e. g., paper, web, and smartphone, using mostly the same infrastructure of algorithms (requirement DEV). It enables the addition of new kinds of question visualizations (time tables, sliders, etc.) since each item has an assigned representation in the data model (requirement QAD, also cf. Section III-B). If there is research about new visualizations, it can be easily adapted in the architecture. Although the reporting was not introduced in detail, the report model uses representations and abstract calculations to extend the analyses with new functionality for more complex statistical analyses (requirement AAD). Different surveys and data sources can be merged into a single report and new content can be added (requirement MUL). For questionnaires and reports, the mathematical and data models naturally define adaptivity as a graph (requirement ADA). Altogether, both models are highly flexible and cover many types of surveys and reports (requirement FLE).

As mentioned at the end of the last section, the architecture uses concepts of SOA. Therefore, almost all parts of the architecture are services. One main service is the survey engine executing compiled questionnaire models (*LiQuid* [34]). This engine is installable and executable also in private networks (requirement PRI). It can be hosted on different servers making it scalable. Since the engine can run on different servers from the other tasks, the processes do not interact and, therefore, do not reduce the performance (requirements DIS and SCA).

The consequent usage and the level of detail of the models during all phases allow to use these detailed information in each phase of a survey. For example, the report model results from a transformation of the questionnaire model. By doing this transformation, the report model gets the same variables, conditions, and codomains like the questionnaire. There is no missing information for the report. Since the questionnaire and report models are generalized and do not only fit to *Coast*, they could be used in other survey tools, too. These models can be stored for their documentation and reuse in future as well.

Other benefits regarding the introduced model of questionnaires (and reports) were shown in previous work [34] [35]. The former considers the erroneous multiple asking of the same variable in a questionnaire. It explains an algorithm based on static and dynamic analyses, which finds multiple occurrences of and assignments to the same variable on the same path. This could lead to the loss of information if a variable was wrongfully assigned to an item.

The latter work [35] reconsiders progress indicators in web surveys, whose calculation is based on an abstract version of the meta-model. This made it possible to define a general algorithm to calculate the progress in complex surveys with branches in paths.

An improvement during questionnaire creation is the visualization of the questionnaire model as a graph. It helps to keep the overview of all paths and variables as well as to maintain the central theme. The control-flow-graph-like structure shows the adaptivity and individual paths for groups of participants can be checked (by pre-assigning variables at construction). For example in a student survey, if a set of items should only be visible to Master students at different points of the questionnaire, the variable representing the degree can be set to "Master" to visualize the remaining paths.

A benefit of the graph-based model of reports is its advanced usage during the data analysis and reporting phases. The graph can be used to define wide varieties of item orders. A topological sorting helps to linearise these orders in a paper-familiar way. Furthermore, the graph can be used to produce code to only select data of the currently considered items. It reduces unnecessary data information for analyses.

The separation of the architecture in components and services is a great benefit during implementation. The previous monolithic architecture of the first version of our tool *Coast* decomposed into logically separable projects. These projects are more reusable in other contexts and are easier to maintain from our own experiences. One mentionable example is the reimplementation of the database done in the architecture without high reimplementation costs in other projects.

The separation into different projects makes it also easier to talk about the architecture in the team since each project has a clearly defined purpose and functionality, and a unique name to refer to it. A great advantage is the focus on the questionnaire and reports instead of their implementation. It matters *what* is done, not *how*.

The new architecture has issues too, naturally. Sometimes, the performance of the system is slower than in our first monolithic application. This comes from the increased overhead by using SOA. Furthermore, there are sometimes a lot of messages being transferred between the different services. Especially, the communication between the client and the server during the design of questionnaires and

reports is verbose.

The fine-grained models for the definition of questionnaires and reports result in large models of sometimes thousand to ten thousand objects. If a user wants to modify such a model within the web application, all those objects have to be taken from the database and have to be sent to the client. Sometimes, this took more than 30 seconds — which is unacceptable. Therefore, the pattern of *lazy loading* [36] objects had to be introduced in the architecture. When the client application tries to access an associated object, the system loads the required object from the server automatically if it was not already loaded before. Nevertheless, to allow a straight forward modelling and programming, the concept of promises [37] was extended to an ordinary if-then-construct making the programming of asynchronous services more intuitive.

Another disadvantage is the restriction of handling special cases within questionnaires and reports only via the data model although it appears sometimes faster and easier to implement them directly. Such special cases need the extension of the data model and, therefore, mostly more time. Examples are the representations of items in HTML. Sometimes these representations need only minor modifications to fit the desired visualization. However, since the modification of the representation may result in undesired side effects in other already implemented questionnaires, a new representation has to be introduced or the representation has to be extended by additional parameters.

There are other kinds of surveys which cannot be handled intuitively with our architecture, yet. For example, in computerized adaptive testing (CAT), the items of the test (survey) are not shown in sequence [38]. Their visibility depends on the answers of the previous items and they are randomly chosen based on a user-specific score. Most parts of CAT can be achieved with our architecture proposal. However, the randomly chosen selection of items and the highly connected structure of the items are not implemented yet and needs extensions of the current data models.

Although there are weaknesses and open issues on the current design, the benefits at practice prevail the issues. Since its introduction in our department, the software completely supports all phases of our surveys with high flexibility.

VI. Conclusion and Outlook

This paper described the realization of a survey system called *Coast*. The survey system keeps the interdependencies between the survey phases intact. Since the analysis and reporting phases of surveys are highly individual tasks and need a lot of information of the preceding phases, it was necessary to focus on the links between the phases.

The focus on the phases manifested in the paper as a detailed consideration of how questionnaires and reports are structured. This consideration took place both as a mathematical and a data model. The latter forms a DSL, which can be used to construct arbitrary questionnaires, reports, and other survey-related parts. Furthermore, the data model is the centre of the architecture of *Coast*. The architecture is, therefore, build up around the data model and describes how the models are transformed within the application. It also describes the necessary services, flows, and components.

In the end, the paper discussed the benefits and disadvantages of the proposed architecture as lessons learned. This was done especially regarding our advanced requirements on a survey tool, which were introduced too. There is no other survey tool, which fulfils all those requirements. This made this work necessary.

Since the *Coast* system is currently in an alpha version, the system is unpublished up to now. The future versions should be available to everyone via the web. For this purpose, the application has to reach a stable stage, and some of the concepts have to be extended. For example, the services and models used in the analysis and reporting phases can be used also for surveys conducted outside the *Coast* environment. This is possible by building a report model up from scratch without having a preceding questionnaire model. This report would receive the externally collected data as input. These data have to be described with the data model introduced in this paper. The concept of the user interface has to be extended to allow the description of variables and codomains subsequent to the data collection phase.

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Facilitating a Statewide GIS Metadata Standard through Training, Outreach and Programmatic Metadata Evaluation

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***Abstract*— Under the supervision of the North Carolina Geographic Information Coordinating Council and Statewide Mapping Advisory Committee, a committee defined and developed a State and Local Government Metadata profile intended for use in North Carolina. This profile is based on the International Organization for Standardization 191** standards. In addition to dictating best practices and conventions for existing metadata entries such as the Title, Publication Date and Use Constraints, this standard accounts for evolving technologies that did not exist when original metadata standards were first developed. While the rate at which geoinformation is created has exponentially increased, the time dedicated to cataloging and subsequently assessing and evaluating this metadata information remains nearly the same. In addition to educating the North Carolina Geographic Information Systems community on the use and application of metadata, as well as this new standard, the research team is developing tools so GIS managers can gauge standard compliance more efficiently and proactively than in the past. In this paper, the research team has been using programming methods in which metadata entries from multiple layers in large geospatial databases can be assessed and evaluated. These methods were tested using various quantitative methods, including the Technology Acceptance Model. This can provide insight into the various accuracies (horizontal, vertical, temporal, etc.) of layers which in turn can dictate future efforts. It can also be used to identify inconsistencies in metadata entries with an end goal of understanding misinterpretation and misunderstanding of the profile so it can be improved in future incarnations.**

Keywords-GIS Metadata; Metadata; Metadata Profile; North Carolina State and Local Government Profile.

I. INTRODUCTION

A Geographic Information System (GIS) serves as the tangible and intangible means by which information about spatially related phenomena can be created, stored, analyzed and rendered in the digital environment [1]. Experts in many dissimilar fields have seen the utility of GIS as a means of quantifying and expanding their research. GIS is used in disciplines such as business, sociology, justice studies, surveying and the environmental sciences. In the North Carolina GIS community, GIS is used to represent transportation routes, elevation, delineate land ownership parcels, school attendance, highlight patterns of crime and help make zoning decisions. The manner in which geospatial data is captured varies. Some methods include using a Global Positioning System (GPS) unit, extracting or improving existing GIS data, downloading data from a web site, connecting to a service, the use of an Unmanned Aerial Vehicle (UAV) or some other remote sensing platform, or creating data from an analog format via digitization or georectification. Regardless of the method, the resources (e.g., the computers, time and people dedicated to the process of collecting and creating geospatial data) are the most time-consuming portion of a GIS-related project [2]. As a result, the GIS community needs to ensure the quality of geospatial data created from these methods is captured, stored and assessed in a systematic way.

Geospatial metadata serves as the formal framework to catalog descriptive, administrative and structural information about geospatial data. Geospatial metadata is inherently different from other forms of electronic metadata because each metadata file can be applied a spatial component that is not implicit with other forms of metadata. These spatial components encompass a wide array of information to include the date, methods and sources by which geospatial information was captured, means to ensure that the geospatial information adheres to acceptable standards and/or aligns with other geospatial datasets to ensure seamless analysis, projection information of the dataset and bounding coordinates of the dataset. All of these entries, in addition to the data's non-spatial components can be queried within the confines of geospatial data portal such as one found at North Carolina OneMap, the geospatial data portal for the state of North Carolina [3].

Given the capricious rate at which all forms of geoinformation can be created, formal metadata (i.e. metadata stored using a widely-recognized and agreed-upon format) serves as a lifeline between the tacit knowledge of the data creator and current and future generations of geospatial data consumers. In the United States, the Federal Geographic Data Committee (FGDC) metadata standard, commonly referred to as the Content Standard for Digital Geospatial Metadata (CSDGM) allows for more than 400 individual metadata elements. The North Carolina GIS community has been proactive about understanding the importance of metadata.

Maintaining a complete and comprehensive metadata record is a continual and interactive process. GIS metadata is one of the most overlooked and underappreciated aspects of any GIS enterprise or project. If time or resources need to be sacrificed in the course of a project, it is usually at the

expense of metadata. Information is key to an organization's vitality, sustainability and success. Metadata should be treated as an investment. Maps and analysis are only as good as the data on which they are based. Metadata is a direct reflection of this investment and the organization which makes this investment. Metadata captures important information related to data creators, data quality and the various accuracies (horizontal, vertical, temporal, attribute, semantic, etc.) with which we can quantitatively measure GIS data. These measurements help guide the decision-making process, especially in larger (hundreds of layers) spatial databases. Not only is good metadata a wise business practice, but saves time, money and resources in the long run. Unfortunately, metadata's true value is not realized until it is absent, and few studies have been done to place a direct monetary value on metadata.

Under the supervision of the North Carolina Geographic Information Coordinating Council (NCGICC) and Statewide Mapping Advisory Committee (SMAC), a committee was tasked to develop a State and Local Government Metadata profile for geospatial data intended for use in North Carolina as well as educating the North Carolina GIS user community about this standard. This standard is based on the International Standards Organization (ISO) 191** format and is an improvement over prior metadata standards to account for evolving technologies such as remotely sensed imagery, online services and ontologies. These were not considered when original metadata standards such as the CSDGM (formally known as *FGDC-STD-001-1998)* were first published.

