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CONTENTS

Comparing Concept Acquisition in Human & Superhuman DeepRL Models

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***Abstract*—In order to better exploit Deep Reinforcement Learning (DeepRL) systems such as DeepMind's AlphaGo & AlphaZero, it is desirable to understand how they acquire knowledge, and how human knowledge acquisition can contribute to or benefit from such an understanding. We analyze a series of DeepRL models called Maia, trained to play the board game of chess in a human–like fashion, to study if these models acquire concepts differently from self–trained DeepRL models such as AlphaZero. Our results indicate that human chess players may acquire concepts differently from self–trained models. We further discuss some of the potential consequences of such an outcome, and opportunities for future work.**

***Index Terms*—artificial intelligence**

I. Introduction

In [1] we explored the question of whether a series of deep neural networks models designed to play chess in a human–like manner, called Maia [2], learnt elementary chess concepts such as *material advantage*. We showed evidence that they indeed learnt a range of simple, hand-crafted concepts. For a simplified version of material advantage, we used linear regression to identify if the player has a material advantage, if the opponent has a material advantage, or if there is no material advantage. Subsequently, we studied an augmented version of material advantage that took piece positions into account. Whereas an accuracy score of 1.0 would be the best possible result (implying that our model was able to detect the concept perfectly from the input data) we obtained a score close to 0.7 for only the prediction of who has an advantage, and approximately 0.5 for advantage prediction using custom evaluation functions for all the versions of Maia we examined. These early results indicated that there was sufficient data in the network to say that the simple version of advantage we used was detectable.

This work builds upon our previous results: we improve our dataset, increasing the locations in the network we examine to include more activation and convolution layers than previously used, expand our methods of evaluation beyond linear regression, and change the concepts we wish to detect, to the more sophisticated concepts provided by the classical position evaluator of the chess engine Stockfish 8 [3], which is the last version of that engine which does not use neural networks to evaluate positions, but instead provides discrete evaluation scores for a range of simple concepts, which we use.

The overall goal of this work remains the same as [1]: to analyze Maia models, which are trained to play the board game of chess in a human–like fashion, to study if these models acquire concepts differently from self–trained DeepRL models such as AlphaZero.

Artificial Intelligence (AI) systems for playing the game of Chess have existed since the early development of computers, and computer chess as an idea has existed for at least seven decades [4], and has continued to see rapid development. Chess has been called the "*drosophila*" of reasoning [5], alluding to the widespread use of the *drosophila* (fruit fly) in biological research. Many advances in chess AI have advanced the state-of-the-art of AI systems generally.

A summary of this paper follows. In Section II we discuss some relevant background. Then, Section III summarizes prior & related work. In Section IV, we detail the methodology used to generate data and discuss investigative goals. In Section V we detail and discuss the results and conclusions drawn from our data and experiments. Finally, in Section VI, we indicate some further research avenues to consider in the future, as informed by our results.

II. Background

Neural networks are commonly referred to as "black boxes" [6]: their operation is not understandable or interpretable to human beings merely by observing the propagation of information through them in the form of high-dimensional and large volumes of numbers, or by directly observing learnt parameters, called *weights*, whose values have no direct or easily discernible connection to the predictive outcome. Neural networks are trained by propagating the error that results from comparing the supervised *training signal* against the error in prediction at an instance of time in the training process.

Nevertheless, neural networks can provide excellent function approximation and produce groundbreaking results on a wide variety of (especially) perceptual tasks. Explainable AI (XAI) techniques are designed to address the opacity of operation that neural networks exhibit [7]. In this work, we use a technique called *linear probing* to determine if a deep neural network model has acquired a human–interpretable concept, at an instance of it's training. This technique is explained in further detail in Section IV.

Recent chess-playing AI systems employ deep neural networks to inform their decision-making process [8] [9] [3]. These deep neural models combine neural network activation values across layers with *normalizations*, *convolutions*, and *skip connections*, in the form of an architecture known as a Residual Neural Network (ResNet) [10]. ResNet, originally developed for computer vision tasks, was used by Google DeepMind in the development of their AlphaGo system, which learned to play the game of Go, the Google DeepMind AlphaZero system which learned to play Go, Chess, and Shogi, and the Leela Chess Zero system, which plays Chess [11] [9].

Maia was chosen due to similarity of the neural network architecture to AlphaZero. The primary difference between them is training methodology: AlphaZero was trained through self-play [9] and moves were selected using the Monte Carlo Tree Search (MCTS) [12] algorithm. MCTS explores the large search space of the various games AlphaZero learned to play, by exploring the consequences of moves suggested by the randomly initialized neural network in a tree–like fashion. The search mechanism is an augmented form of tree search that exploits probabilistic sampling of the search space.

Randomly initialized weights are initially used, and eventually updated using the neural network training process, guided by the move prediction output. The Monte Carlo Tree search process is made up of a series of repeated steps. First is the selection of nodes in a search tree until a node which has had no simulations is selected. The expansion where this incomplete game's node is chosen to be played. The simulation or rollout uses the neural network in this case to choose a move play out that game. Finally, backpropagation is used to update all the nodes in the path from the played node to the root with the results of the game.

This is the technique used to guide self–play and produce training data for our neural networks: after many rollouts and the backpropagation of their results, this produces a dataset of input games and predicted results. Small amounts of noise are used to reintroduce some randomness into the network's prediction to enable it to continues to explore the search space, where it might otherwise continue to focus on a single approach and not explore and thereby learn from other yet unexplored approaches.

Each neural network is a general function approximator that learns through an algorithm known as backpropagation [6]. A neural network at its most basic is a two-state regression or classification model which takes in some input and produces one or more outputs. The network will take the input and produce derived features, which are used further to produce more derived features depending on the depth of the network, and the derived features are used to produce the final output. The derived features are produced using linear combinations of the inputs and non-linear activation functions and other operations such as *convolutions*, which occur at different layers of the network. The first few layers more closely match the structure of the initial input, but as further derived features are generated, they become increasingly abstract.

The neural networks we examine here observe the current state of the chess board, prior states of the chess board, and a number of parameters specific to the game of chess, such as the current castling status, as input, and produces two outputs: one for each of the network "heads". One of these is the *policy head*, which outputs the probability distribution of possible moves. The other is the *value head*, which output the predicted outcome of the game: a win, loss, or draw. These are based on Maia, which is in turn based on Leela Chess Zero, which is itself based on AlphaZero [2][13][9].

The results of these games are then evaluated during the tree search, so that the move predicted is the one most likely to result in a win. The neural network guides the exploration and exploitation of the tree. After a sufficient number of games played out, these game results are then used to train the neural network. This process continues to repeat as the neural network is improved, to explore increasingly better moves. The MCTS search, based on exploring and exploiting moves selected by the neural network, results in the model choosing incrementally better moves.

AlphaZero was based upon AlphaGo, which first learned from human experts and then from self–play. The original AlphaGo was designed to only play Go and its neural network first learned to make moves which approximated human games through supervised learning. This means it would examine a given board position, and learn to generate the move that the high–level Go player made. Then, AlphaGo trained on data generated through playing against itself. This prevents the network from choosing moves based on approximating those of the human experts and instead find the aim to find the optimal sequence of moves to a win [11], in a way not constrained by human conceptual understanding and possible *mis*understandings.

Maia takes a different approach from AlphaGo and AlphaZero in that it does not select moves based on using MCTS at all. Instead, it uses a supervised learning technique similar to the early stage of AlphaGo where AlphaGo used supervised learning to train on the top moves of human go masters, but instead of choosing the best chess players in the world as its sample to learn from, the versions of Maia were each trained on groups of players coinciding with specific skill groups, based on the ELO rating, which is the universally accepted rating system in chess. So, instead of learning to approximate moves based on what the best players in the world are choosing (presumably to win), each version of Maia learns to play in such a way that it would approximate both the good moves and mistakes that players in that skill bracket would make [2]. While the neural networks that formed the various versions of Maia were similar to that of LeelaChess Zero (Lc0), which itself was based on AlphaZero's chess implementation, the Maia networks were structured with 6 convolutional blocks and 64 filters, as a compromise of performance and computational costs.

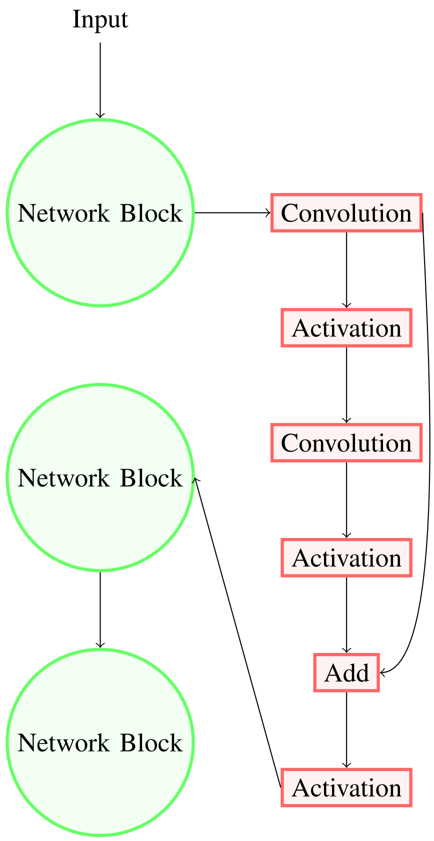


Fig. 1. Simplified view of a neural network. The area of interest in the network is made up of six network blocks, here illustrated in circles. As information passes through the network's block, the layers of interest within the blocks are here illustrated in rectangles. The skip connections are noted by the Add layer. Each network block contains many of these layers, connected sequentially. We omit the squeeze-and-excitation and batch normalization layers in our illustration.

III. Related Work

There have been analyses of AlphaZero's neural network's development [14], and neural network based versions of Stockfish [15]. However, to our knowledge, there has been no analysis of such a network designed to approximate human play as Maia. How the self–playing trained networks and the human–supervised learning trained networks differ, may provide further insight into what networks which learned from scratch like AlphaZero do, that entirely supervised learning networks such as Maia do not.

Within the field of explainable chess models there are also alternative versions of the game which are less computationally expensive to process such as minichess [16]. While these versions of chess are generally similar to normal chess, their smaller boards and restricted numbers of pieces are more computationally inexpensive. These more obscure versions of chess do not have the same level of data to support training a supervised learner in the same fashion as Maia.

In addition to linear probing, the idea of *counterfactual explanations* as an concept interpretation technique was also considered. These describe the smallest change to the world that can be made to obtain a desirable outcome, or to arrive at the closest possible world, without needing to explain the internal logic of the system [17]. Such an explanation of a chess concept could indicate what the chess playing program was considering when evaluating a position on a case–by–case basis. This amounts to considering what a chessboard that is in as close as possible a configuration would need to look like, to produce a specific move that we would select, instead of the move that was chosen in reality. This technique would allow us to better understand why particular moves are made when compared to other moves, but would not give us an indication of what broad concepts are being acquired by the network, informing the selection of moves overall.

We also considered *non-negative matrix factorization* [18]. This approach allows concept detection for concepts that we did not define and therefore provides a mechanism for unsupervised concept discovery. This is done by taking some matrix such as layer activation values and decomposing into two non-negative matrices, a matrix of features and a matrix of coefficients. The product of these two smaller matrices should approximate the original matrix. This would allow us to approximate how much a given feature contributes to the activation values in the networks, but would not indicate what the feature actually is and would therefore not help us understand what differentiates our network from Leela Chess Zero and similar networks.

There are other notable neural network architectures outside of ResNet which have proven capable of playing chess. One increasingly popular architecture is that of generative large language models, which have been applied to chess in addition to many other topics [19]. Further analysis of concepts in some of the other chess playing systems, such as like chess AI trained on language models that use transformers, may provide further insight into concept utilization. In particular, the context of previous moves have a strong influence on which move will be made in the future [19], motivating the use of a transformer or other memory–based architectures. This is in contrast with the observations of Leela, which only retains the last eight moves in the game and not the complete move history. Language models may also be used for explainable chess concepts outside of interpreting neural network models, such as building chess commentary from language models trained on human comments [20]. These language models provide an alternative to the interpretation methods we examine here in detail. However, using LLMs as an interpretability method is still in its infancy.

Currently, the performance of these language based networks falls short of the superhuman standard set by networks such as Leela Chess Zero. The twelfth major version of Stockfish and onward (after 2020) use efficiently updateable neural network evaluations (NNUE) [3] and this network architecture has been analyzed in a fashion similar to that used for AlphaZero [15]. This network design is based on work used for playing Shogi [21], and when used in chess it is a much more shallow network (with fewer but more wide layers) than AlphaZero, Leela Chess Zero, or Maia. These networks were not examined here, due to there not existing a human-play trained version of them, for comparison against.

IV. Methodology

To explore concept usage by the neural network models in question, we assembled a dataset of unique chess positions and produced Stockfish 8 classical evaluations for each of those positions. We then matched the output of each activation layer in each neural network model to the corresponding Stockfish 8 evaluation for that position. We were able to generate regression functions using three linear regression techniques, and produce metrics that show how predictable our outputs are from our data.

```
for all unique chess positions do
    StockfishList ←STOCKFISHEVALUATE(position)
end for
for all versions of Maia do
    for all layers in each version of Maia do
        LayerEvalList ←LAYEROUTPUT(position)
    end for
end for
for each set of activations in LayerOutputs do
    x ← activations
    y ← stockfishevaluations
    RegressionFunction ←LINEARREGRESSION(x,y)
    RegressionFunction ←LASSOREGRESSION(x,y)
    RegressionFunction ←RIDGEREGRESSION(x,y)
end for
```

A. Data

We selected the games from the Maia dataset used to train the 1500 ELO version of Maia. There were between 15000 and 20000 unique game boards used for analysis in the random sample we drew from the initial dataset. Each game was converted into a format suitable for use in Maia using the same Trainingdata-tool used for generating Maia data [22]. Trainingdata-tool takes complete games in Portable Game Notation (PGN), after extraction with pgn-extract [23], and converts them into the binary data format that the Maia networks use. This conversion was done in the same manner that was used to train the Maia networks initially. This dataset was paired down to only unique game positions based on the position of pieces on the chess board by that board's unique FEN (Forsyth-Edwards Notation). The FEN format was necessary because it allowed us to input these positions into Stockfish 8's classical evaluator. We detected the active player and mirrored the board as necessary, because Maia (and by extension Lc0) requires the input to be in a certain orientation, while FEN always initially positions the black pieces on top and white on the bottom. Therefore, it was necessary to produce a way of translating from the Maia to Stockfish 8 formats.

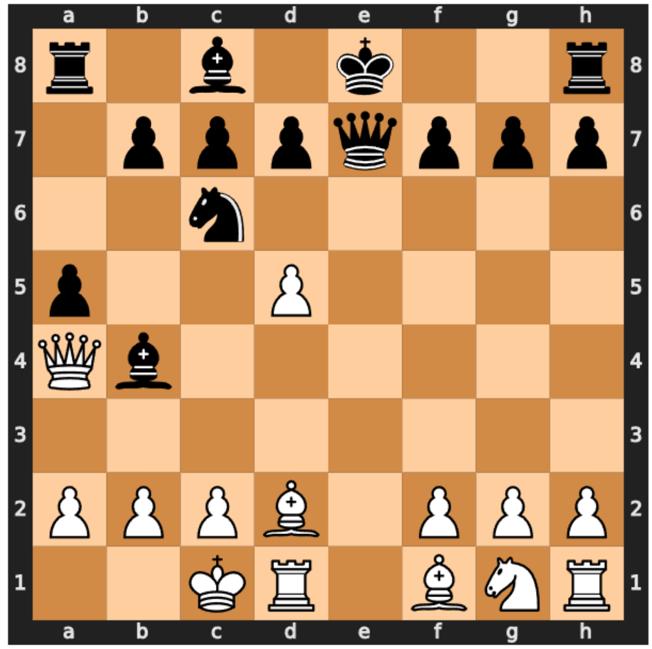


Fig. 2. Example Chess Position from out dataset.

B. Stockfish 8 Evaluations

After adjusting for these formatting changes, we compiled a set of Stockfish's classical evaluations. We chose to evaluate each position as though it were the *middle game*, as the binary data format that Maia uses does not encode the move number. Stockfish 8 produces both a middle game and an early game evaluation and as the line between the opening and middle game can be unclear and arbitrary, we chose to use the middle game evaluations for all evaluations used here. The concepts with a classical evaluation were material imbalance, the relative value of the following pieces: pawns, knights, bishops, rooks, queens, mobility (how many legal moves pieces have), king safety, threats (which pieces are currently under attack or weakly protected), passed pawns (blocked or unblocked passed pawns), and space (squares controlled by each player's pieces). Each of these produces a numerical value that estimated a value that the concept contributed to a given board position. These are concepts that the Stockfish developers chose as important, to evaluate a given chess position. The evaluations are a single value per concept for the black and a value for the white player, and the net of these two values as a total. These Stockfish 8 evaluations are then the concepts we aimed to probe for.

In the example shown in Figure 2 Stockfish 8 evaluates its middle game scores for total material score as -0.05, Knights score of 0.06, Rooks score of 0.19, Queens score of -0.14, Mobility score of -0.01, King Safety score of -0.48, threats score of 0.86, space score of 0.10, and zero for the other metrics evaluated.

C. Neural Network Architecture

The Maia neural network is structured as a *convolutional residual network* (ResNet). It is composed of a series of six convolutional blocks, where each block is made up of convolutions, batch normalizations, and activations using rectified linear units (ReLU). The input to each of the network blocks also has skip a connection to the end of its block, where the two are added together, and the combined output is then used to feed into the next block. The structure of this network uses 6 blocks and 64 filters, where choice of the number of blocks and filters was informed by computational costs. This is smaller than the typical number of blocks (10 to 24) and filters (128 to 320) found in a network like Leela Chess Zero [13].

As information is transformed by successive layers of the neural network, the input is processed from a series of bitmaps to represent piece positions on the board into increasingly abstract numerical values through convolutions, batch normalization, and unit activation up to the output layer. This activation data is used by our linear probing model, described as follows.

D. Linear Probing

The linear probing experiment was based on a similar process used to analyze AlphaZero and a more recent version of Stockfish, where the output of a given activation layer is used as input to a linear regression model to examine if the activation is sufficient to predict the output of the concept that is being probed for [14][15]. These probes are based on *concept activation vectors* [24][25], which tie user–defined concepts to neural network activation results: their values indicate how strongly a concept influenced the output of the network. This technique was modified to be applicable to concepts and topics outside of computer vision domains. The process requires isolating the concept(s) we wish to examine, recalling the abstract structure illustrated in Figure 1. We created a version of the network which terminates at a given layer. For example, instead of sending the first convolution layer's output to the first activation layer we stored that output as our regression model's input.

E. Logistic Regression Model

As a baseline we trained a binary classifier using logistical regression, to predict the concept of *material advantage greater than 3*, across activation layers 1 through 9 and 11 through 17, defined as a Stockfish evaluation of material advantage as $>= 3$, with anything < 3 indicating the absence of significant material advantage. The results were similar to those in [1]. In this paper we focus on the more difficult task of predicting the exact real–valued Stockfish–generated concept scores, using linear regression.

F. Linear Regression Model

Like in [14], we trained a regression model from activation z^l at a given layer l to our Stockfish concept s using a linear predictor for the continuous concepts in question. We trained a regression function from the output of the l^{th} activation layer of the network to predict the Stockfish concept s. We analyzed the set of continuous concepts reported by Stockfish 8 by using Linear Regression, LASSO, and Ridge Regression on a training dataset of activation values and their matching concepts, to generate three linear models, as follows:

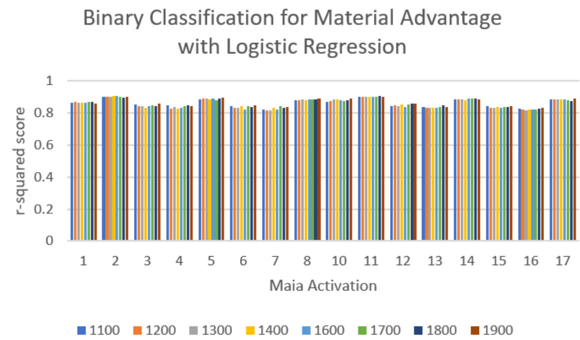


Fig. 3. Binary classification r-squared scores for different versions of Maia across the network.

- *Linear Regression* or ordinary least squares linear regression fits a linear model to minimize the residual sum of squares between the observed targets in the dataset, and the targets predicted by the linear approximation.
- *Lasso* is a linear model trained that does both regularization and variable selection, and uses L1 regularization. It uses the standard linear regression model and modifies this using the sum of the absolute values of the parameters being estimated multiplied by some tuning parameter. When the number of tuning parameters is large, more coefficients are driven to zero so as to remove features which are not useful.
- *Ridge regression* minimizes the squared error with L2 regularization in the same way as previous research has shown [15].

V. Results

Starting with baseline logistic regression, our scores conform to our expectations and previous results [1]. These are shown in Figure 3. They indicate that the binary concept of *material advantage greater than 3 points* is quite accurately classifiable from the feature vectors of the pre–trained Maia networks, showing that, across the breadth of the network, each version of Maia learns representations conducive to easily predicting if a given player has such an advantage. Similar results using linear regression to probe for a real–valued concept would indicate that the exact Stockfish concept score is predictable in the same manner: a more challenging task.

We sampled over 10000 unique chess positions to generate our dataset, and for each linear regression split out data into 4 equally sized folds. Each fold was combined using k-fold cross validation to ensure that our sampling was not affecting the performance of our model. We then performed a hyper–parameter search over the alpha values (which are used as the L2 term multiplier) using values of 0.1, 1.0, 10.0, 50.0, 100.0, 500.0, and 1000.0. Finally, we used the r-squared score of the held-out testing fold to indicate the regression accuracy. After producing these scores for each fold, we calculated the mean of the folds and we have reported these values in this section, for each activation and for each layer.

As shown in Figure 4, across the various options for alpha, none of our results attained r-squared scores above 0.30. These results were duplicated across every version of Maia we examined. A r-squared score close to 1.0 would indicate that we were able to generate a model which can perfectly predict the concept manifestation from the activation data. A result of zero or negative indicates that the input was not sufficient to predict the output (if the model was constant and always predicted the output without regard to the input the result would be 0.0), and models could be arbitrarily negative in their resulting score.

Figure 5 shows that nearly all of the concepts under examination have a negative r-squared score, for all versions of the network. The overall pattern of the r-squared scores for these networks are not notably dissimilar. The later network activation values are similar.