At this time, assessing and evaluating adherence to this standard for large spatial databases is an exhaustive process, as users must toggle through multiple levels of metadata records among multiple features a using a metadata editor. In this day and age, it is ''unrealistic to depend on traditional humanly generated metadata approaches'' when attempting to assess metadata integrity [4]. However, a happy medium must be found between quality assurance, quality control and the necessary human component involved in this process that cannot be replicated in the digital environment. While some research [5] subscribes to the mechanization of metadata assessment processes as the most effective and efficient, other research [6] [7] concedes that metadata is best managed through the integration of the human and digital components. While the level of human interaction in this process should be minimal, it should not be eliminated altogether. On that end, the goal of this paper is to propose a programmatic and faster assessment and evaluation alternative within the context of statewide metadata training that can be used by GIS management to facilitate decision-making. In doing so, it addresses and reinforces how programmatic metadata assessment and evaluation has begun to be implemented by the professional community.

The rest of this paper is organized as follows. Section II describes the evolution of metadata. Section III describes the specific use and application of the North Carolina State metadata profile. Section IV addresses the how standard compliance is addressed. Section V discussed preliminary results. The acknowledgement and conclusions close the article.

II. THE EVOLUTION OF METADATA SCIENCE AND ASSESSMENT

Metadata serves as an organized means to describe a dataset, and it provides the formal framework for providing information about a dataset's lineage, age and creators. Metadata is composed of both qualitative and quantitative information and while metadata's original use was simply as a means to catalog data, its storage and assessment has become a science in itself.

The FGDC regularly meets to determine all possible values, parameters and domains that can be captured and expressed within the confines of GIS metadata. First formed in the early 1990s, the FGDC serves as a governing body for geospatial data and metadata in the United States. The FGDC defines metadata as the following:

> A metadata record is a file of information, usually presented as an XML document, which captures the basic characteristics of a data or information resource. It represents the who, what, when, where, why and how of the resource. Geospatial metadata are used to document geographic digital resources such as Geographic Information System (GIS) files, geospatial databases, and earth imagery. A geospatial metadata record includes core library catalog elements such as Title, Abstract, and Publication Data; geographic elements such as Geographic Extent and Projection Information; and database elements such as Attribute Label Definitions and Attribute Domain Values [8].

FGDC metadata standards dictate that a plethora of individual entries (now more than 400 and counting) are populated for compliant GIS metadata [8]. Thus, ensuring metadata integrity for large spatial data sets is a time-consuming process if done by hand. It is not uncommon for organizations to employ thousands of individual data layers within their digital warehouses. Since traditional GIS data are ever-evolving, metadata standards must be flexible enough to account for new technologies. Policy should dictate that these standards be revisited periodically to ensure adaptability that can be implemented through large-scale changes or the publishing of new metadata standards. The GIS community has employed a set of content standards to ensure compatibility across the entire GIS community. The updated State and Local Government Metadata profile developed by the NCGICC based on the ISO 191** discussed in this paper highlights this adaptability and is an example of one of these standards.

While regarded as a relatively new concept, both formal spatial and non-spatial metadata has existed in one form or another for the past 50 years. *MARC* (Machine Readable Cataloging) and its successor *MARC 21* are used by the Library of Congress to catalog bibliographic resources. This

system has been in place since the 1960s, but it was not originally designed for computer interfacing, and the format is not very intuitive [9]. A more popular format called the *Dublin Core* was created in 1995 for electronic recourses such as web pages and software applications. While the FGDC and GIS metadata standards described here actually predate this more generalized format, GIS metadata data contains a variety of geographically-explicit descriptors that may not be fully understood by the non-GIS community [10].

Dublin Core and FGDC generally share a base level of descriptive metadata elements. While Dublin Core is used to describe electronic resources and digital representations of physical resources such as artwork, GIS metadata adheres to FGDC and more recently ISO standards. These requirements are always changing as dictated by technology. Because of the spatial nature of GIS data, FGDC requirements dictate that information pertaining to absolute location be retained. These fields include datum, coordinate system, false easting, false northing and bounding coordinates. While Dublin Core does make accommodations for place keywords and spatial descriptors, it does not contain placeholders for elements that help describe geodetic elements associated with the quantitative representation of location with as much detail as GIS metadata.

Because of the different goals of each standard, a precipitous balance between MARC, Dublin Core and FGDC Metadata must be found. Cross-walking, a tedious and sometimes imprecise process where either people or algorithms find matching elements between the different standards may be necessary because various organizations use these popular formats interchangeably on a routine basis. Cross-walking methods have been used to match geospatial data to standards outside of FGDC, such as examining the feasibility of compatibility with the Dublin Core metadata standard [11][12].

Current research in the field of metadata can be closely associated with statistics and high-speed processing. Given the exponential increase in electronic resources and media, technologies must be able to accommodate the automation of resources that are viewed, accessed, and assessed. Research examined the role of metadata and its ability to be assessed, arguing that metadata for metadata's sake does no good [13]. Metadata must have some utility as it needs to be assessed and have a role within the decision-making process. Metadata must ultimately serve a purpose and specifically the greater good of the user community. While other research proposes a quality assessment for metadata, it fails to do so with regards to changes in metadata quality, their accompanying values and the holistic structure used to store them [14]. With the standardization of XML-based FGDC and ISO metadata standards, metadata can be compared from one time period to the next. One of these structures is through ontology, a semantic representation of a concept through various domains and properties. Most recently, e-learning technologies were applied to these ontological metadata structures [15]. However, the lack of human cognition within these ontologies cannot eliminate unnecessary or ambiguous terms using results from previous analysis, sometimes referred to as semantic accuracy within the confines of GIS Quality Assessment/Quality Control (QA/QC) circles.

The role of metadata assessment can be seen in a variety of different fields. An Electronic Metadata Record (EMR), for example, is an emerging technology that is produced and edited when an electronic document is edited or created, such as a patient record or digital x-ray. A number of other related technologies for the medical industry have been developed to serve as a quality assurance and administrative tools. The process of accessing, viewing, and commenting on patient files or x-rays by physicians in electronic form can be documented and stored in a metadata file. Hardcopy records are often times time-consuming to complete, and they can be easily lost or destroyed. Thus, the ease of storing, accessing, and retrieving electronic metadata and files for medical data can help prevent litigation against malpractice lawsuits [16]. For example, a complex statistical analysis was developed to retrieve biomedical articles from more than 4,800 journals to help support the decision-making process [17]. It is impossible to scrutinize each of 14 million individual manuscripts. Clustering and classification methods performed on metadata derived from traditional statistical techniques are used to explore and retrieve related information within biomedical literature. If properly maintained, metadata serves as a capable surrogate when querying scanned imagery or hard copy information is not feasible and further validates in-situ decisions as they are reinforced by easily accessible support literature.

Metadata has the flexibility to capture many forms of qualitative and quantitative information stored as numbers, text strings, domain values and dates. However, it does have its drawbacks. In addition to the time, resources and expertise required to populate the information, ancillary concerns exist. Metadata can be applied to any electronic resource, but there are data privacy concerns, especially within the medical community. For example, metadata can be updated and collected to determine the number of times a medical professional has viewed patients' information within the EMR [16]. Not only does this address privacy concerns by documenting access to particular records, but serves to report when, by whom and how long a digital record was viewed. In addition, EMR should not serve as an end-all diagnostic tool, especially when clinical data do exist. Metadata should aid in the evaluation and decision-making process. Other research used image sharing community to further reinforce this point and brought up more excellent points [18]. Metadata for an image (date of image, place, context, etc.) is collected and stored with the image. Furthermore, social metadata not only explores information about the image itself within its place in the social media environment, but also tangential information related to an image such as comments about the image, information about

people who have posted comments about the image and the user groups to which these commenters belong [19]. Limiting this information greatly reduces the amount of analysis that can be performed on the accompanying image, decreasing the availability to knowledge in order to make sound business decisions. As this applies to GIS metadata, a happy medium must be found so privacy concerns can be satisfied while dutiful analysis can be performed. Given the relative infancy of these subjects and lack of established doctrine, the body of knowledge is still growing in this subject.

The very nature of spatial data dictates that a different approach must be taken for assessment and reporting within the digital environment. The proliferation of spatial technologies underscores the widely accepted and legitimate role of metadata within the GIS user community [20]. All elements intrinsic to spatial data, such as those associated with position (e.g. latitude, longitude) as well as its representation (e.g., accuracy) must be carefully documented and recorded in GIS metadata. It is important that information about the data format, a description of the data, the processes by which the data were created, the areal extent of the data and the people who aided in data creation be retained. Formal controls may dictate specific tolerances for horizontal and temporal accuracy. This information is not only important from a legal standpoint, but it also validates GIS analysis by speaking directly to such necessary components as its horizontal and temporal accuracy. Since GIS analysis is only as good as the data on which it is based, metadata reinforces the data and ultimately the analysis and organizations which develop the GIS data.

As mentioned previously, metadata is important in helping to document dimensions of quantifiable GIS data quality such as attribute accuracy, horizontal accuracy and attribute completeness. Other forms of GIS data accuracy do in fact exist. FGDC and spatial data transfer standards (SDTS) also consider vertical accuracy (error in measured vs. represented elevation), data lineage (source materials of data) and logical consistency (compliance of qualitative relationships inherent in the data structure) as part of data quality [21][22]. In some GIS circles, temporal accuracy (age of the data compared to usage date) and semantic accuracy or "the quality with which geographical objects are described in accordance with the selected model" are also considered elements of data quality [23]. Placeholders within FGDC metadata exist to capture all of this information either quantitatively or qualitatively.

Early pioneers of GIS recognized the importance of data quality, not only from a cost efficiency standpoint, but because of the legal ramifications in publishing incorrect spatial information which may lead to accidents or the misuse of data [24]. Even then, they understood the reconciliation between accuracy, the cost of creating accurate data and the eventuality that some error will occur. It is unreasonable to expect an organization such as the North Carolina Department of Transportation (NCDOT) to photo-revise and field check every single road in their GIS database, re-attribute it correctly and then verify them using another party in a timely manner given current personnel and financial constraints. This compromise is referred to as *uncertainty absorption* [25]. Regardless of resource allocation, verification of data quality should be done by discipline experts with a long-term goal of developing data quality standards. This helps to protect the GIS data producer from the potential misuse of GIS data and metadata serves as the means to formally inform the data user of data quality measures applied to data, as well as protect GIS data stewards from its mismanagement [26].

In and of itself, data quality has no inherent value or worth, but is ultimately realized when action is taken on information pertaining to data quality [27]. Along those same lines, the end goal of information quality is to satisfy customer needs, in this case being the many users who utilize GIS data with the understanding that the data have undergone some form of validation [28]. Quantitative measures related to this validation with qualitative processes needs to be highlighted in metadata.

Early research and commentary on the concept of geospatial metadata has touted its value as an effective decision-support tool, regardless of its native format [29].
These formats include Hyper Text Markup Language (HTML), Extensible Markup Language (XML) along with its various ISO standards (19115, 19115-1, 19139), TXT (Text File), Geography Markup Language (GML) and Standard Generalized Markup Language (SGML), as well as proprietary formats. Methodology has explored the ability to integrate spatial metadata to a stand-alone database long before GIS metadata was stored in a standardized format, as well as compiling statistics about metadata elements within the confines of specific software [30] [31].

To that end, the population of geospatial metadata is a monotonous process and subject to error, although research has explored the large-scale production of standards-based metadata in order to alleviate these issues [32] [33]. Because of this, research maintains that human nature alone undermines the immediate and long-term goals of metadata for an organization and the GIS user community [34]. While the omission of one minor element would not degrade a layer's metadata or invalidate the geospatial data on which it is based, it may compromise quantitative data quality measures captured from which decisions can be made. More recently, feature level metadata has been able to capture data quality information, but is typically limited to quantitative measures of positional accuracy and qualitative information related to data lineage within eight of the more than 400 entries that comprise a complete FGDC-compliant metadata file [35] [36]. Even now, the population of these metadata elements is not fully automated and some entries must be done by a GIS data steward. However, methodologies to explore its assessment and evaluation are evolving. Efforts have been made to quantitively assess metadata quality using both a human and statistically-automated element [37] and this paper explores this notion within the confines of and applied to a particular standard.

III. THE NORTH CAROLINA STATE AND LOCAL GOVERNMENT PROFILE

Geospatial metadata standards serve as a cohesive and standardized means by which organizations can define, store and more importantly share information about geospatial data. It defines the categories of information that needs to be stored, individual entries, or tags, of individual elements within these categories and the types of data (text, date, number) and their lengths that can be stored while representing these tags. FGDC metadata is divided into 7 sections or divisions that transcend descriptive, administrative and structural components. They are: Identification Information, Data Quality Information, Spatial Data Organization Information, Spatial Reference Information, Entity and Attribute Information, Distribution Information, and Metadata Reference Information [38].