For all of the versions of Maia and layer activation values we examined (i.e., Maia for ELO 1100, 1200, 1300, 1400, 1600, 1700, 1800, and 1900, and activation 1 through 8: see Figure 5, and activation values 10 to 17: see Figure 8), returned similar r-squared scores. At best they were very mildly positive when using the higher alpha values. None were near even 0.5, instead scoring near 0.2 at best. Each version of Maia performed similarly for all concepts identified. Our expectation was that the lower rated versions of Maia would have less conceptual understanding while the higher rated versions would have superior conceptual understanding. However, our data indicates that the level of understanding was similarly poor for all versions of Maia, at least with the concepts under examination.

We also examined some of the outputs of the convolutional layers, as a potential source of concept regression: these are illustrated in Figure 6.

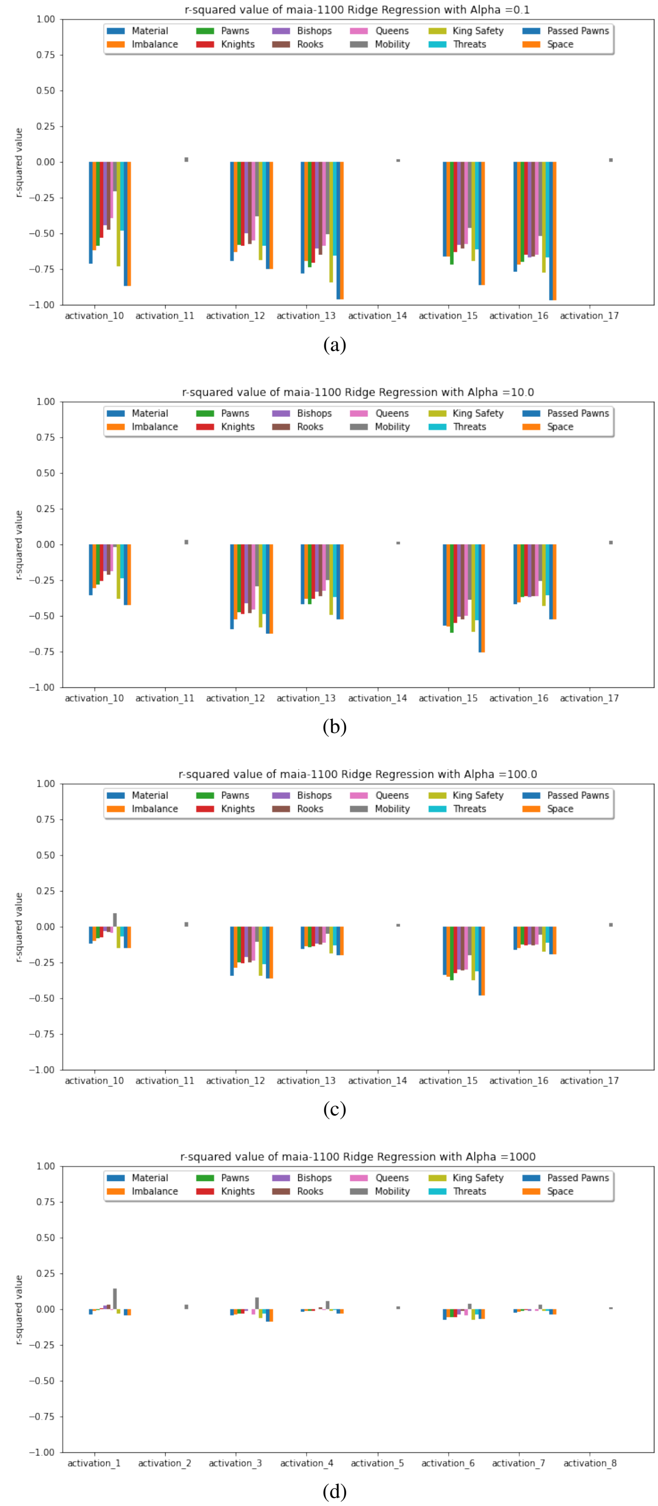


Fig. 4. Graph Showing the r-squared scores of the concepts examined across alpha 0.1, 10.0, and 1000.0.

VI. Discussion & Analysis

While previous work [1] indicated that our hand–crafted preliminary human–interpretable concepts could be accurately detected within the network with r-squared scores of up to 0.7 out of 1.0, here our conclusions differ. The concepts we explored previously were simple in nature: indicating if it was possible to regress which player had an advantage or if none was present (but not a mathematical evaluation of their advantage) and used a dataset which included duplicate positions. After removing those duplicated positions to better match similar datasets in similar research [15] and increasing the complexity of the concepts under investigation, the scores of the evaluation metrics dramatically decreased.

This is not to say that our present claims are incompatible with our previous results. Originally, we asked if we can probe for *whether or not* there is a *significant* material advantage present, as a binary classification problem. Our present work

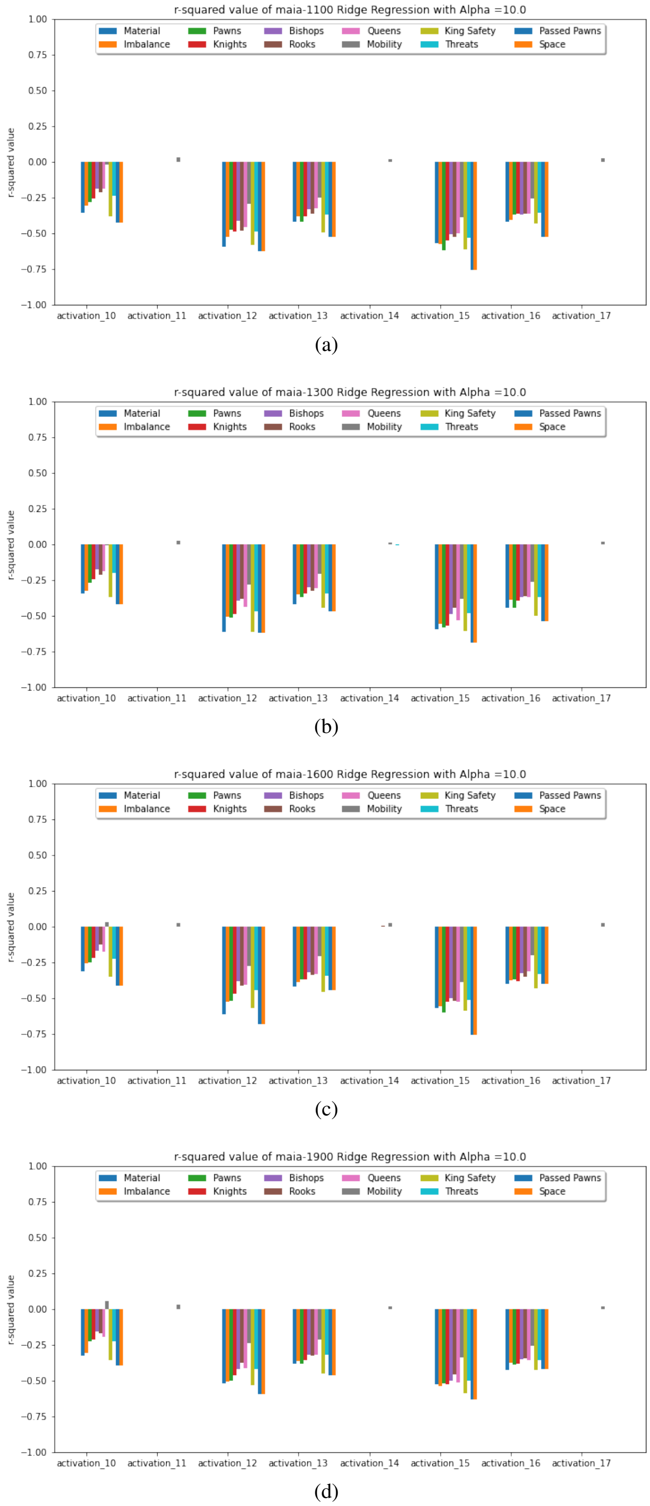


Fig. 5. Graph Showing the r-squared scores of the concepts examined across multiple versions of Maia.

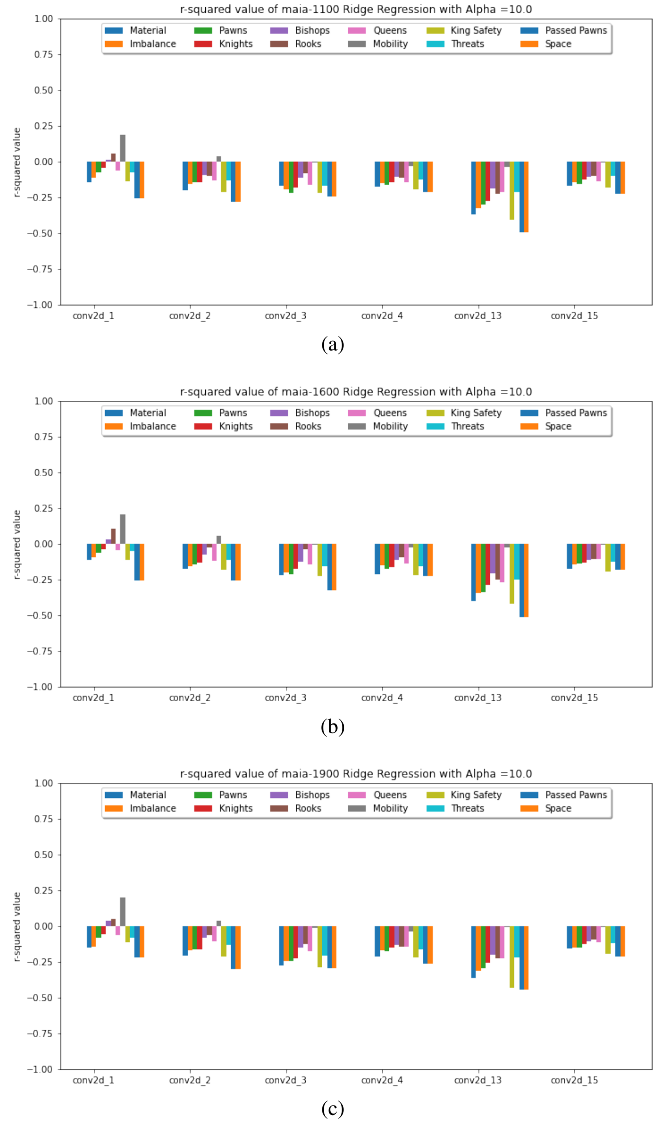
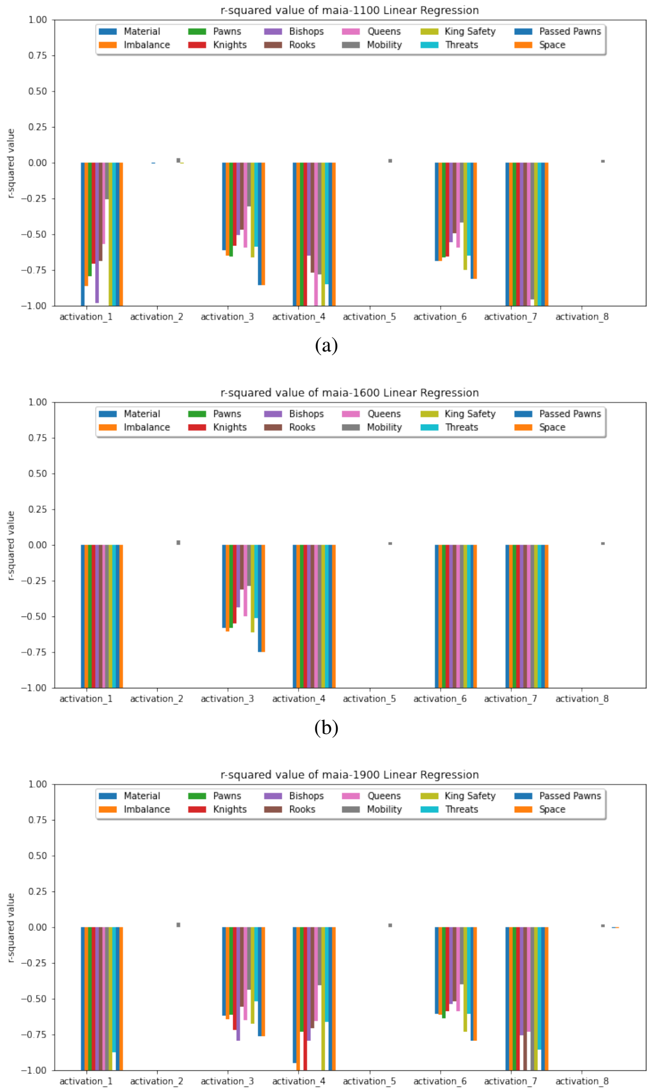


Fig. 6. Graph Showing the r-squared scores of the concepts examined across multiple versions of Maia for the initial and final convolution layers.

attempts to distinguish between the abilities of versions of Maia to predict the *precise scores* of the concepts examined. That is: can our linear probing of different versions of Maia predict not only if a concept is present or absent, but also the precise value of that concept? Our results here indicate that not enough information is being distilled by the Maia networks for linear probing to succeed at this more challenging task.

The more sophisticated concepts we examined here better reflect meaningful conceptual differences between various versions of Maia for the purpose of determining what, if anything, differentiates them in ways that human chess players are able to understand and draw conclusions from. Our initial belief was that the various Maia models, like a human player, would learn many of the concepts we examined. For example, it was intuitive to believe that the 1100 ELO version of Maia would have a much lower r-squared score for evaluating *king safety* compared to the 1900 ELO version of Maia. However,

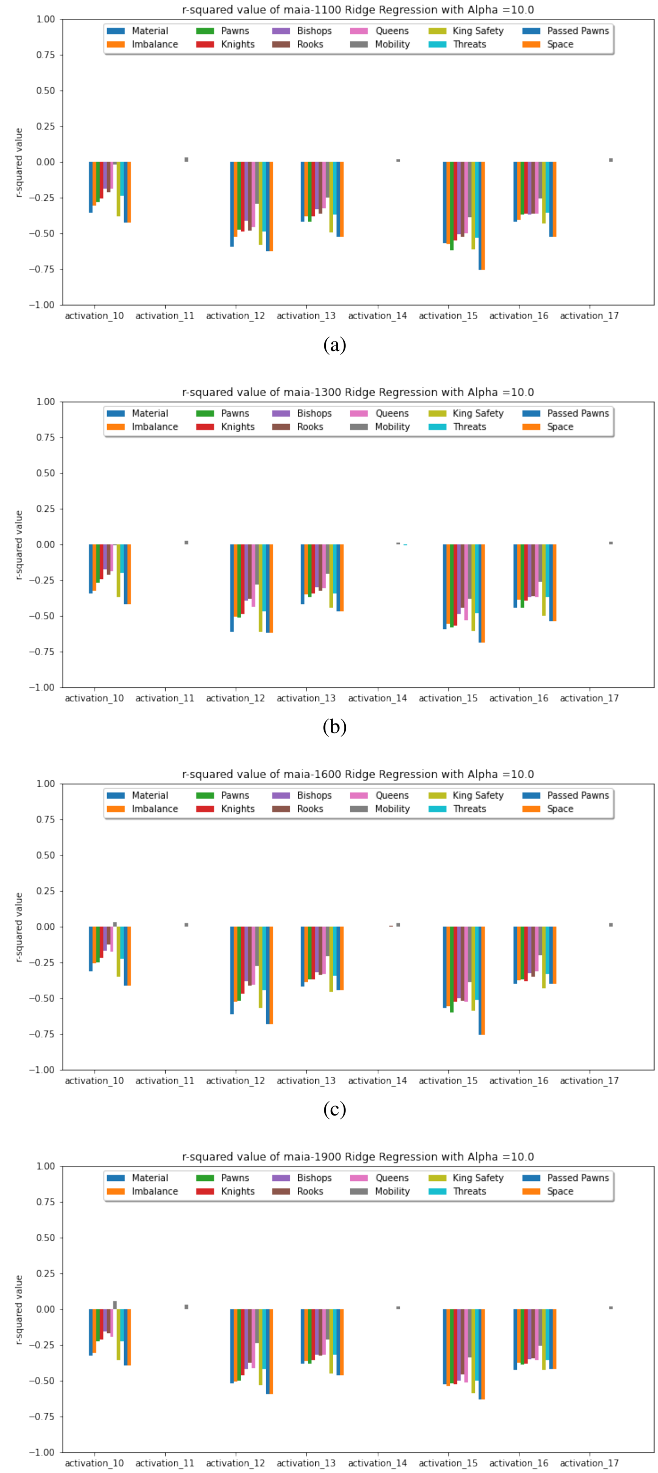


(a)

(b)

(c)

Fig. 7. Linear Regression.



(a)

(b)

(c)

(d)

Fig. 8. r-squared scores of concepts examined across multiple versions of Maia, in the later activation layers.

our results indicate that this is not the case. Our regressed models were not able to accurately score above 0.3: which does not lend itself to the conclusion that this concept is being used at that point in the network.

As deeper layers of the network are examined, this conclusion does not change. At no point do these concepts become detectable to a significant degree. Further into the network it would seem likely that some of the more complex concepts would emerge, but our results indicate that this is not the case. The concepts that one would expect to emerge early and then get lost in the network, such as like Stockfish's *material score*, the more abstract concepts like king safety and scores related to the positional value of the other pieces do not improve further in the network. One notable concept is that of *piece mobility*. This concept has much higher scores than the others, but to be more confident in saying that our values are meaningful and that the networks are detecting and using mobility would require a score, in our estimation, above 0.50, which is not the case.

Instead the data indicates that the sophisticated concepts examined here are not detectable across any version of Maia inside the portions of the neural networks examined. While their play sufficiently differs from one another, the concepts which they use do not match up to the concepts we examined. Our results indicate that the way that Maia understands the game, across each version of itself, roughly match up similarly when compared to the concepts examined here in that the data necessary to detect the concepts in question was insufficiently present. The closest concept that was able to be detected with some measure of confidence is mobility.

We conclude that the Maia networks are not distilling representations with *sufficient direct informational content about our hand–crafted concepts*, to predict them on a real–valued scale via linear probing, from the feature vectors of the network. It is possible that a more sophisticated probing technique, such as using a neural network, may result in better predictability. Alternatively, a *larger* version of the Maia networks with more parameters may allow for the distillation (given sufficient training data) of a wider range of conceptual information, with the same result. Both of these possibilities suggest that the internal representations of Maia may more directly encode *other concepts*, perhaps unknown to human experts, or not considered fundamental/pedagogical/intuitive to the game by them. These concepts *may indirectly* predict or align with the concepts that *are* frequently described in chess literature, but requiring further neural information processing to uncover that alignment. In short: humans and Maia–like networks may be looking at chess through different conceptual "lenses", despite similar behavior in terms of playing similar moves (most of the time). This suggests the possibility that the concepts humans learn and understand may not be the most efficient representations from a predictability perspective, even solely to mimic human–like play. There may be underlying assumptions and patterns in our behavior that we do not explicitly formulate or understand, and our human concepts may reflect mere imperfect "shortcuts" or heuristics to achieving the desired outcome of a win, which a neural learning process would have no cause to explicitly learn to mimic.

Two contributing factors are proposed. The first is a question of the means by which Maia was trained. Instead of using MCTS like Lc0 or AlphaZero, the training for Maia was entirely based on human games and emulating human behavior. This may have resulted in a lower amount of exploration when compared to MCTS. The neural network would train itself to make moves a human would make in a given situation, but appears not be evaluating the position in the way the human who would make that move would. For example, material advantage would be foundational to a human's examination of the game but Maia does not seem to learn this concept.

Secondly, Maia's network architecture itself may also contribute to the low scores reported here. It may be a challenge for the model to separate the concepts linearly, due to the smaller size of the Maia network compared to Lc0. While Maia was sufficient for modeling human behavior with a smaller network than Lc0 [2], this smaller network may provide more challenges for our conceptual analysis here. However, this does lend evidence to the idea that a smaller neural network capable of producing human-like moves in a given situation may not be learning concepts that humans. Instead, like the example of AlphaGo before the MCTS and self–play, it is merely learning what moves a human would make, but not the cognitive processes that motivate such a choice of move, from a human perspective. The scope of our work did not include the construction of formal belief models of human and artificial agents playing the games, which are key to human decision processes. The next section outlines an approach for addressing this concern.

Maia is able to learn to play like a human being without internalizing human–like chess concepts. AlphaZero has been shown to use many of the concepts explored above [14], yet Maia does not. Our hypothesis that versions of Maia would learn these concepts to meaningful degrees at various levels of training was not validated in our results: the architecture chosen to sufficiently encode human–like play does not require the use and internalization of the hand crafted human–like concepts explored. Instead of a distribution of these concepts across Maia to varying degrees based on the ELO of the network, it is shown that these concepts were unnecessary for effectively emulating a human–like chess–playing agent.

The goal of the Maia networks was not necessarily to learn to play better chess. Instead, the goal was to make moves that approximate the skill level of human players across a range of skill levels. The data necessary to understand and evaluate a chess position in the way that humans expect, using something like Stockfish's classical evaluations is, according to our results, unnecessary. We hypothesize that the Maia networks are learning different concepts from the ones probed for in this work. In the next section, we discuss some avenues for investigating the truth of this hypothesis.

VII. Conclusion and Future Work

The various versions of Maia are designed to replicate moves humans would make in a similar situation, even going as far as to intentionally include blunders, but not necessarily to learn what is necessary to win. This is unlike Leela Chess and AlphaZero, where the goal is to create the best possible chess–playing agent. Therefore, the concepts that Maia must learn may be different from the concepts that the previously mentioned agents learned.

Future work may focus on what unique concepts Maia does use, to better differentiate it from the other networks discussed, and how Maia is able to achieve the goal of human–like moves without the same level of depth and filter size that the other networks use. Unsupervised techniques to detect concepts that Maia does use, and to which degree they are used, and to associate the before-unlabeled concepts to human concepts is another avenue for further work. These concepts detected through unsupervised means would need to be associated to human concepts through manual examination and may provide insight into what is more important to the inner workings of a human–like model.

Once such interpretability technique is a *saliency map* (or *pixel attributions*), which help indicate what part of the input (usually an image) contribute to the final classification of that image [26]. This technique would allow us to examine the factors that influence the decision of our network on a single example by examine basis. Generating a sufficient number of notable examples and attempting to interpret the decisions of Maia and possibly Leela and similar models, on the same examples, remains posited as future work.