Within these high-level divisions, subdivisions and eventually individual metadata tags can be populated to catalog various forms of information about the GIS data layer. The hierarchy of these divisions and subdivisions are consistent with a standard. In addition to providing this structure, the FGDC also creates guidelines by dictating which metadata elements are to be populated. The FGDC requires seven metadata elements be populated for all GIS data. The FGDC also suggests that fifteen metadata elements be populated. These suggested and required elements are included in Table I below.

TABLE I: REQUIRED AND SUGGESTED FGDC ELEMENTS.

FGDC -Required Elements	***FGDC- Suggested Elements***	
Title Reference Date Language Topic Category Abstract Point of Contact Metadata Date	• Dataset Responsible Party • Geography Locations by Coordinates (X) • Geography Locations by Coordinates (Y) • Data Character Set • Spatial Resolution • Distribution Format • Spatial Representation Type • Reference System	• Metadata Character Set • Lineage Statement • Online Resource • Metadata File Identifier • Metadata Standard Name • Metadata Standard Version • Metadata Language

Organizations actively create content standards for new technologies and manners in which geospatial data are collected and stored. One such example is the FGDC content standard for Remotely Sensed Data. This includes two divisions germane to the equipment and methods such as platform name, sensor information and algorithm information used to capture the imagery, in addition to the seven existing aforementioned divisions [39]. In order to further elucidate descriptive, administration and structural information, additional addendums to existing metadata standards are also attached to specific geospatial-specific data such as addresses, biological data, shoreline data, and vegetation data. Standards such as these must be increasingly flexible and updatable to account for the evolving technologies in which geospatial data can now be captured (crowdsourcing, Unmanned Aerial Vehicle, large scale geocoding), processed (new geostatistical and interpolation algorithms) and ultimately delivered (web map service, web feature service) to the GIS user community.

In recent years, the North Carolina SMAC has recognized most GIS data managers lack the time and resources necessary to learn and apply a metadata standard that maintains dataset integrity and retains pertinent information while not being too demanding on existing resources, most notably time and people. To address the problem of missing or incomplete metadata records among state and local data publishers, the SMAC chartered an ad-hoc Metadata Committee in October 2012 to "recommend ways to expand and improve geospatial metadata in North Carolina that are efficient for the data producer and benefit data users in the discovery and application of geospatial data." The Metadata Committee submitted a draft of this profile, based on the ISO 19115 (for Geographic Information – Metadata: 2003), ISO 19115-1 (for Geographic Information – Metadata – Part 1: Fundamentals: 2014) and ISO 19119 (Geographic Information – Services: 2016) standards. After review and modification by SMAC and its standing committees, the most current version of this standard has been in effect since December 30, 2016 and is available through the NCOneMap portal [40]. While not entirely ground-breaking, North Carolina has been a forerunner in developing sub-country metadata standards. The SMAC worked with the Canadian Province of Alberta, who has already developed a standard germane to their province while states such as Missouri and Virginia have developed some level of uniform metadata available with their products. Internationally, GeoDCAT-AP is a metadata profile designed to facilitate interchange for data portals operated by EU Member States. It uses the aforementioned ISO 19115 format and the INSPIRE metadata standard, which is primarily used in Europe [41].

Given seven required and fifteen recommended metadata elements are fairly ambiguous and less than ideal for many organizations whose data is integrated into the NCOneMap, the North Carolina state geospatial data portal, this profile provides explicit guidance on required/suggested metadata elements, wording for these elements, standardization of naming/date conventions and domain fields for topic categories for more than 75 metadata tags [42]. A few examples of the rules for geospatial metadata include:

1. Title is required as a free-text entry.
2. Publication Date is required and the format for Publication Date is YYYY-MM-DD or YYYYMMDD. If day is not known, use YYYY-MM and use YYYY if month is not known.
3. Abstract is required as a free text entry. Do not use YYYYMM since it can't be distinguished from the incorrect, but still used YYMMDD.
4. Status is required and only possible values are 'historicalArchive', 'required', 'planned', 'onGoing' 'completed', 'underDevelopment' and 'obsolete'.
5. Topic Category is required and can be one of 23 possible values from domain table.
6. Use Constraints required as a free-text entry to describe any restrictions with using the data.

7. Online linkage is required to an URL address that provides access, preferably direct access, to the data.

In addition, given their nature and distinct differences between their geospatial data counterparts, the SMAC has defined rules for geospatial services to include the following:

1. Metadata Scope code must be 'service'.
2. Online Function code is required from domain of one of five possible values.
3. Title is required as a free-text entry.
4. Metadata Contact is required as a free-text entry, representing Organization Name of the agency that serves as a point of contact for the metadata record.

This richer metadata enables content consistency and improves the search and discovery of data through NCOneMap.

As part of a needs assessment for this project, a survey was developed to help dictate and direct metadata needs within the state of North Carolina. This survey was developed in 2017 and distributed to the North Carolina GIS user community. Forty (40) respondents answered the survey, who ranged from GIS Technicians and Property Mappers to GIS Coordinators and Managers throughout the state of North Carolina. Questions were asked about respondents' experience with data development, metadata, as well as organizational requirements as it pertains to metadata.

Most prominent was the schism between respondents' experience with data development and experience with metadata, as shown in Figures 1 and 2. Respondents generally had an 'excellent working knowledge' of data development, but only 'some experience' or 'working knowledge' on the metadata created as a result of these data development techniques. These underscore technical experience in creating new data in support of analysis and projects, but less experience in cataloging these same data used for analysis and maps.

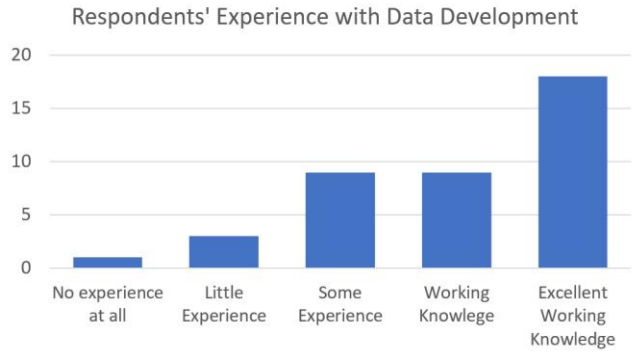

Figure 1: A survey of GIS professionals and experience with data development.

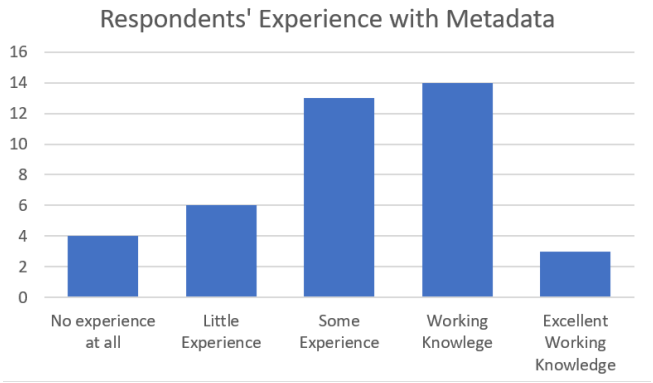

Figure 2: A survey of GIS professionals and experience with metadata.

Not only is this schism evidenced at the individual level, but also at the organizational level. In a same survey of these 40 GIS professionals, they describe their organization's approach to metadata as shown in Figure 3. More than half of all respondents' organizations have no metadata requirement whatsoever and only five respondents work in an organization that has a firm metadata requirement. The rest do have a metadata requirement, but it is not upheld.

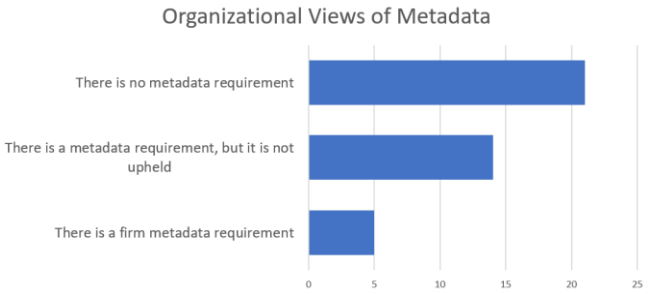

Figure 3: A survey of metadata requirements at the organization level.

In response to this need and the motivation for this paper, the research team earned a research and education grant through the NCDOT and NCGICC to provide metadata training, education and support to the state of North Carolina. The goal of the "Facilitating the New Statewide GIS Metadata Standards Through Training and Outreach" grant ran from August 2016 through March, 2019. The goals of this project include:

1. Assessing the existing knowledge base of GIS users on the subject of GIS metadata through surveys given to training attendees.
2. Technical and material support to the implementation and education of the new metadata profile to the North Carolina GIS user community.
3. Understanding needs of GIS data managers when it comes to metadata population and requirements for data under their purview through surveys given to GIS data managers.
4. Determining best methods to deliver metadata training to the North Carolina GIS user community that close gaps

between existing knowledge base and needs of GIS data managers and the larger NC GIS community.
5. Assessment and evaluation of training activities to determine best practices for future training and future support through post-training quantitative and qualitative surveys.

This grant has provided support to the North Carolina GIS user community through an assessment and evaluation of current metadata activities by the North Carolina GIS user community, work on the North Carolina State and Local Government Metadata Profile, development of online and face-to-face training materials and data in response to this evaluation, and the delivery of face-to-face and virtual training to the North Carolina GIS user community. This grant has provided the opportunity for North Carolina Central University (NCCU) students to develop metadata skills and interface with members of the North Carolina GIS user community in this niche and unique training opportunity relatively unique to this state. As such, specific measurable research tasks over the life of the project include:

1. Curriculum Review and QA/QC
2. Material and Training Support
3. Data Development
4. Facilitation of Online Resources
5. Development and Assessment of Metadata Templates
6. Development of Metadata Scripts
7. Report of Training Activities
8. Outreach to Educational Institutions and Professional Organizations

In support of many of these tasks, face-to-face training was provided on the campus of North Carolina Central University (Figure 4), as well as online.

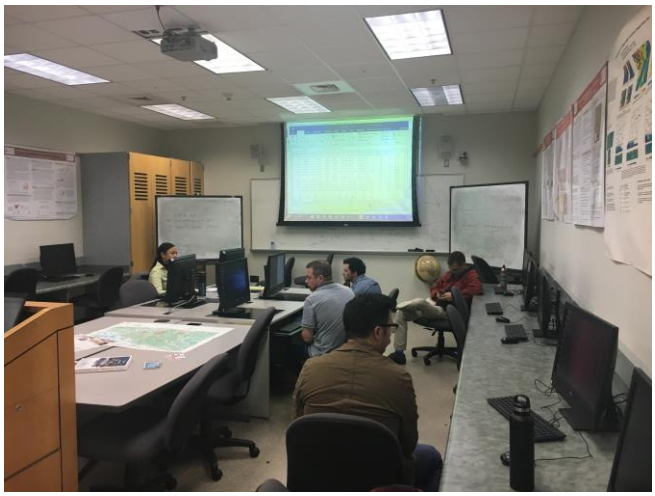

Figure 4: Face-to-face metadata training given at North Carolina Central University in 2018.

The Department of Environmental, Earth and Geospatial Sciences (DEEGS) at NCCU hosts YouTube tutorials ranging from metadata basics and the use and application of the North Carolina State and Local Government Profile to more advanced topics such as XML translators and Python programming solutions in metadata assessment and evaluation [43]. These tutorials have been utilized more than 3,500 times.