A comparison featuring Maia–like networks with drastically different skill levels, such as 400 ELO vs. 2400 ELO, has the potential to provide additional insight, due to the sharp contrasts expected in concept acquisition. This might enable synthetic concepts to be constructed by a secondary model, that a 400 ELO model is guaranteed to not learn, but a 2400 ELO model is guaranteed *not* to learn. However, this study remains to be conducted, because of our original hypothesis that the versions of Maia that are already trained would show the sort of differences we expect.

Training deep neural networks of the depth of Maia from randomly initialized weights is a time consuming process, given the large datasets required for training, testing, and validation [2] of Maia, due to the associated memory requirements. Without the time and resources necessary to do so, alternative approaches are required, such as using pre–trained models. This is the approach we have taken, but as a necessary drawback, our work here is constrained by existing models. If we were training "from scratch" a version of Maia that precisely matches other similar chess playing networks, we could adjust our network architecture to maximize chances of concept retrieval. This is a general drawback of using pre–trained models, and the raison d'être of post–hoc explainability techniques, such as the linear probing we used in this work.

Differences in concept overlap and acquisition order may contribute to the stylistic differences attributed to self–playing systems. A study of optimal style characterization may advance the goal of effective concept and style *transfer* between humans and deepRL systems.

Our post–hoc approach enables concepts to be represented symbolically (as opposed to probabilistically), enabling formal specification of concept relationships and hierarchies, and computational inference of their deductive closure. Knowledge representation challenges for concepts and concept hierarchies warrant further research, as well as the associated deductive processes, as an important intermediate goal to concept-guided deepRL policy synthesis. It remains to study the use of formal logics, possibly "cognitive" modal logics (in the form of epistemic modal logics) to represent concepts leveraging arbitrary-order beliefs, with the objective of constraining or guiding deepRL systems with symbolic constraints that are either learnt post-hoc or inferred by automated reasoning. This may be seen as a neuro-symbolic approach to concept-guided deepRL. It may be necessary to design an efficient *description logic* reasoner for concept deduction in these modal logics.

Prior work has aimed to explain individual decisions in terms of acquired conceptual knowledge. Yet, in most normative domains, decisions are viewed as a sequence of steps to a goal, i.e., a plan [27]. The selective employment of conceptual knowledge in plan generation may be seen as embodying a strategy, subjectively requiring (computational) creativity. Conceptual knowledge may therefore be seen as informing and constraining strategic planning in sequential decision-making systems (such as deepRL systems). This motivates a comparison of how humans and machines exploit conceptual understanding in their decision making, with the goal of plan explainability. Humans and machines may differ in their *use* of acquired conceptual knowledge in plan formulation. Using the self-playing and human-games-trained models of Chess and Go games, it may be possible to design metrics to compare concept manifestation in sequential decision-making, based on quantitatively different plan outcomes in those games. Concept usage differences may enable explainability of human-generated plans in terms of machine-acquired concepts, and vice versa.

The scope of application of our work is not restricted to chess and other games played by AlphaZero-like systems, but is imminently relevant to a range of societal domains that may be modelled as a game between parties and requiring sequential decision-making, such as what has been called "nuclear chess", i.e., nuclear deterrence, and economic and trade strategies & policies.

Further, the ability to explain & interpret deepRL-acquired political and economic strategies in terms of the conceptual understanding of a deep learning model trained on historical data – representing actual strategies from human history – may be invaluable in understanding the ways in which deep reinforcement learning strategies carry the threat of violating human ethical norms, and in building a path to ensuring that these systems comply with them.

References

[1] A. Marchiafava and A. Sen, "Toward comparing knowledge acquisition in deeprl models," in *Proceedings of 2022 IARIA DIGITAL*, Special Track, 2022.

[2] R. McIlroy-Young, S. Sen, J. Kleinberg, and A. Anderson, "Aligning superhuman ai with human behavior: Chess as a model system," in *Proceedings of the 26th ACM SIGKDD International Conference on Knowledge Discovery & Data Mining*, ser. KDD '20, Virtual Event, CA, USA: Association for Computing Machinery, 2020, pp. 1677–1687, ISBN: 9781450379984. DOI: 10.1145/3394486.3403219. [Online]. Available: https://doi.org/10.1145/3394486.3403219.

[3] *Introducing nnue evaluation*. [Online]. Available: https://stockfishchess.org/blog/2020/introducing-nnue-evaluation/.

[4] C. E. Shannon, "Xxii. programming a computer for playing chess," *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, vol. 41, no. 314, pp. 256–275, 1950. DOI: 10.1080/14786445008521796. eprint: https://doi.org/10.1080/14786445008521796. [Online]. Available: https://doi.org/10.1080/14786445008521796.

[5] G. Kasparov, "Chess, a drosophila of reasoning," *Science*, vol. 362, no. 6419, pp. 1087–1087, 2018. DOI: 10.1126/science.aaw2221. eprint: https://www.science.org/doi/pdf/10.1126/science.aaw2221. [Online]. Available: https://www.science.org/doi/abs/10.1126/science.aaw2221.

[6] T. Hastie, R. Tibshirani, and J. Friedman, *The Elements of Statistical Learning* (Springer Series in Statistics). New York, NY, USA: Springer New York Inc., 2001.

[7] C. Molnar, *Interpretable Machine Learning, A Guide for Making Black Box Models Explainable*, 2nd ed. 2022. [Online]. Available: https://christophm.github.io/interpretable-ml-book.

[8] J. Schrittwieser, I. Antonoglou, T. Hubert, *et al.*, "Mastering atari, go, chess and shogi by planning with a learned model," *Nature*, vol. 588, pp. 604–609, 2019.

[9] D. Silver, T. Hubert, J. Schrittwieser, *et al.*, "A general reinforcement learning algorithm that masters chess, shogi, and go through self-play," *Science*, vol. 362, no. 6419, pp. 1140–1144, 2018. [Online]. Available: http://science.sciencemag.org/content/362/6419/1140/tab-pdf.

[10] K. He, X. Zhang, S. Ren, and J. Sun, "Deep residual learning for image recognition," in *2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 2016, pp. 770–778. DOI: 10.1109/CVPR.2016.90.

[11] D. Silver, A. Huang, C. Maddison, *et al.*, "Mastering the game of go with deep neural networks and tree search," *Nature*, vol. 529, pp. 484–489, Jan. 2016. DOI: 10.1038/nature16961.

[12] R. Coulom, "Efficient selectivity and backup operators in monte-carlo tree search.," in *Computers and Games*, H. J. van den Herik, P. Ciancarini, and H. H. L. M. Donkers, Eds., ser. Lecture Notes in Computer Science, vol. 4630, Springer, 2006, pp. 72–83, ISBN: 978-3-540-75537-1.

[13] Pascutto, Gian-Carlo and Linscott, Gary, *Leela chess zero*. [Online]. Available: http://lczero.org/.

[14] T. McGrath, A. Kapishnikov, N. Tomašev, *et al.*, "Acquisition of chess knowledge in alphazero," *Proceedings of the National Academy of Sciences*, vol. 119, no. 47, e2206625119, 2022. DOI: 10.1073/pnas.2206625119. eprint: https://www.pnas.org/doi/pdf/10.1073/pnas.2206625119. [Online]. Available: https://www.pnas.org/doi/abs/10.1073/pnas.2206625119.

[15] A. Pálsson and Y. Björnsson, "Unveiling concepts learned by a world-class chess-playing agent," in *Proceedings of the Thirty-Second International Joint Conference on Artificial Intelligence, IJCAI-23*, E. Elkind, Ed., Main Track, International Joint Conferences on Artificial Intelligence Organization, Aug. 2023, pp. 4864–4872. DOI: 10.24963/ijcai.2023/541. [Online]. Available: https://doi.org/10.24963/ijcai.2023/541.

[16] P. Hammersborg and I. Strümke, *Reinforcement learning in an adaptable chess environment for detecting human-understandable concepts*, 2022. arXiv: 2211.05500 [cs.LG].

[17] S. Wachter, B. Mittelstadt, and C. Russell, "Counterfactual explanations without opening the black box: Automated decisions and the gdpr," *Harv. JL & Tech.*, vol. 31, p. 841, 2017.

[18] P. Paatero and U. Tapper, "Positive matrix factorization: A non-negative factor model with optimal utilization of error estimates of data values," *Environmetrics*, vol. 5, no. 2, pp. 111–126, 1994. DOI: https://doi.org/10.1002/env.3170050203. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/env.3170050203.

[19] D. Noever, M. Ciolino, and J. Kalin, "The chess transformer: Mastering play using generative language models," *CoRR*, vol. abs/2008.04057, 2020. arXiv: 2008.04057. [Online]. Available: https://arxiv.org/abs/2008.04057.

[20] H. Jhamtani, V. Gangal, E. Hovy, G. Neubig, and T. Berg-Kirkpatrick, "Learning to generate move-by-move commentary for chess games from large-scale social forum data," in *Proceedings of the 56th Annual Meeting of the Association for Computational Linguistics (Volume 1: Long Papers)*, Melbourne, Australia: Association for Computational Linguistics, Jul. 2018, pp. 1661–1671. DOI: 10.18653/v1/P18-1154. [Online]. Available: https://aclanthology.org/P18-1154.

[21] Y. Nasu, "Efficiently updatable neural-network-based evaluation functions for computer shogi," *The 28th World Computer Shogi Championship Appeal Document*, vol. 185, 2018.

[22] D. Uranga, *Trainingdata-tool: A tool for lc0 training data operations*. [Online]. Available: https://github.com/DanielUranga/trainingdata-tool.

[23] D. Barnes, *Pgn-extract:a portable game notation (pgn) manipulator for chess games*. [Online]. Available: https://www.cs.kent.ac.uk/people/staff/djb/pgn-extract/.

[24] B. Kim, M. Wattenberg, J. Gilmer, *et al.*, "Interpretability beyond feature attribution: Quantitative testing with concept activation vectors (tcav).," in *ICML*, J. G. Dy and A. Krause, Eds., ser. Proceedings of Machine Learning Research, vol. 80, PMLR, 2018, pp. 2673–2682. [Online]. Available: http://dblp.uni-trier.de/db/conf/icml/icml2018.html#KimWGCWVS18.

[25] G. Alain and Y. Bengio, *Understanding intermediate layers using linear classifier probes*, 2018. arXiv: 1610.01644 [stat.ML].

[26] K. Simonyan, A. Vedaldi, and A. Zisserman, "Deep inside convolutional networks: Visualising image clas-

sification models and saliency maps," in *Workshop at International Conference on Learning Representations*, 2014.

[27] S. Sreedharan, U. Soni, M. Verma, S. Srivastava, and S. Kambhampati, *Bridging the gap: Providing post-hoc symbolic explanations for sequential decision-making problems with inscrutable representations*, Mar. 19, 2022. DOI: 10.48550/arXiv.2002.01080. arXiv: 2002.01080[cs]. [Online]. Available: http://arxiv.org/abs/2002.01080 (visited on 06/11/2023).

A Programming Model for Heterogeneous CPS from the Physical POV with a Focus on Device Virtualization

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***Abstract*—The emergence of cyber-physical systems leads to an integration of the digital and physical worlds through sensors and actuators. Programming such systems is error-prone and complex as a plethora of different devices is involved, each of which may be mobile and unreliable. In existing approaches, the developer views the world from the digital point of view. He or she has to implicitly interpret digital values as sensor measurements of the environment or as control values, which influence the environment through actuators. This leads to an increase of complexity as the number of sensors and actuators in cyber-physical systems is ever-increasing and different types of devices may become available during the runtime of the system. These devices may be located in different physical contexts that may bear no relation to each other. Therefore, the developer has to take the properties of the environment into account when designing his or her application as he or she has to acknowledge the impact of varying devices being located in different contexts. Additionally, he or she has to consider the coordination of interactions between different types of distributed sensors and actuators. This increases the likelihood of errors in the programmer's implicit interpretations of the digital values. Current approaches mainly focus on providing abstractions from the distribution and heterogeneity of the system, but fail to explicitly address the impact of digital calculations on the physical world and vice versa. We present a programming model, which reverses the view of the developer on the system. It allows him or her, to take the perspective of the physical system of interest and to explicitly describe its desired behavior. Therefore, a virtualization of devices is possible. This allows to transparently handle failing, moving, as well as emerging sensors and actuators.**

Keywords*—*cyber-physical systems; programming model; context awareness; heterogeneity; virtualization.

I. Introduction

This paper expands on our work presented in [1]. There, a programming model for Cyber-Physical Systems (CPS) is introduced which allows the developer to take a physical point of view. The paper at hand provides a more detailed description of the model and further elaborates on the possibilities of introducing device virtualization, especially concerning sensors.

Sophisticated programming models as well as device virtualization play a crucial role in enabling the developer to create adaptable and robust applications for CPS. This proves especially valuable in the contexts of the Internet of Things [2], Smart Grid [3], automated warehouse logistics [4], and Industry 4.0 [5] as an increasing number of possibly unreliable devices are interconnected and have access to a multitude of different sensors and actuators in their environment. The emergence of such CPS leads to an integration of digital computations and the physical world. This entanglement raises multiple challenges, which do not exist in classical distributed systems [6]. Apart from being distributed over space, the different devices possess varying capabilities, regarding what they measure and how they influence their environment. Therefore, the developer has to ascertain that the employed sensors and actuators are able to achieve his or her goals with respect to affecting and monitoring the physical world. Additionally, the devices may be unreliable and mobile. They may therefore fail, move between different physical contexts of the system (e.g., between two different rooms within a house), or leave the system entirely. This leads to changes in the semantics of their abilities with respect to which parts of the physical world they observe or influence.

Current approaches leave the task of managing the continuously changing set of heterogeneous devices to the programmer. When compared to classical distributed systems, this leads to an impairment of the portability of applications and an unproportional increase in complexity for the design process. Applications for CPS are currently created via classic programming models, where the application implicitly converts sensor measurements to a digital representation of the physical phenomenon of interest (e.g., reading a value from a register of a sensor). Based on this digital representation, the programmer's application performs calculations of which the results are implicitly converted to impacts on the physical world (e.g., writing a value into a register of an actuator). This procedure further increases the difficulty of designing applications as digital values do not directly translate to observations of and influences on the physical world. Our goal is to relieve the programmer from having to work with this implicit conversion of distributed measurements of physical phenomena to a digital representation and subsequently the translation of digital computations to a variety of actuator influences on the physical environment.

This paper presents a programming model for reducing the complexity of application design for heterogeneous CPS. To achieve this, we provide the developer a new view on the system. We reverse the programmer's perspective, such that he or she no longer directly controls the devices through digital computations. Instead, he or she describes the properties of the physical system of interest and how these properties should evolve over time to reach a desired target state. The developer is concerned with the CPS' effect on the environment (i.e., the desired state change) rather than the cause (i.e., the controlled actuators). This perspective is comparable to declarative programming where the properties of a solution are described rather than the procedure of achieving the solution.

As the programmer designs the application from the view of the physical system, he or she does not have to implicitly translate physical phenomena to digital representations and vice versa anymore. Rather, the Runtime Environment (RTE) transparently handles this conversion by utilizing sensor and actuator specifications in addition to the programmer's physical system and target state descriptions. As the RTE is able to decide which sets of sensors and actuators are suited for the tasks at hand, this approach enables the virtualization of sensors and actuators. Therefore, the developer does not have to account for failing or moving devices as the RTE is able to transparently evaluate and choose alternatives. To achieve this, the RTE maintains a location-aware digital representation of the physical system by interpreting sensor measurements.

Not all sensor measurements may be related to each other due to their positioning and environmental circumstances. Therefore, the RTE requires a description of environmental contexts to precisely identify locations of interest within the system that can be observed by available sets of sensors. Each environmental context refers to a region of space that restricts the interpretability of sensor measurements. For example, a picture taken by a camera in one room of a house may not be interpretable for other rooms of the house. The definitions of contexts allow the RTE to decide which sensor readings stand in relation to each other and for which locations they provide relevant information. Therefore, it is able to create a more precise and less error-prone digital representation of the physical environment while taking the motion of sensors and the resulting physical context changes into account.

The RTE uses the digital representation of the system to compute sufficient actuator inputs to reach a target system state. It achieves this by utilizing a constraint solver which takes the digital representation of the system and the programmer's target state description as inputs. Its computations provide a sufficient set of actuator inputs to reach the desired target state. Hence, our programming model abstracts from complex conversions between digital computations and physical phenomena. Moreover, it provides transparency to the developer with respect to changing device configurations (i.e., through motion, failure, or emergence). It is intended to be used in applications utilizing a variable set of arbitrary sensors and actuators to measure and influence physical systems with well-understood properties and dynamics.

From an Operating System (OS) perspective, the presented programming model enables the decoupling of the system and application programmers for CPS. Therefore, a system programmer is not bound to certain applications anymore. This allows him or her to provide required system functionalities to the RTE (e.g., device drivers) as well as commonly utilized abstractions to the application programmers (e.g., libraries for the specification of the physical system). Additionally, the application developer is not bound to hardware specifics anymore due to the employment of the RTE and unified interfaces. This makes the development of applications for CPS more robust as the reusability of code is enhanced and the portability of applications is improved. For the remainder of the article, we refer to the application developer as developer or programmer, and the system developer will be specifically labeled so.

This paper is structured as follows. Section II reviews the related work. Section III presents two running examples for illustrative purposes. Section IV depicts our system model. Section V describes the application programmer's view on the system. Section VI presents the RTE as a link between the programmer's specifications and the physical world (i.e., sensors, actuators, and physical objects). Section VII supplies a conclusion and an outlook for future work.

II. Related Work

A CPS incorporates the digital and the physical world. The configuration of such heterogeneous distributed systems may change at any point in time due to device failures and the emergence of new sensors or actuators. Under such circumstances, programming errors are easily introduced as current solutions rely on the developer to work out the physical semantics of the digital inputs and outputs of varying sets of devices.

Approaches like *Aggregate Computing* [7] focus on convergence. They enable the developer to write an application for a set of computational nodes situated in a given region. The computations of each node take place on the basis of its local state and its neighbors states. Therefore, the behaviors of the nodes in a region converge over time. Such approaches abstract from the distribution of the system. Nevertheless, they are only suited for homogeneous CPS since a converging node behavior implies that the devices possess similar capabilities.

Physical modeling languages like *Modelica* [8] or *Simulink* [9] enable the developer to describe the properties and the behavior of a physical system. These approaches are designed for the simulation of physical systems and for code generation purposes for non-distributed systems. Here, the developer explicitly handles the heterogeneity of the system. The main goal of physical modeling languages is to draw conclusions on the design of a system rather than controlling and observing it directly in a distributed fashion.

Approaches like *Regiment* [10], *Hovering Data Clouds* [11] or *Egocentric Programming* [12] provide mechanisms for the rule-based aggregation and dissemination of environmental data in a distributed CPS. The goal of these propositions is to monitor the environment, rather than to influence it. The programmer therefore has to utilize additional frameworks to describe the desired changes of the physical system state.

Other propositions like *Spatial Views* [13] or *Spatial Programming* [14] allow the programmer to control specifically, which part of the code is executed in which region within the system. These regions can be interpreted as environmental contexts in which certain devices are situated. They do not take the impact of the physical regions of space on the capabilities of the devices into consideration. For example, multiple robots being located in different closed rooms may not be able to cooperate but if they are located on two hills located next to each other their camera measurements may be related to each other. The discussed programming models do not allow this differentiation. Regarding the control of devices, the developer statically specifies which types of sensors and actuators are required for the execution of the program for different spatial regions. Thus, the programmer cannot take changing types of devices into account.

The presented programming models tackle challenges like providing distribution transparency or managing heterogeneity. The programmer's main concern still is the management of digital data, which obstructs him or her from focusing on the main goal: influencing the physical environment. Our programming model reverses the developer's view on the system. He or she describes the properties and the desired behavior of the physical system from which the RTE deduces the required digital computations while managing a possibly changing set of heterogeneous devices. Additionally, we take the impact of sensors being located in different contexts into account. Our approach provides the programmer with the possibility of defining the relevant physical contexts for determining which sensor measurements are related.

III. Running Examples

This section presents two running examples that we will use for illustrative purposes: robot soccer and a street surveillance system. The former focuses on the control of actuators and their impact on the physical world while the latter is mainly concerned with observing the environment. This allows us to demonstrate the expressive power of our programming model in the domains of observing as well as influencing the physical environment of the CPS. The rest of the paper will show that both use cases can be adequately treated by the developer by utilizing the presented programming model.

A. Robot Soccer

The first running example consists of a set of robots that interact with a soccer ball. There are different sensors and actuators attached to each robot and the system consists of multiple physical objects of interest (i.e., the robots, the ball, and the goal). The robots possess different properties such as varying masses and different maximum velocities. Both characteristics influence the robots' capabilities to move and kick the ball. Naturally, the developer has to take the mobility of the objects into account as well. Therefore, this example offers all the system traits that are of interest to us when focusing on influencing the physical environment.

Figure 1 shows an exemplary team of three robots R_1, R_2, and R_3 as well as a ball B. Two cameras are installed on the robots R_1 and R_2 which are therefore mobile. Their fields of view are depicted as dashed lines. One static camera is located above the playing field. Its field of view is represented by the dotted line.

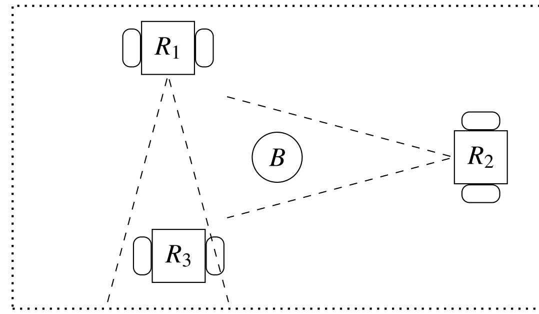


Figure 1. Robot soccer with three robots R_1, R_2, and R_3, as well as a ball B. R_1 and R_2 possess a camera and a stationary camera is installed above the playing field. The fields of view of the cameras are indicated by dashed and dotted lines.

B. Street Surveillance System

As a second running example, we utilize a street surveillance system. Its purpose is the identification of environmental hazards close to the road such as wildfires or burning cars. The system consists of multiple static cameras located at the roadside and dashboard cameras situated within the cars driving by. Additionally, cars possess temperature sensors measuring their interior that are located under the driver seat as well as temperature sensors measuring the exterior of the car situated behind the bumper bar. Each car has tinted windows in the back which do not allow outside cameras to observe the inside of a car. In contrast, cameras within the car are able to observe locations outside through these windows. This example offers all relevant features for identifying physical objects of interest via sensors that are constrained by varying environmental contexts (e.g., tinted windows).