IV. ASSESSING STANDARD COMPLIANCE

Given the ever-increasing size of GIS data sets and the metadata requirements for each data layer, there needs to be a mechanism to assess the quality of these metadata not seen in previous generations or documented in existing literature. There also needs to be a means by which individual metadata entries adhere to predefined profiles and standards. This is in support of Task 6 of the research tasks. Computer programming languages and templates have helped to streamline this process. Templates populate redundant features that are common throughout an entire GIS database such as the purpose, supplementary information, distribution liability statements and ordering instructions that can be specific to an agency or department. These templates can be imported one at a time, but programming techniques and software packages have allowed users to assess information that would take a human days or perhaps weeks to do. The NCGICC provides a number of templates through their web portal, NCOneMap [44]. The themes for these templates are at the request of North Carolina GIS users, and include buildings, cadastre, municipal boundaries, school attendance districts, street centerlines, address points and orthoimagery. These templates contain much of the verbiage about a layer's description and creation processes, and can be easily imported and edited specific to the user's contact information. A sample of the identification information for the cadastral data template can be seen in Figure 5.

```
  Description:
    Abstract: Digital cadastral data describing the parcel dataset of ZZZZZ County,
North Carolina.  This dataset includes attributes such as parcel boundaries,
ownership, acreage, source references, assessments, and other core cadastral
attributes.
    Purpose: This dataset was generated to publish a geospatial inventory of real
property in ZZZZZ County, NC.  It serves to support and assist governmental agencies
and others in resource management decisions. Additionally, these data provide a set
of core attributes defined by North Carolina Content Elements for Statewide
Publication of Core Geospatial Parcel Data and is used to facilitate the sharing,
display, and use of cadastral data across the state.  The core data are intended to
integrate local parcel information on a statewide level and eventually build a
seamless parcel map for North Carolina.
    Supplemental_Information: This dataset is prepared for the inventory of real
property found within this jurisdiction and is compiled from recorded deeds, plats,
and other public records and data.  Assessed value of real property is based on
market value as defined in the Machinery Act of North Carolina (Section 105-283). The
latest assessment was completed in 88888.  Users of this dataset are hereby notified
that the aforementioned public primary information sources should be consulted for
variation of the information contained in thes data.  ZZZZZ County assumes no legal
responsibility for the information contained in these data.
  Time_Period_of_Content:
    Time_Period_Information:
      Single_Date/Time:
        Calendar_Date: 20051207
```

Figure 5. Identification information metadata entries for cadastral template provided through NCOneMap web portal.

Open source programming solutions using Perl and R have been used to assess and evaluate metadata by traversing geospatial metadata stored in XML format as per FGDC requirements, resulting in quantitative metrics, graphs and reports regarding metadata compliance, as shown in Figure 6 [45].

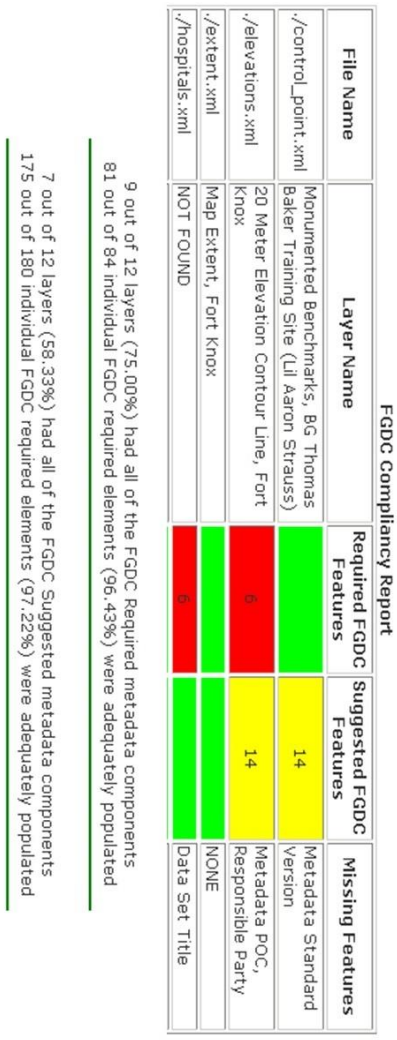

Figure 6: Sample of Metadata Compliance Report Generated Using Open Source Assessment Tool.

As applied to the NC State and Local Government Profile, one major challenge exists. Primarily, geospatial data and metadata is typically software specific. While optimal open source solutions could be used to gleam information from metadata stored in XML using an appropriate xPath, these software-agnostic solutions are typically loosely-coupled and not intuitive to the average user. As a result of reliance on Esri products throughout the state, the Python programming language is being used to run this iteration of an assessment and evaluation tool before open source solutions are explored.

Using the NC State and Local Government Profile as a guideline, the research team has been developing tools for data managers to access and evaluate metadata entries. At the current time, metadata entries are written to CSV (Comma Separated Values) files. While doing this, string operations are run to ensure that required entries are populated, date entries comply with required conventions and domain entries match those in the domain table, all while agglomerating results and statistics at the database, layer (record) and tag (attribute) level. This can provide GIS managers with insight on non-compliant metadata entries to determine relationships between non-compliant entries and the responsible data steward or particular attributes that are continually non-compliant.

While QC procedures need to be performed to determine if a metadata entry is accurate, below are a few examples of the many programming rules employed to determine if entries are populated properly.

1. *Title, Responsible Party Organization Name, Online Linkage, Abstract, Use Constraints, Feature Catalogues, Process Description, Spatial Reference Information* and *Metadata Contact Name* cannot be Null
2. *Data Type* can only have values of ‘creation’, ‘publication’, or ‘revision’.
3. *Publication Date, Temporal Extent of Data* and *Metadata Creation Date* must follow appropriate format. This entails:
   a. The date cannot be Null and must be populated.
   b. The date can only have a length of 10 (YYYY-MM-DD) 8 (YYYYMMDD), 7 (YYYY-MM) or 4 characters (YYYY).
   c. Besides the hyphens (‘-‘), the date can only contain numbers whose value range from 0 through 9. Letters and other characters are not allowed.
   d. If a date contains hyphens (‘-‘), there will be 2 hyphens in a string that has a length of 10 (YYYY-MM-YY) and there will be 1 hyphen in a string that has a length of 7 (YYYY-MM).
   e. Regardless of the format used, the first character of a string will either be ‘1’ or ‘2’ since the year of publication or creation will begin in only those 2 numbers.
4. *Metadata Contact Role Code* can only have values of ‘custodian’ or ‘pointOfContact’.
5. *Progress Code* can only have values of ‘completed’. ‘historicalArchive’, ‘obslete’, ‘onGoing’, ‘planned’, ‘required’ or ‘underDevelopment’.
6. *Maintenance and Update Frequency* can only have values of ‘continual’, ‘daily’, ‘weekly’, ‘fortnightly’, ‘monthly’, ‘quarterly’, ‘ biannually’, ‘annually’, ‘asNeeded’, ‘irregular’, ‘notPlanned’ or ‘unknown’.

The current application has a basic GUI (Figure 7) that allows for 4 input parameters: 1) an input database that contains the features classes for which metadata will be checked 2) an output folder to which XML metadata is written. Python cannot directly access metadata in geodatabase format, so this proprietary metadata is converted to XML format and traversed. Options exist so these XML files are immediately deleted. 3) The name and location of the output entries that store all metadata entries that are checked from the North Carolina State and Local Government Profile, as well as a summary of the percentage of individual metadata elements that are correct and a summary of percentage of correct elements on a feature class by feature class basis and 4) the location of an error file that highlights errors within the metadata (Figure 8).

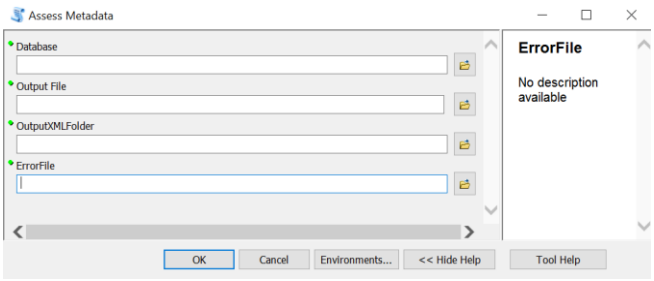

Figure 7: Metadata Assessment and Evaluation Tool.

spot_elevation_point:

The Title is: spot_elevation_point
THE PUBLICATION DATE IS MISSING
THE RESPONSIBLE PARTY IS MISSING
THE ONLINE LINKAGE IS MISSING
The Abstract is PRESENT
THE PROGRESS CODE IS MISSING
THE UPDATE FREQUENCY IS MISSING
The Theme Keyword Does Not Match The ISO Topic Categories Criteria -> landform
The Use Constraints are PRESENT
The Topic Category is PRESENT
The West Extent is PRESENT
The East Extent is PRESENT
The North Extent is PRESENT
The South Extent is PRESENT
THE BEGINNING DATE FOR THE TEMPORAL EXTENT IS MISSING
THE ENDING DATE FOR THE TEMPORAL EXTENT IS MISSING
THE FEATURE CATALOGUE IS MISSING
THE PROCESS DESCRIPTION IS MISSING
The Spatial Reference is: WGS 1984 UTM Zone 17N
The Metadata Creation Date Starts with '2', 21st Century
The Metadata Creation Date Has FULL Date Listed!
THE METADATA CONTACT NAME IS MISSING
The Purpose is PRESENT
THE POINT OF CONTACT IS MISSING

Figure 8: Sample Error File Output from Metadata Assessment and Evaluation.

V. RESULTS

The Technology Acceptance Model (TAM) was used to assess and quantify the effectiveness of the metadata assessment tool. The TAM that we know of today was originally created as a means to universally quantify the effectiveness of technology by exploring relationships between the technology's Perceived Ease of Use, Perceived Usefulness, Attitude Towards Using and the Intention to Further Use the technology [46]. Using Chronbach's Alpha, Principal Components Analysis and Simple Linear Regression, associations can be found between these various components, as shown in Figure 9.

Given that the intended usership of this research is geared towards GIS professionals as opposed to developers or programmers, a testing mechanism geared toward this group would be more appropriate than testing code efficiency or complexity. The TAM has served as a means to assess and quantify the effectiveness of a technology for more than 35 years and will do so once again for this research. The TAM was originally created as a means to universally quantify the effectiveness of technology [46]. It was born from the fact that the adoption of new technologies is dependent upon ambiguous and sometimes qualitative notions such as psychological disposition, attitudes, intentions and our own personal biases related to this new technology that make it difficult to test and validate [47]. TAM is actually the technical manifestation of the Theory of Reasoned Action (TRA) [48]. TRA is the theory in which beliefs, composed of attitudes, values and opinions at the individual level, eventually result in enacted behavior. Within the TAM, this enacted behavior is the decision to adopt technology.

Empirical studies on the use and application of TAM find that a technology's acceptance is most related to its 1) Perceived Usefulness and 2) Perceived Ease of Use. Perceived Usefulness refers to the quality in which a technology would help one's job performance. While research [49] [50] [51] has explored this usefulness dimension, TAM also looks at this in concert with this technology's "freedom from difficulty or great effort" [45]. This ease of use factor helps support the self-efficacy theory which focuses on one's innate ability to accomplish goals [52]. While there are differences between the roots of this effectiveness and seminal outcomes which at times can be paradoxical, TAM encapsulates this within one encompassing desired end-state of ultimately accomplishing one's tasks with as little effort as possible. Studies have actually shown the relationship between this Perceived Usefulness and Ease of Use with the adoption of technology is regardless of variables such as gender and computer experience [53].

Using these two indicators as a guideline, Davis creates questions that try to explain the usage and acceptance patterns of a technology as per TRA. Users of the technology are asked to scale responses to these questions similar on a 7-point Likert-type scale, representing "Strongly Agree" through "Strongly Disagree". Regression analysis between this effectiveness and ease of use variables is determined at various confidence intervals. In addition, principal components analysis is used to explain the variance of usage intentions as a function of Perceived Usefulness and this attitude towards the technology. This and other hypotheses related to Perceived Usefulness, Perceived Ease of Use, Attitude Towards Using the technology and behavioral intention of use are tested among each other [54].

TAM represents a milestone towards understanding human behavior as applied to the technology realm. Germane to this research, TAM has been applied to e-learning [54] as well as its place in the e-commerce environment as TAM integrates technology and human behavior when applied to online shopping [55]. Visiting an online store for the first time has overwhelming consequences on whether the visitor will visit again or make unplanned purchases. Making this online shopping experience an easy, enjoyable and memorable one is of utmost concern to these businesses. The order in which material is presented, the amount of material presented and the user's cognitive impression of this material, its volume and its underlying messages play into this perceived enjoyment factor. Finally, all of these facets need to be assessed in a manner free of bias, confusion, misconception and misunderstanding.

The validity of these assessment tools was tested using a TAM. Responses from GIS professionals regarding the results of this methodology were captured to find a relationship between this technology's Perceived Ease of Use, Perceived Usefulness, Attitude Towards Using and the Intention to Further use this technology.

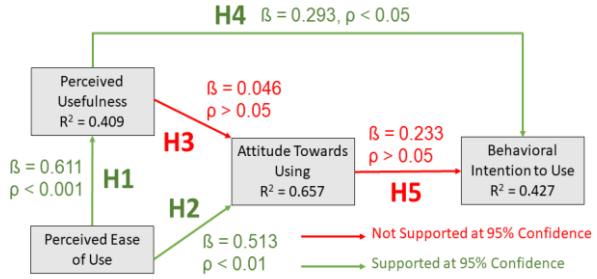

Figure 9: Regression Used to Test Research Hypotheses where TAM was Tested Against Null Hypotheses to Test Correlations.

The results from TAM analysis (Figure 9) show 3 out of the 5 research hypotheses (H1, H2 and H4) relating the tool's Perceived Ease of Use, Perceived Usefulness, Attitude Towards Using and Intention to Use were accepted at a 95% confidence interval. Another (H5) could be accepted at about a 70% confidence interval. In one non-supported hypothesis (H3), it seemed that the strong responses from the Perceived Ease of Use component obfuscated the Perceived Usefulness component. As a result, the Perceived Usefulness did not have much of an effect on the linear regression model used to support the hypothesis. In the other model (H5), the dependent variable is the Intention to Use component using the Attitude Towards Using component as the independent variable. The two components delve into the question of implementing these assessment tools onto their individual system and have elicited a wide array of responses from respondents due to technical experience and familiarity or understanding with the programming environment, which is essentially an extension to the typical GIS system and typically requires training above and beyond that of a GIS Technician or Junior Analyst. While the efficacy for these programming solutions exists, the efficiency may not reciprocate for this reason. Nonetheless, these are difficult to model. Even modeled by themselves without the Perceived Usefulness component, a linear regression model between these two factors (Attitude Towards Using MART vs. Intention to Use) only produces an R^2 value of .118. Other factors – either those not captured within the assessment or just unquantifiable by their very nature factor into the non-support of this hypothesis. For example, GIS Technicians working on few GIS data layers have little to no need for metadata assessment and therefore no intention to further use it. When enough GIS Managers have completed the assessment on which TAM is based, it will be run once again on this new tool to assess its effectiveness for a more germane usership. Regardless, these results help satisfy the theoretical impetus of this research and are both intriguing and promising for the future of GIS metadata and widening role as an effective tool to elicit action.

VI. DISCUSSION

While a powerful and efficient tool, the programmatic assessment and evaluation of geospatial metadata still cannot altogether replace the human component. While these technologies can traverse metadata schema and extract tags to deem if they are complete, compliant or belong to a particular domain, it does not necessarily mean they are correct. For example, while the *Publication Date* tag may be properly populated (2016-02-29 for example) as per the rules dictated in the North Carolina State and Local Government Profile, it may not necessarily mean the data were published on that date. QA/QC techniques should be used to determine metadata quality across the entire dataset via American National Standards Institute (ANSI), American Society of Quality Control (ANSQ) or other institution-wide QA/QC procedures that best fit needs, resources and limitations.

While the level of attribution within metadata has improved with each new standard and this particular profile, it is in no way complete. As technologies improve and there include more diverse ways to collect, manipulate and create GIS data, metadata must be flexible enough to accommodate all of these techniques. For example, the standard CSDGM does not contain placeholders germane to the collection of data created via a GPS unit like the various Dilution of Position (DOP) measures such as vertical, horizontal and 3D. In addition, detailed information directly associated with the quality of data specific to GPS-collected data such as ephemeris can be entered via a free text field, but lacks the placeholders within the CSDGM as well as this standard. In addition, GIS data now extend well beyond the typical raster and data models that a GIS professional may have solely encountered only a decade earlier. GIS data may now include stand-along tables, Triangulated Irregular Networks (TINs), relationship classes and even topologies. They each have their own intrinsic qualities that make their creation and update difficult to encapsulate within a single catch-all metadata format.

In addition, TAM does have its limitations. TAM may not adequately explain for social influences [56]. More specifically, it is difficult to discern whether intent, attitude or some other referent characteristic sufficiently explain usage behavior. Principal Component Analysis can only do so much within the paradigm of the testing environment. In addition, it is difficult to explain how this physiological attachment related to attitude and behavioral intention can be assessed within TAM. Research has attempted to explain this by expanding the dimensionality of testing elements within a rotated component matrix, but this begins to fall outside of the scope of this research [57]. Nonetheless, any technology is an investment. Even using this model, it is difficult to realize the value of the large-scale investment for

an organization at an individual level given the multiple intrinsic behaviors and intentions independent of this organizational goal.

While the intersection of these various subjects serves as the theoretical impetus of this research, assessing these techniques can take on a variety of different forms. How will technology be further disseminated in the working world? How can this technology be assessed? While factors such as lost income and usership are quantitative in nature, they are interwoven with determinants such as marketing, depth and level of human-computer interaction, organizational structure and management of the technology, which are tangential at best to this technology. Some of these factors do not speak to the effectiveness of the technology, but the diffusion of this technology which helps to proliferate its use. With this 'chicken or the egg' scenario, it is sometimes difficult to compartmentalize a valid measurement scale to assess technology acceptance alone for a single piece of technology within the user community.

VII. CONCLUSION

The increasing schism between the rate at which data are created and the efficiency at which the metadata are assessed serves as the impetus of this research. GIS metadata serves as the means by which spatially-related phenomena can be catalogued within a formal framework. It is here where implicit information can be codified for use by the larger GIS community. Given the ever-increasing size of GIS data sets and the proficiency with which GIS data are created, there needs to be a mechanism to educate, assess and evaluate the human element to keep up with this proficiency. A means has been created to educate and inform a statewide GIS data community about a new standard, created by North Carolinians for North Carolinians based on input from North Carolinians. Programming techniques and software packages have allowed users to assess descriptive information about this standard that would take a human days or perhaps weeks to do.

In addition to addressing the quantitative need for metadata as well as a means to educate the GIS community about the salient procedures and technologies necessary to be conversant in the science of metadata, this paper addressed solutions to educate a statewide community about metadata as well as measure adherence to a state-level profile. As per one of the goals of this paper, a programmatic solution using the Python programming language has been implemented. However, it is too early to tell how well these can be integrated into business processes at organizations such as the NCGICC. Revisiting this at a later time will provide time for acceptance of these techniques into mainstream GIS with little to no prior programming knowledge.

This research highlights the importance and need of programmatic approaches to the assessment and evaluation of metadata for large spatial datasets. This information can provide GIS Managers with already limited resources with the tools to make informed decisions that are not feasible with visual inspection or a qualitative understanding of these increasingly large datasets.

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A Constructivist Grounded Theory of Trust in Agile Scrum Teams

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***Abstract*— As Scrum is predominantly a team-based activity, it is consequently an intensely social endeavour. In order to deliver on the mutually agreed goals of the Sprint, Scrum teams need to collaborate and share knowledge effectively. Many authors have cited trust as being crucial to fostering collaboration and knowledge sharing. However, to date there has been no published research into this crucial social construct in the context of agile software development teams. This paper revisits the conceptual model of trust presented at SOFTENG 2018 in light of the findings from a preliminary Constructivist Grounded Theory study conducted on two Scrum teams in a major multinational software development company in the West of Ireland.**

Keywords-Agile; Scrum; Team; Trust; Collaboration; Knowledge-sharing; Constructivist Grounded Theory;

I. INTRODUCTION

Agile software development is a "task oriented, social activity [1]." This is particularly true of Scrum, the ubiquitous software development framework most closely associated with Agile. The Agile Manifesto [2] advocates "business people and developers must work together daily throughout the project... build projects around motivated individuals. Give them the environment and support they need and trust them to get the job done." In Scrum, this is accomplished by the Scrum team. The Scrum team is vital to achieving the goals of the software development initiative.

As Moe, Dingsøyr and Dybå posit "Software development depends significantly on team performance, as does any process that involves human interaction [3]." In part, this is because, according to Schwaber, "When people work by themselves, they can achieve great things. When people work with others, they often achieve synergy, where the joint effort far exceeds the sum of the individual efforts [4]." In order to fully achieve synergy team members need to share knowledge within the team and collaborate to achieve the goals of the Scrum Sprint, which is the timeboxed period used to develop a software increment. Dorairaj, Noble and Malik cite trust as "one of the key factors [5]" in successful Agile projects. Largely this is because, "trust has been found to be a critical factor facilitating collaboration [6]." Tschannen-Moran elucidates, "collaboration and trust are reciprocal processes; they depend upon and foster one another [7]." With regard to knowledge sharing Ghobadi posits "the unique and inherent characteristics of software development signify the importance of effective knowledge sharing, referring to the exchange of task-related information, ideas, know-hows, and feedback regarding software products and processes [8]." Butler refers to research conducted by Zand when he states that "trust leads to the disclosure of information [9]." Furthermore Zand describes how "persons who trust one another will provide relevant, comprehensive, accurate, and timely information, and thereby contribute realistic data for problem-solving efforts [10]." The study by Fields and Holste acknowledged the role of trust in a "willingness to share and use knowledge [11] ."

Whilst trust has often been included in the academic discourse it has predominantly been through a sociological, psychological, economic or organizational lens. Consequently, the findings have been somewhat incongruous when applied to a software development context. McKnight and Chervany referred to the lack of consensus about trust as causing "conceptual confusion [12]." In this study a preliminary constructivist grounded theory will be presented which seeks to understand the construct of trust and how it develops in the Agile Scrum software development team engaged in the development of software products.

Section II of this paper presents the background to the study in terms of knowledge sharing, collaboration and trust. Section III outlines the research that was conducted including a breakdown of the study methodology and how it was implemented. Section IV presents the results of the research and leads into Section V, where the findings are presented. Section VI presents a discussion of the results and leads into Section VII which examines the limitations of the research. Finally, Section VIII concludes and outlines the plans for future work.

II. BACKGROUND

According to the co-creators of the Agile Manifesto, Scrum teamwork is characterised by "intense collaboration [2]." Tabaka specifically refers to the concept of collaboration in a software development context, citing as useful, the sharing of "ideas, information, decisions and

solutions [13].” The relevance of collaboration to Agile software development was highlighted by Nerur, Mahapatra and Mangalaraj who expounded “A cooperative social process characterized by communication and collaboration between a community of members who value and trust each other is critical for the success of agile methodologies [14].” It is important for the team to work cooperatively to share information where cooperation, according to Collier involves the “ smooth transfer of work in progress, work products, and information from one member to another [15].” Collaboration, by contrast, “elevates groups beyond cooperation, adding an essential ingredient for emergent, innovative, and creative thinking [15].”

Ghobadi and Mathiassen posit, “Software development is a collaborative process where success depends on effective knowledge sharing [16].” Thus it may be argued that knowledge sharing plays a vital part in enhancing the success of the Sprint. As Ryan and O’Connor assert “knowledge sharing is a key process in developing software products [17].”

In order to facilitate collaboration and knowledge sharing in a Scrum team there is one key ingredient, which binds the team together, trust. Chen, Lin and Yen state unequivocally that “trust leads to better inter-organizational collaboration and knowledge sharing [18].”

A. *Knowledge Sharing*

Cummings (2004) argues that knowledge sharing within a group “includes the implicit coordination of expertise … and information about who knows what in the group [19].”

There are two types of knowledge which are of vital significance in Scrum teams, explicit knowledge and tacit or implicit knowledge. The distinction between these two distinct types of knowledge was highlighted by Nonaka in 1994 when he wrote about the “joint creation of knowledge [20]” in organizations. Wyatt defines explicit knowledge as consisting of “of facts, rules, relationships and policies that can be faithfully codified in paper or electronic form and shared without need for discussion [21].” Nonaka concurs, describing that explicit knowledge “refers to knowledge that is transmittable in formal, systematic language [20].”