Figure 2 shows an example of such a street surveillance system with two static cameras SC_1 and SC_2 on the roadside and one camera mounted on the dashboard of a car C. Similar to Figure 1 static cameras' fields of view are depicted as dotted lines and mobile fields of view are depicted as dashed lines.

IV. System Model

This section describes our system model. It is divided into modeling physical objects, sensors, and actuators.

A. Physical Objects

The programmer desires to influence a physical system through digital computations such that a certain goal is reached. A physical system Σ consists of a set of locations X_Σ in which a set of physical objects of interest O is situated. Each object $o \in O$ takes up a region of space $X_o \subseteq X_\Sigma$ and features a state $\vec{z}_o$ which comprises multiple properties $z_o^{(i)}$ (e.g., color and shape):

$$\vec{z}_o(t) = \left[z_o^{(1)}(t) \quad \dots \quad z_o^{(w)}(t)\right]^T \tag{1}$$

Each property is characterized by a type and a value, e.g., a ball's shape may be round and its color red.

B. Sensors

The RTE creates instances of such physical object properties by utilizing interpretation methods. They are provided by the system developer and interpret the available sensor measurements as described in [15]. The RTE instantiates a property by performing one or more interpretation methods on a set of suitable sensor outputs (e.g., performing image recognition on camera outputs to identify objects of a given shape). Each instance of a property is valid for a region in space. The extent of this region depends on multiple factors:

1) the method chosen for interpreting the sensor measurements (e.g., spatial interpolation for a set of temperature sensors or triangulation for multiple cameras),
2) the locations a sensor may be able to measure (e.g., a camera takes measurements of a cone in front of it and a temperature sensor measures a single location), and
3) the environmental contexts of the sensors as they restrict their measured locations (e.g., a camera within a closed room can not take measurements of locations outside the room).

The RTE requires a sensor capability model to decide which sensors can be utilized for the available interpretation methods to observe the desired physical object properties. This model is implemented by the system developer through a corresponding driver that provides the required information to the RTE. In our capability model, a sensor s is specified by the following five tuple.

$$s = (q, \mu, \vec{x}(t), \vec{p}(t), X(\vec{x}, \vec{p}, t)) \tag{2}$$

A sensor provides measurements of a physical quantity q for a region in space X. This region is dependent on the sensor's position $\vec{x}(t)$ and other sensor-specific parameters $\vec{p}(t)$ (e.g., the orientation and angle of view for a camera). Both parameters $\vec{x}$ and $\vec{p}$ may change over time due to changes in the configuration of the sensor and its mobility. A sensor provides its measurements in the form of a digital output signal v which it creates by performing a measurement process μ on its physical input.

$$v(t) = \mu(q, t) \tag{3}$$

An example of this is a camera measuring electromagnetic radiation in a cone in front of it which it transforms into a digital array of pixels.

A sensor belongs to a certain sensor class based on the physical quantity it observes and its measurement process. Based on these sensor classes, the RTE determines which sensor outputs are suitable for each interpretation method. The RTE may utilize multiple different interpretation methods $\vec{m}_z$ for instantiating a property z. For example, for determining the shape of an object it may utilize image recognition on cameras as well as methods for interpreting the output of laser scanners. This allows the conversion of various types of sensor outputs to a more holistic and precise digital representation of the physical object. Additionally, different sensors of the same class may replace each other when providing inputs for methods based on their failure or motion. The RTE chooses the set of methods for determining the properties of a physical object based on the available interpretation methods, the corresponding property of interest, and the currently accessible sensors.

Figure 3 gives an overview of the creation of the state vector of a physical object o, multiple sensors s_j, and multiple different interpretation methods $\vec{m}_{z_o^{(k)}}$ for each of the properties $z_o^{(k)}$ of the object o. Dotted lines refer to a mapping that may or may not be used. These mappings depend on the object's properties, the sensors' measurands, and the required method inputs.

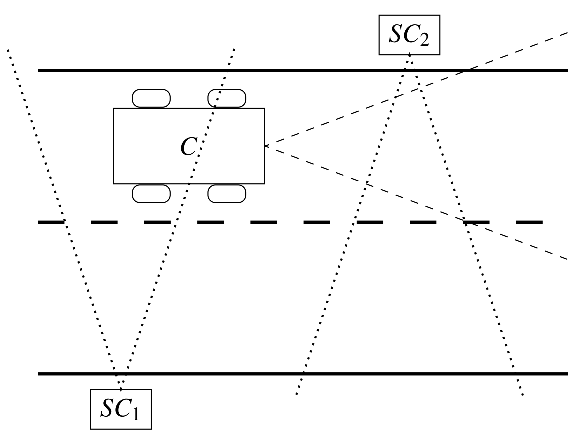


Figure 2. Street surveillance system with one car C that incorporates one interior temperature sensor, one exterior temperature sensor, and a dashboard camera. On the roadside two stationary cameras SC_1 and SC_2 are installed. The cameras' fields of view are indicated by dashed and dotted lines.

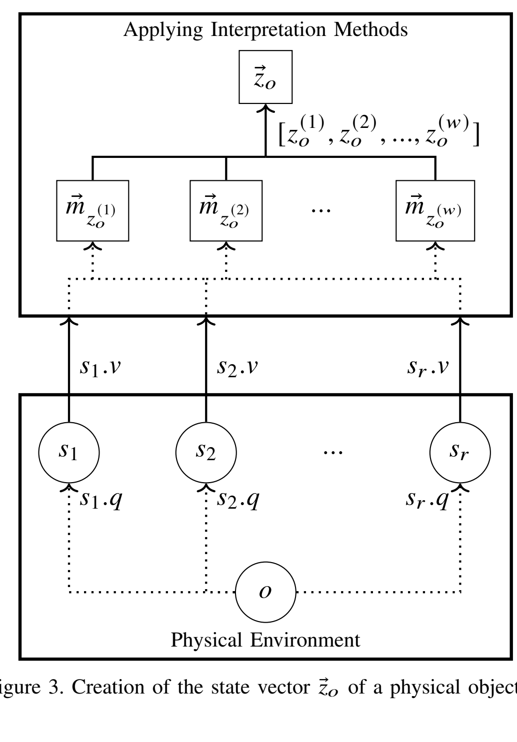


Figure 3. Creation of the state vector $\vec{z}_o$ of a physical object o.

Additionally, the RTE has to take the environmental contexts C of sensors into account as these restrict the locations $s.X$ for which a sensor s provides measurements. The contexts also allow the RTE to reason on whether sensor measurements stand in relation to each other. An example of this are camera measurements from different closed rooms that can not be utilized for a method like triangulation. In contrast, if the cameras are situated in the same room and their measurement regions overlap they may be used for such a method. Recognizing these relations allows the RTE to decide which sensor measurements may be used as inputs for an interpretation method. Therefore, the provision of environmental contexts is essential for determining the properties of physical objects of interest. An environmental context is a possibly mobile region in space that influences a physical quantity. The measurement regions of sensors that observe this physical quantity may be constrained by the corresponding contexts. This depends on whether the context is inward-blocking or outward-blocking:

- inward-blocking implies that sensors from the outside are not able to observe locations within the context, and
- outward-blocking refers to sensors located within the context not being able to observe locations outside of the context.

An example of this is a car with tinted windows. Cameras from the outside are not able to observe the inside of the car but the opposite is possible.

In conclusion, a context c is characterized by the following five tuple.

$$c = (\vec{x}(t), \vec{r}(t), X(\vec{x}, \vec{r}, t), q, \neg in, \neg out) \quad (4)$$

The vector $\vec{x}$ depicts the anchor location of the context which may change over time. The vector $\vec{r}$ relates to the orientation of the context which may also change over time. The spatial extent of the context is described by the set X. It depends on the context's anchor location and its orientation to be fit correctly into space. Additionally, the context influences a physical quantity q depending on the boolean attributes $\neg in$ (inward-blocking) and $\neg out$ (outward-blocking). A sensor is situated within a context if its location $s.\vec{x}$ is in the spatial region $c.X$ of the context c. As contexts may overlap, a sensor may be located in multiple contexts at once. A context c influences the spatial interpretability of the output of a sensor s if the context influences the same physical quantity the sensor measures (i.e., $s.q = c.q$), and either

1) the sensor is located within the context and the context is outward-blocking (i.e., $out_c^s = s.\vec{x} \in c.X \wedge \neg c.out$), or
2) the sensor is located outside the context and the context is inward-blocking (i.e., $in_c^s = s.\vec{x} \notin c.X \wedge \neg c.in$).

The set of all contexts $C^s \subseteq C$ that influence a sensor s can therefore be described by the following equation.

$$C^s = \{c \in C : (s.q = c.q) \wedge (out_c^s \vee in_c^s)\} \quad (5)$$

Based on these contexts C^s, a sensor's interpretable locations $s.X$ are narrowed down to the actually observed locations $s.X'$.

$$s.X' = s.X \cap \Big(\bigcap_{\substack{c_{out} \in C_s \\ out_c^s = true}} c_{out}.X \Big) \setminus \Big(\bigcup_{\substack{c_{in} \in C_s \\ in_c^s = true}} c_{in}.X \Big) \quad (6)$$

Therefore, the sensors' outputs are exclusively valid for these locations. The results of interpretation methods are also only valid for certain locations. This depends on the used sensors (i.e., their observed locations $s.X'$) and the methods themselves. For example, interpolation of temperature sensor readings increases the size of the set of valid locations and triangulation via cameras decreases it. For the valid locations of method results the RTE evaluates whether given physical object properties are present and if so instantiates corresponding state vectors for the physical objects of interest.

In conclusion, based on the presented information regarding sensor capabilities, their environmental contexts, and the utilized interpretation methods, the RTE is able to determine regions of space in which physical objects of interest are present (i.e., X_o for each object o). Subsequently, it is able to instantiate their state representations $\vec{z}_o$.

C. Actuators and Internal Object Dynamics

The properties of a physical object may change over time, which leads to a change of its state $\vec{z}'_o$. This change of state can be caused by internal dynamics (e.g., a rolling ball) or external influences $\vec{u}_o$ due to actuator actions (e.g., a ball being kicked). The change of state at each point in time is a function f of the object's state and the corresponding external influences.

$$\vec{z}'_o(t) = f(\vec{z}_o, \vec{u}_o, t) \quad (7)$$

An actuator takes a digital signal as input and transforms it into one or more actions that affect their environment. These actions have measurable impacts on the properties of physical objects. For example, a gripper arm performs the action of grabbing an object. This action can be measured as a force (in Newton) acting on the object from two directions. The set of all actuators makes up the output interface of the CPS. The external influences $\vec{u}_\Sigma$ on the physical system of interest are the concatenation of the external influences on the different physical objects.

$$\vec{u}_\Sigma(t) = \begin{bmatrix} \vec{u}_{o_1}(t) & \dots & \vec{u}_{o_m}(t) \end{bmatrix}^T \quad (8)$$

The state $\vec{z}_\Sigma$ of the system is a concatenation of the different physical object states $\vec{z}_{o_i}$.

$$\vec{z}_\Sigma(t) = \begin{bmatrix} \vec{z}_{o_1}(t) & \dots & \vec{z}_{o_m}(t) \end{bmatrix}^T \quad (9)$$

The change of the state of the physical system $\vec{z}'_\Sigma$ depends on the internal dynamics of the physical objects that populate the system and their external influences. The function f_Σ describes the system's state change.

$$\vec{z}'_\Sigma(t) = f_\Sigma(\vec{z}_\Sigma, \vec{u}_\Sigma, t) \quad (10)$$

We regard actuator actions as external influences on physical objects (e.g., a robot kicking a ball). This stands in contrast to viewing any interactions between arbitrary physical objects as external influences (e.g., a ball rolling against another ball). Considering all possible interactions between any physical objects would lead to an explosion in complexity, as there may be an arbitrary number of specified and unspecified physical objects. Instead, we treat interactions between objects as disturbances, which may or may not require countermeasures by the CPS.