By contrast, Nonaka maintains that tacit knowledge is “a personal quality, which makes it hard to formalize and communicate. Tacit knowledge is deeply rooted in action, commitment, and involvement in a specific context [20].” Chau et al. posit that tacit knowledge includes “system knowledge, coding convention, design practices, and tool usage tricks [22] .” The authors argue that “developers tend not to document this knowledge and it is usually not explicitly taught through formal training [22].”

From a Scrum team perspective the sharing of both types of knowledge is crucial to Scrum team performance since as Levy and Hazzan claim “software development work requires various forms of explicit as well as implicit knowledge [23].”

At the outset, in a Scrum team, the Sprint Planning meeting is the forum where the product backlog is discussed and negotiated. In general the information is shared explicitly among the team members. However, when the Sprint commences it is not unusual for developers to discover obstacles which are shared with the team at the Daily Scrum. The sharing of information at the Daily Scrum is mostly explicit in nature given that the team uses the meeting as the vehicle to describe what progress has been made during the previous day; what progress is expected to be made in the current day and what, if any, blockers are impeding progress and causing an impasse in the development.

However, knowledge sharing, whilst vital is not sufficient on its own for successful software development. Judy and Krummins-Beens describe how the Agile Manifesto emphasizes “collaboration among team members and project sponsors [24].”

B. *Collaboration*

Tabaka establishes the importance of collaboration by stating that “when teams declare a collaborative imperative in their work, it is their pledge to employ consensus-based decision approaches through participatory decision-making. They apply high-bandwidth information gathering coupled with well-formed and well-articulated priorities [13].” The Agile Manifesto argues strongly for collaboration advocating “customer collaboration over contract negotiation [2]” and “developers must work together daily throughout the project [2].” Fowler and Highsmith contend that “only through ongoing collaboration can a development team hope to understand and deliver what the client wants [25].” Tabaka summarises that collaboration in Agile has become “an integral component of what would be considered a responsive, adaptive software development approach [13].” Chau and Maurer concur, positing software development is “a collaborative process that needs to bring together domain expertise with technological skills and process knowledge [26].”

That Scrum software development is a collaborative endeavour is undeniable. The Agile Manifesto advocates strongly for “face-to-face conversation [2].” Paulk argues that this can best be achieved by having the team members in close proximity to each other, stating “Agile teams are expected to be co-located [27].” In Scrum, Deemer *et al.* advocate “An excellent practice is for the team to be collocated [28].” In addition to the informal opportunities offered by collocation of having team members discuss ideas and solutions to possible problems the Scrum framework has a number of events which facilitate

knowledge sharing and problem solving by providing opportunities for collaboration.

McHugh, Conboy and Lang cite "sprint/ iteration planning, daily stand-up, and sprint/iteration retrospective [29]" as three key practices which require the "collective participation of all team members with a focus on people, communication, interaction, and teamwork [29]."

The Sprint planning meeting is the timeboxed meeting which happens prior to each iteration. It is at this meeting that the planning for the upcoming Sprint "is created by the collaborative work of the entire Scrum Team [30]." It is at this meeting that the Scrum team negotiates a shared understanding of the work to be completed for the upcoming Sprint.

The development team uses the Daily Scrum or Daily Stand-Up as it is often called "to inspect progress toward the Sprint Goal and to inspect how progress is trending toward completing the work in the Sprint Backlog. The Daily Scrum optimizes the probability that the Development Team will meet the Sprint Goal [30]." The Daily Scrum is the optimum vehicle for collaboration since it considers what was accomplished in the previous day of the Sprint. It explores what will be achieved in the coming day and it seeks to clarify what, if any, impediments exist to progress. It is at this point that collaboration comes into its own. If a team member has a particular obstacle which is causing an impasse to progress, the team can come together to brainstorm possible solutions in what Levy and Hazzan refer to as a "*collaborative workspace* – a space which supports and facilitates communication [23]."

In similar vein, the Sprint Retrospective is the forum to "encourage the Team to revise, within the Scrum process framework, its development process to make it more effective and enjoyable for the next Sprint [31]."

C. Trust in the Academic Discourse

Mach, Dolan and Tzafrir argue, "trust is an integral part of teamwork because team tasks require a high level of interdependence between members [32]." Furthermore, Sandy Staples and Webster postulate, "team members must rely on each other and share required knowledge with others. If sharing does not happen within the team, it is unlikely to meet its objectives [33]."

As previously stated, the literature on trust examines it from a number of different perspectives. Consequently the result is highly fragmented and unintegrated when it comes to applying it to the Scrum team context. Nevertheless, it is possible to take some generalities from the extant research into trust.

Sociologists have often seen trust as a type of mystical 'faith' that one person has in another. Simmel in 1950 wrote "confidence is intermediate between knowledge and ignorance about a man. The person who knows completely need not trust [34]." Giddens would appear to concur advocating "There would be no need to trust anyone whose activities were continually visible and whose thought processes were transparent [35]." It is likely that from a psychological viewpoint these sociologists were referring to trusters having a "propensity to trust" or "trusting disposition" as referred to by Rotter [36] and McKnight and Chervany [12].

The notion of expectancy or expectation is often synonymous with trust in the literature. Largely this notion emanates from the realm of social psychology. Deutsch offers as a definition of trust that "Person I trusts Person II to do something and I perceives that the behavior he expects of Person II is perceived by II to have relevance to I [37]." Barber concurs with Deutsch acknowledging that trust is "a dimension of all social relationships [38]." In his seminal volume The *Logic and Limits of Trust* he describes how actors in social relationships have "expectations" of each other [38]. Given that expectation has the connotation of often being reciprocated, Deutsch associated trust with a "reciprocal, cooperative relationship between people who make the decision to trust [1]." Additionally Deutsch introduced the notion of 'competence' being involved in the fulfilment of expectations. One can only meet someone's expectations, if one has the competence to so do.

Gabarro added to Deutsch's notion of competence and included "openness about task problems [39]." Openness, "freely sharing ideas and information [40]," and integrity, "honesty and truthfulness [40]," were also cited by Butler and Cantrell who listed these as conditions of trust.

Assuming that we trust people that we know better than those we do not know Luhmann contended that familiarity should also be seen as the "prerequisite for trust [41]."

Whilst initially Mayer [42] and Mishra [6] perceived trust as a willingness to accept vulnerability, Mayer described this willingness as largely cognitive. That this cognitive based trust should eventually develop affective or emotional overtones was postulated by McAllister who described "affect based trust [43]." This view was advocated also by Lewicki and Bunker who described initial trust as being "calculus based [44]." To clarify, calculus based trust is arrived at in a stepwise process with each trusting endeavour being used as the basis for the next level. In this sense it is described as "tactical climbing [44]." From this cognitive position Lewicki and Bunker then describe "knowledge based" trust as relying on "information rather than deterrence. The better we know the other individual, the more accurately we can predict what he or she will do [44]." The authors also described "identification based" trust in which a "collective identity develops [44]."

Thus, it would seem that the academic discourse presents trust as initially cognitive in that one makes a judgement call on whether to trust, and if expectations are fulfilled, this calculative trust can develop into an emotional

connection with the person being trusted into a deeper bond of genuine affect where both the trustee and the truster have "fully internalized the other's preferences [45]."

D. The Scrum Team

Katzenbach and Smith define a team as "a small number of people with complementary skills who are committed to a common purpose, set of performance goals, and approach for which they hold themselves mutually accountable [46]." According to Schwaber and Sutherland, the co-creators of the Scrum framework, Scrum teams should be "small enough to remain nimble and large enough to complete significant work within a Sprint [47]." Three to nine team members is regarded as being optimal. In terms of complementary skills Scrum team members, viewed as an entity, tend to possess "technical expertise (knowledge about a specialized technical area), (2) design expertise (knowledge about software design principles and architecture), and (3) domain expertise (knowledge about the application domain area and client operations) [48]."

In addition Katzenbach and Smith advocate the need for "problem-solving and decision-making skills, and interpersonal skills [46]."

The common purpose element of the team definition contributed by Katzenbach and Smith is unquestionable. By its very design Scrum teams collaborate to achieve Sprint goals. As Moe, Dingsøyr and Dybå explain "In a software team, the members are jointly responsible for the end product and must develop shared mental models by negotiating shared understandings about both the teamwork and the task. Project goals, system requirements, project plans, project risks, individual responsibilities, and project status must be visible and understood by all parties involved [49]."

Similarly, mutual accountability in Scrum is *de rigeur* given the requirement to account for progress at the Daily Scrum meeting. Cervone explains "the purpose of the daily Scrum is to both track the progress of the team as well as allow team members to make commitments to each other and the Scrum Master so that work can proceed in the most expedient and unimpeded manner." McHugh,Conboy and Lang concur that the Daily Scrum meeting "provides transparency and visibility on the day-to-day progression of tasks [29]."

E. Trust in the Scrum Team

Having examined trust in isolation in the academic discourse and furthermore having introduced the Scrum team as the vehicle for collaboration and knowledge sharing and collaboration it is somewhat surprising that no published studies appear to have "examined trust in an agile context [29]." Consequently, what follows is an attempt to synthesize the extant literature with a view to applying it to a Scrum team. Figure 1 represents a first stage conceptual model of trust in a Scrum team.

1) Perception

Whilst perception does not really appear in the literature on trust the authors contend that in any team scenario, perception may well play a role. An individual who is new to a team will most likely be subject to a degree of initial judgement. Based on how they are initially perceived the calculus based trust will enhance or detract from their position.

2) Reputation

Some authors [29] contend that reputation is involved in the trust construct. Undoubtedly, a team member's reputation for delivering on their commitments plays a part in whether or not they can be trusted to deliver on their next commitment. This too must surely play a part in the decision to trust or calculus based trust scenario.

3) Integrity

As a team member becomes enmeshed in the Scrum team their integrity and credibility is often tested by other team members. Insofar as a team member does what s/he says s/he will do, integrity is strengthened in the calculative decision to trust.

4) Competence

As shown in Figure 1 the first four conditions for trust, as described above function to enhance the positive reinforcing feedback loop that is calculus based trust. In other words, as a team member demonstrates integrity or competence, for example, the trust in them grows. This allows the relationship to transition to knowledge based trust in which familiarity and openness themselves function as positive feedback loops as described below.

5) Familiarity

As the team members spend time together they come to know each other better; a good rapport is established and the relationships within the team can move past the calculus-based, cognitive decision to trust to a more affect-based knowledge of the other. It is at this stage that the team has really bonded. As Santos et al. describe "Agile values and principles foster changes in team members' attitudes and strengthen their relationships [50]."

6) Openness

Largely as a consequence of an increase in familiarity the team members should become more open with each other. As Zand described in Section I, "persons who trust one another will provide relevant, comprehensive, accurate, and timely information, and thereby contribute realistic data for problem-solving efforts [10]." This happens directly as a result of the openness in the team.

Once this reinforcing loop has begun it is argued that the team members come to identify with each other's goals and the goals for the Sprint itself. At this stage the calculus based trust has been sidelined in favor of affective bonds within the team.

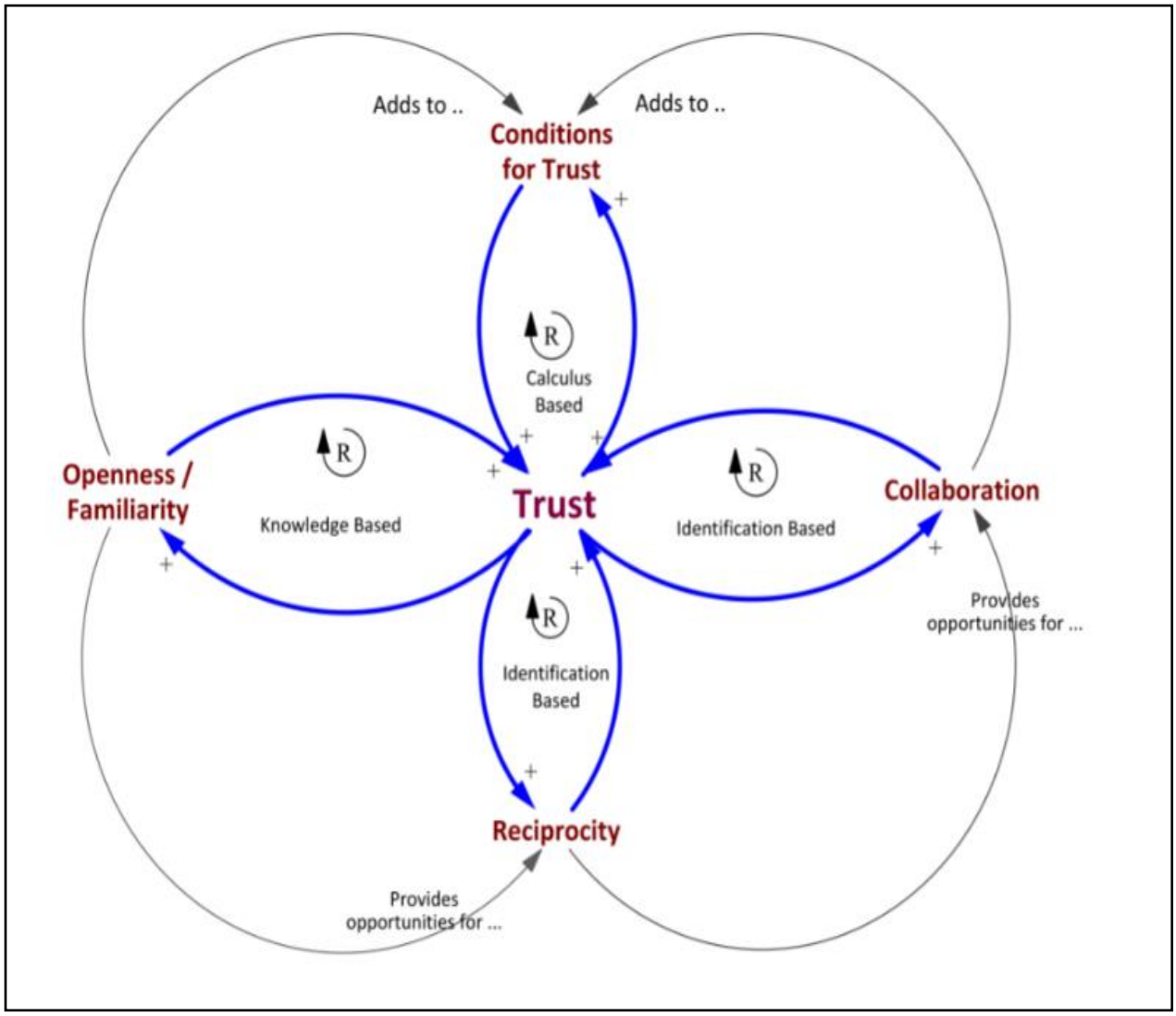

Figure 1. Conceptual Model of trust in a Scrum Team

7) Reciprocity

Once familiarity has become embedded in the team DeVries et al. describe "a cycle of reciprocity, in which team members are more likely to exchange (i.e., both donate and collect) knowledge with each other [51]" becomes the norm.

This again would appear to be a reinforcing loop since as the team bonds the emotional ties become stronger and team members are more likely, and willing, to help each other.

It should be noted, however, that this is a conceptual model of trust within the Scrum team. With a view to understanding the construct of trust in the Scrum team and how it develops in the Agile Scrum software development team engaged in the development of software products the research study that was undertaken will now be described.

III. THE RESEARCH

As this research involves the construct of trust, which does not well suit quantitative analysis it would be more usual for social science topics such as trust to fall into the realm of qualitative data. Johnson and Onwuegbuzie outline the strengths of qualitative research as "The data are based on the participants' own categories of meaning [52]."

Since this research is quite unequivocally involved in the perceptions and feelings of the Agile team members who will be interviewed the ontological perspective of this study must be subjective. In terms of the epistemology that underpins this research the constructivist epistemology (also referred to in the literature as Interpretivist) asserts, "social phenomena and their meanings are continually being accomplished by social actors. It implies that social phenomena are not only produced through social interaction

but are in a constant state of revision [53].” According to Vanson, the interpretivist approach “suggests that facts are based on perception rather than objective truth. With this approach, the conclusions are derived from the interpretations of the participants rather than the abstract theories of the researcher [54].”

Thus, it is intended to use a constructivist grounded theory approach to this research with the intent of gathering the views, perspectives and feelings of the members of a purposive sample of Agile software development teams from a selection of different industries with a view to generating a theory of how trust is developed and serves to enhance collaboration in Agile teams.

It is hoped that using this inductive approach this study will in some way contribute to understanding the construct of trust enhancing team performance in Agile software development teams.

Grounded theory was initially conceived by Glaser and Strauss as a polemic against the logico-deductive method of generating a theory whereby new knowledge (theory) follows from old knowledge through the application of research hypotheses and sound arguments that verify these new theories. Glaser and Strauss, by contrast, argued against data collection being influenced by pre-conceived hypotheses. Rather, “systematic data collection and analysis should lead into theory [55].” However, whilst Glaser and Strauss adopted an ontologically positivist approach Charmaz [56], by contrast advocates an interpretivist approach to the process acknowledging “subjectivity and the researcher’s involvement in the construction and interpretation of data [56].” Since trust is socially constructed the study will adopt the Constructivist Grounded theory (CGT) method as described by Charmaz.

In CGT the researcher must obtain “rich data [56]” from interviews with participants. Rich data refers to collecting data which fully addresses the complexities and depth of the topic under study. The data is then analysed, initially using what is termed “initial coding [56]” where each sentence is fractured and analysed for meaning. Through the process of constant comparison the open codes eventually build into focused codes which are basically at a higher level of abstraction. Eventually the theory emerges from the data as codes are elevated to categories.

With a view to ensuring that the codes fully describe the emerging theory a process known as theoretical sampling is used to elaborate and refine the newly-constructed categories. This is achieved by continuing to sample until no new categories emerge.

In order to conduct this study purposive sampling was used to contact software development companies that use Scrum as their development methodology. Purposive sampling [57] is a type of focused sampling and in this case an organization known to use Scrum was approached and permission was sought to conduct the research. The company has a number of onsite Scrum teams and given the logistical issues, viz team availability, participant workload etc. we were able to interview participants from two of the local onsite teams as shown in Table I.

TABLE I. TEAM COMPOSITION AND ROLES

Participant #	Team A	Participant #	Team B
P#1	Scrum Master	P#6	Scrum Master
P#2	Product Owner	P#7	Product Owner
P#3	Developer	P#8	Developer
P#4	Developer	P#9	Developer
P#5	Developer	P#10	Developer
		P#11	Developer

In-depth interviews were conducted with all of the participants with a view to eliciting what Charmaz refers to as *‘rich data’* [56]. The interviews lasted from 30 minutes to 50 minutes. Each interview was audio recorded and transcribed. With a view to ensuring that all of the nuances and subtleties were captured by the author, as illustrated in Figure 2, the transcribed interviews were subsequently returned to the participants for verification.

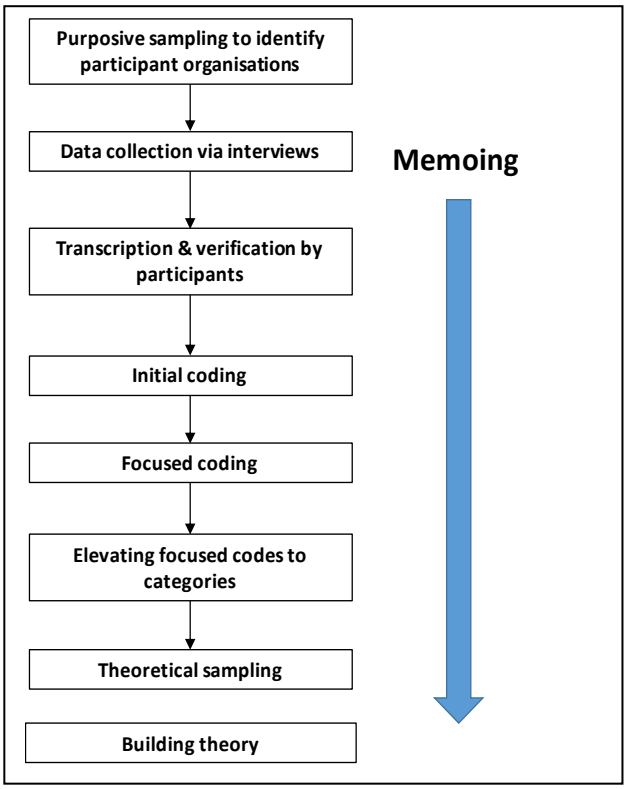

Figure 2. The Constructivist Grounded Theory process

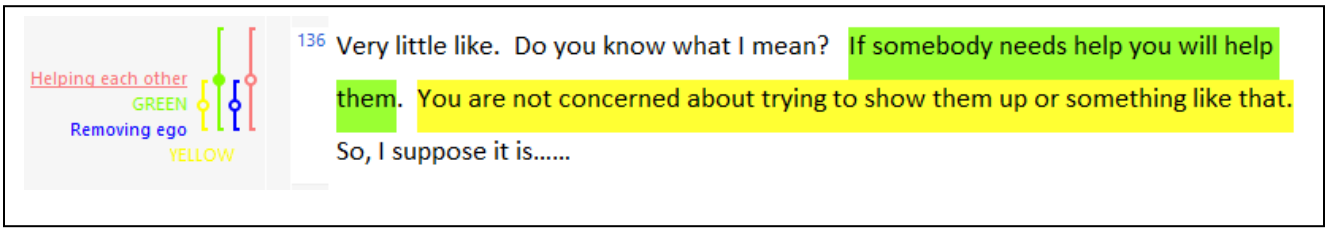

Figure 3. Coding fragment from Interview with P#9

Subsequent to gathering background data and obtaining consent for audio recording from each participant, the interviews focused initially on collaboration and then moved on to describing how trust is established in the Scrum teams. Following the interviews, the researcher, in accordance with the established constructivist grounded theory methodology, transcribed the interviews. Additionally, memos detailing ideas and refinements that, it was hoped, would advance theoretical understanding were written. It is, perhaps, noteworthy that interviews were largely unstructured but participants who were not naturally loquacious were prompted in a semi-structured manner for their response to topics that had been of interest in a prior interview with a previous interviewee.

IV. Results

In keeping with the tenets of Constructivist Grounded Theory the transcribed interviews were uploaded into a qualitative analysis software package. MAXQDA was chosen for its intuitive easy to use interface. Transcribed interviews can be stored, analysed and coded in MAXQDA. Once participants interviews were transcribed and validated the process of initial coding began. This is where each line of the participants' transcription was analysed with a view to encapsulating the meaning in a code which essentially describes what the segment of text is about.

Ideally the codes are gerunds which describe actions e.g., "removing ego" [P#9] which is depicted in Figure 3. On the right hand side, highlighted in yellow, is the fragment of what was said by the participant. On the left, in blue font, is the code that was used to encapsulate what it was felt the participant meant. Similarly the code 'helping each other' on the left hand side is associated with the fragment of the interview on the right hand side where the participant commented that "if somebody needs help you will help them."

Once the interview was coded, subsequent interviews were analysed in a similar manner and compared to each other. Constant comparison is a key strategy used in grounded theory where each piece of elicited data is compared to other pieces of data by the researcher to identify and highlight similarities and differences in the participants' experiences.

MAXQDA was helpful in facilitating this process as codes assigned from previous transcripts were available to view in a portion of the window as shown in Figure 4. On the right of Figure 4 is an interview displaying codes.

This facilitated what Charmaz refers to as "focused coding" [56] where codes are analysed to advance the theoretical direction of the study. Charmaz describes these codes as more conceptual than the initial coding.

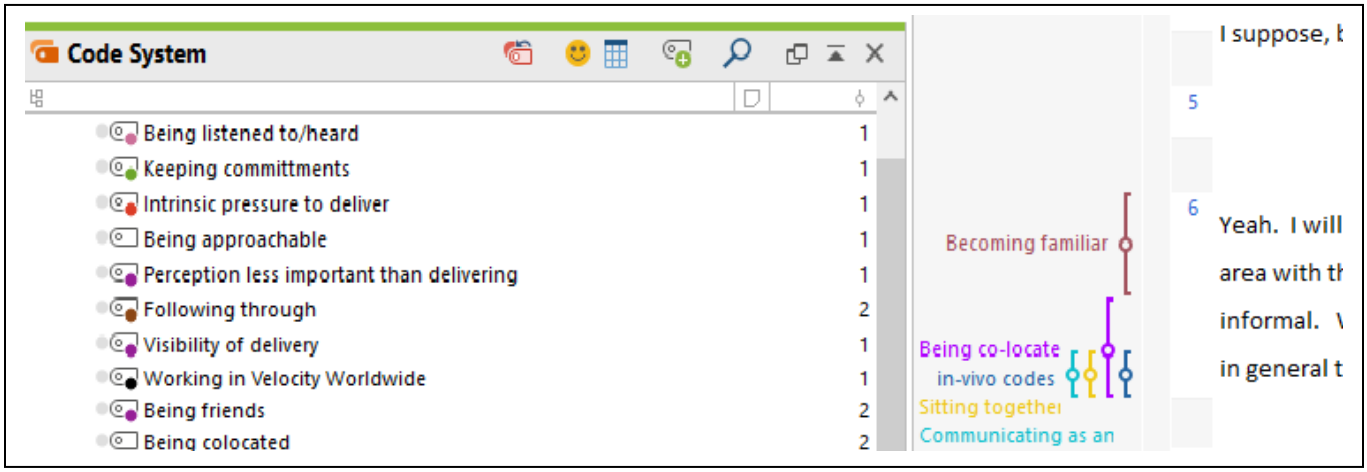

Figure 4. MAXQDA Window depicting codes and coding

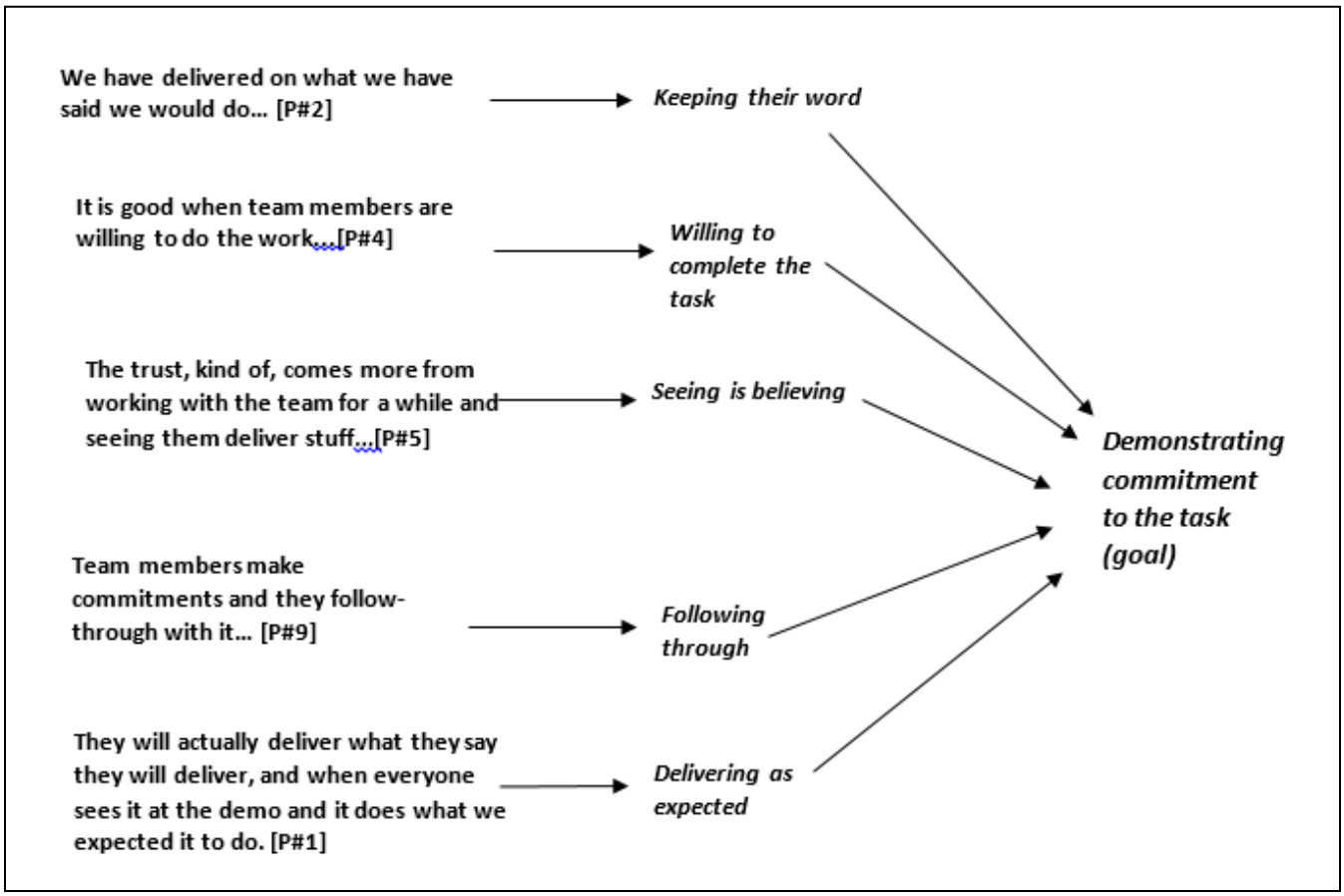

Figure 5. Emerging categories from codes

Finally, the focused codes were raised to conceptual categories which, when integrated, addressed the question of how trust is fostered and developed in Scrum teams. It is at this stage that we had to co-construct the meaning with the participants. Central to Constructivist Grounded Theory the researcher brings their own experience into the analysis to help make sense of the focused codes. Figure 5 depicts an example of how the codes emerge as categories.

V. FINDINGS

Whilst this research is still ongoing it is nevertheless believed useful to present the initial key findings.

For successful knowledge sharing and collaboration to exist in Scrum teams, such as the ones investigated in this study, various factors must be in place to promote inter-team trust.

A. Commitment to the Sprint goal

During the Sprint planning meeting the team reaches a consensus about the Product backlog. This dictates the plan of what will be achieved in the upcoming Sprint, who will undertake it and how long it is estimated to take. That the teams are working towards a common goal for their team Sprints is evidenced by:

"*We are all focused in around a common goal, and a common vision of what we are doing, and the guys buy into that."* P#1, Scrum master.

Commitment to a common goal is of significant importance as Badke-Schaub *et al.* state "Team performance can benefit from shared mental models in situations with a high need of information exchange in the team [56]."

B. Having integrity

As a team member being honest and transparent with team mates is a key requirement to foster trust. It is important that:

*"they do what **they** say, not what **you** say"* P#3, Developer.

Another participant highlighted the importance of:

"If they say they are going to do something, they do it or they put their hand up and say that didn't get done today we'll get it tomorrow." P#7, Developer.

"You could have saved us a lot of hassle and it would have made for a lot simpler conversations if you had just gone ahead and done what we had advised you to do in the first place." P#1, Scrum Master

C. Openness and Honesty

Openness and honesty are a crucial component of the Scrum teams' ability to move the project forward as evidenced by:

"I have never heard anybody come in and lie at the stand-up, you know, to say, oh, yeah, I am doing great, when they are not." P#5, Product Owner,

The participants agreed that delivering on what has been committed at the Daily Stand up is the final arbiter of success:
"There are a lot of people who talk but it doesn't prove anything really until it is actually done." P#8, Developer.

D. Familiarity with team members

There was unanimity that having friendly relations with one's team mates improved trust and thus enhanced knowledge sharing and collaboration:

"The more familiar you are with people and the friendlier you get with them, the easier it is to work with them and have those informal conversations." P#9, Developer.

"You would be sitting together at lunchtimes and you would be chatting about this and that and the rest of it." P#7, Product Owner.

"I know them all fairly well on a personal level outside of work. We wouldn't meet too much outside of work like, but talk at breaks, etc." P#4, Developer.

In fact, some members of the team seemed to know each other so well that:

*"You know the name of the kids, you know, more or less when the birthday of the kids are, and that, kind of thing."*P#2, Developer.

And from another team member:
"I would see Joe in here every day. His wife bought my car." P#3, Developer.

To sum up:
"Outside of work I would say that team members would know each other socially, in either their kids going to Clubs or sporting things." P#1, Scrum Master.

E. Seeking and Accepting Help

It was somewhat surprising that one of the key findings from the study was the importance of team members being able to both ask for and accept help from their peers.

"it is okay to not be able to do something straight away like you can ask your Team-mates and you will eventually get it done" P#8, Developer.

"When the team is working well everyone is prepared to say I do not know how to do this today but give me a day and I'll find out who is really good at it and they will help me." P#7, Developer.

"If you see someone has any problem or any concern, or they, even any, kind of, questions that you have, we are really not scared to ask them." P#2, Developer.

Perhaps the rationale for this came from the developer who commented
"Definitely, on our Team, people are motivated by delivering a good product and delivering what they say they will deliver. That is our primary motivation and we are willing to help each other. There is no selfishness in it." P#9, Developer.
This lack of selfishness and team spirit was encapsulated by the Scrum master who stated
"We are not an individual, we are a group here, we have to fight this battle" and
"We are all in this or none of us are in it." P#1, Scrum Master.

F. Competence

It was expected that competence would feature prominently in the interviews but surprisingly this did not appear to be the case. Rather there was an acceptance that
"I think that with time enough everybody can be competent" P#2, Product Owner.
There appeared to be a recognition that
"You have to accept that everyone has different levels of abilities." P#4, Developer and

*"Some people within the team could have competence in certain areas and would have lower competence in other area*s." P#1, Scrum master.

VI. DISCUSSION

It woud appear from the research that the conceptual model as illustrated in Figure 1 came very close to accounting for the empirical findings. However, the use of CGT was not intended to validate the model. The strength of CGT in this study lies in exploring the participants' view of trust within their Scrum teams. CGT builds the theory out of the 'rich data' collected from the participants' own experience.

Whilst integrity, openness and familiarity featured strongly throughout the interviews it would appear that perception and reputation do not appear to matter unduly. It might be argued that the category of seeking and accepting help are components of reciprocity but there is a degree of limitation in this as reciprocity has a two way connotation whilst asking for and accepting help tends to only benefit the team member who has requested the help.

Competence really did not seem to be as crucial to building trust as had been expected. The emphasis appeared to be more on the willingness to learn.

There was unanimity throughtout all of the interviews in the team unifying behind the Sprint goal and this resonates with the shared mental model as mentioned in Section II D.

The literature refers to a stepwise calculative approach to building trust. Lewicki and Bunker describe how "achievement of trust at one level enables the development of trust at the next level [44]." This appears to be the approach taken in the company we worked with. New team members are firstly invited to pair with a more experienced developer and tasks are worked on jointly. After a period of time (which largely depends on the new team member) an individual task is assigned and the experienced developer steps back but is still available to mentor on an as needs basis. As this happens the new team member is becoming known to the team, familiarity and integrity are established. Once the new team member has become embedded in the team s/he begins to fully identify with the team, knowledge sharing and collaboration are enhanced and the teams' goals for the Sprint are met.

VII. LIMITATIONS

The key limitation is that the research is not yet concluded. Thus what is presented is a snapshot which pertains to two collocated Scrum teams in a single multinational. Consequently, at this stage the findings are in no way generalizable.

VIII. CONCLUSION AND FUTURE WORK

Although this study forms the first of what is intended to be part of several similar studies carried out as part of our research on trust in Scrum teams in various Irish software development organizations the findings are nevertheless considered to be significant in that they represent the findings from a large successful software development multinational company based in the West of Ireland.

In terms of future work the research is ongoing in other multinationals. It is hoped that from this work the body of knowledge regarding the development of trust in co-located Scrum teams will be enlarged.

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