V. The Application Programmer's View

In our programming model, the developer views the system from the standpoint of physics. He or she provides specifications for the objects that populate the physical system. These specifications encompass information on the properties of the physical objects (i.e., their state) and a definition of their behavior, based on internal dynamics and external influences. Additionally, the developer provides environmental context descriptions that restrict the capability of sensors to observe their environment. These descriptions allow the RTE to decide which sensor measurements stand in relation to each other and for which regions the measurements are valid. This enables the RTE to decide in which regions the given physical object properties are present, based on the available sensors, the utilized interpretation methods, and the relevant context regions. The RTE requires all of these specifications to determine which sensors are necessary for observing the physical objects and how the objects react to given actuator inputs.

For the RTE to decide which actions have to be taken by the actuators to reach a target state, a target state description is necessary. This description refers to the whole physical system rather than a single physical object, as relative relationships between physical objects may be of interest to the programmer. The target state description spans a state space, because different states may satisfy the goal of the developer. Table I summarizes the described requirements for the functionality of the RTE and for which of its actions they are necessary.

TABLE I. REQUIREMENTS FOR RTE ACTIONS.

ID	Specification Requirement	RTE Actions
Req.1	Physical objects' properties	Recognizing objects and comparing the current system state with the target state space.
Req.2	Physical objects' internal dynamics	Estimating when objects reach the target state through internal dynamics.
Req.3	Physical objects' reactions to external influences	Estimating when objects reach the target state through external influences.
Req.4	Target state description	Calculating actuator actions to reach a target system state.
Req.5	Environmental context specifications	Determining which sensor measurements are related and localizing objects.

A. Physical Object Specification

The physical system consists of possibly multiple physical objects of interest, each of which possesses a designated state and behavior. Hence, the object-oriented programming paradigm fits the described requirements and system model. A class enables the developer to specify attributes (state) and methods (change of state) of a physical object. From such a class, the RTE creates a digital representation of a physical object whenever it recognizes the corresponding properties of the described object in the environment. If the RTE recognizes multiple objects of the same class, multiple instances are created. As a physical system may encompass a variety of physical objects, the programmer may have to provide multiple different class specifications.

Through inheritance, a class may extend the state and behavioral descriptions of other classes. This simplifies the specification of different types of objects that partially share their state and behavior descriptions. For example, a car and a ball both possess the properties of moving objects (i.e., position, velocity, and acceleration) and they also have similar internal dynamics in the sense that their position changes with their velocity and their velocity changes with their acceleration. The specific differences in the behavior and properties of balls and cars are then described in their specific classes respectively, e.g., how external influences affect their positions, velocities, and accelerations. Figure 4 shows an example of a ball that extends the class of a moving object.

```
Class MovingObject extends PhysicalObject {
    MovingObject() {
        this.p = Position(m) : true;
        this.v = Velocity(m/s) : true;
        this.a = Acceleration(m/s^2) : true;
    }
    motion(ElapsedTime delta) {
        this.v = this.a + delta * this.a;
        this.p = this.p + delta * this.v;
    }
}

Class Ball extends MovingObject {
    Constructor Ball() {
        this.s = Shape : sphere(radius==30cm);
        this.m = Mass : mass==0.3kg;
    }
    Requirement(Act(v) == Act(m) AND
                Act(v).position == this.p)
    kick(Velocity v, Mass m) {
        this.v = 1/(this.m + m) * (this.m * this.v +
             m * v + m * 0.8 (v - this.v));
    }
}
```

Figure 4. Example for physical object specifications.

The programmer provides the state description of a physical object of interest by providing a set of tuples (τ_i, r_i) where τ_i is the type of a property (e.g., a shape) and r_i is a rule for further specifying the characteristics of the object (e.g., its shape has to be a sphere with a radius of 30 centimeters). Based on the type τ_i, the RTE determines which interpretation methods to utilize for evaluating the available sensor measurements (see Section IV). The RTE continuously assesses the results of these methods with respect to whether the corresponding rule r_i is satisfied. If it is satisfied, the object attribute is instantiated with the methods' result. The logical representation of the object's state vector is the instantiation of all its attributes.

For a programmer to declare such attributes comfortably, the system developers provide libraries that supply definitions of commonly used attribute types including their domains (e.g., the type `Shape` which encompasses values like `sphere` and `cube`). The values of a type may be further constrained depending on their characteristics (e.g., the shape `sphere` can be additionally characterized by its radius). In Figure 4, a ball is defined as a spherical object with a radius of exactly 30 centimeters. Its position, velocity, and acceleration are not specific to the object and therefore the corresponding rules always evaluate to `true`.

The methods of a class describe the state change induced by the physical object's internal dynamics and its reactions to external influences. Each method has access to the object's state and describes a change of its state. A method's calculations may depend on parameters that represent inputs from actuators. They affect the digital object's state and correspond to external influences on the physical object. For example, in Figure 4, the method `kick` takes the actuator's velocity and its mass as parameters, which influence the velocity of the ball after the impact.

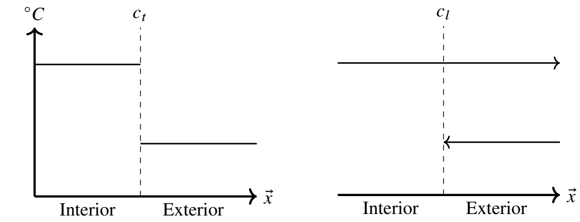
Multiple actuators may provide the inputs to an object's method. This enables the RTE to coordinate a variety of actuator actions for better efficiency or to supply inputs, which a single actuator may not be able to provide. For example, if a building component has to be clamped, two forces on opposite sides of the component have to be at work toward its center. From a result perspective, it does not matter whether this is accomplished by one single actuator or two independent actuators.

Depending on the properties of the physical object and the method parameters, the programmer may have to specify requirements for the inputs from actuators. For example, an actuator has to be close to a component to exert a force on it. The actuator requirements may incorporate the following information:

- the origin of the inputs to the method (e.g., they have to be provided by the same actuator),
- the actuators' states (e.g., their positions), and
- the object's state (e.g., its position).

This allows the RTE to choose actuators capable of influencing the given object and achieving the desired results.

Figure 4 depicts two methods for the classes `MovingObject` and `Ball`. Method `motion` describes the change of position and velocity, based on the object's velocity and acceleration, respectively. The `delta` parameter stands for the elapsed time between two evaluations of the method. Method `kick` takes two parameters `v` and `m`, which correspond to an actuator's velocity and mass, respectively. For this method, requirements for the actuator inputs are given. They specify that both mass and velocity have to be provided by the same actuator and that the actuator has to be situated at the position of the ball. The method calculates the approximate velocity of a ball after being kicked by an actuator with a coefficient of restitution of 0.8.



(a) Discontinuity in the interpretation of the output of a temperature sensor within a car by a context c_t.

(b) Discontinuity in the interpretation of the output of a camera sensor caused by a context c_l.

Figure 5. Discontinuities in interpretations of sensor measurements caused by contexts.

B. *Environmental Context Specification*

The RTE localizes physical objects within the system by employing interpretation methods on sensor measurements and inspecting whether the given object properties are present and the corresponding rules are fulfilled. To achieve this, the RTE requires a description of environmental contexts within the system (see Section IV). An environmental context restricts the regions for which a sensor provides measurements. As already mentioned, a context consists of an anchor location, a spatial extent, an influenced physical quantity, and an annotation of whether it is inward- and/or outward-blocking. Each context may either have a static anchor location or be bound to a physical object of interest. The latter option may lead to the context being mobile.

The borders of a context exist wherever discontinuities arise in the interpretation of a sensor measurement between the sensor's location and the location for which the measurement is interpreted. Figure 5a exemplifies this for a temperature sensor located within a car. From its temperature readings no inferences can be made on the ambient temperature outside the car and the readings of interior as well as exterior sensors do not stand in any relation to each other. Something similar can be observed when considering light passing through a tinted window. In this case, the discontinuity is only present if the light passes through the window in one direction (see Figure 5b). The programmer has to consider these discontinuities to determine for which regions in space he or she has to define contexts. The RTE offers a module to support the developer in this regard. It infers the possibly utilized interpretation methods from the object property descriptions of the programmer. The methods allow the RTE to reason which sensor classes may be required to observe these properties. Based on this, it is able to provide the programmer the sets of relevant physical quantities. Subsequently, the developer is able to examine the system space for corresponding contexts that influence these physical quantities.

When specifying a context, the programmer utilizes a similar paradigm when compared to specifying a physical object. He or she creates a class that describes the required parameters for a context, i.e., its anchor location, orientation, spatial extent, influenced physical quantity, and whether it is inward- and/or outward-blocking. Figure 6 shows an example of the specification of a context for the temperature within a car. The context is inward- and outward-blocking as there is no relation between temperature readings from the interior and the exterior of the car. The position and orientation of the car are determined by the RTE through available positioning systems (e.g., GPS and/or camera triangulation). The developer provides the definition of the spatial extent of the context in the form of a CAD model to ensure sufficient precision. In most cases, such models are in use already such that the programmer is able to utilize them. Otherwise, he or she has to utilize modeling tools to create the definition of the spatial extent.

C. Target State Description

The preceding sections depicted how the developer specifies physical objects and environmental contexts such that the RTE is able to localize objects of interest. To infer required actuator actions the RTE requires a target state description. We chose a variant of declarative programming, i.e., constraint logic programming [16], as a programming interface for describing the target state. It allows the developer to specify the properties of a solution to a problem rather than how to reach the solution. This fits our requirements, as the developer describes a desired physical system state and the RTE deduces the sufficient actuator inputs to the physical system. This approach abstracts from the individual actuators. Therefore, the developer is able to focus on the impact of the actuators' actions on the individual physical objects rather than controlling individual devices.

Since relations between the different states of physical objects may be of interest, the programmer defines target states based on the overall system state. To analyze whether a target state is reached and whether the system state develops correctly, the RTE evaluates the set of constraints periodically.

Figure 7 shows an example of a defending constraint for a game of robot soccer. The target state refers to the positions of the players of the own team with respect to the ball, goal, and opposing player positions:

- all players of the own team should be close to an opposing player (i.e., closer than one meter),
- there should always be one player between the ball and the own goal, and
- there should always be one player between any opposing player and the ball.

This positioning allows to intercept the ball and prevents undisturbed passes as well as attempts of the opponent to score. To reach this objective, the RTE has to coordinate the available actuators, such that the physical properties of the robots (i.e., their positions and velocities) are changed accordingly.

```
Context CarInteriorTemp {
    this.physicalQuantity = Temperature;
    this.anchorLocation = Car.position;
    this.orientation = Car.orientation;
    this.spatialExtent = fitCAD(
        this.anchorLocation,
        this.orientation,
        carInteriorCAD
    );
    this.inwardBlocking = true;
    this.outwardBlocking = true;
}
```

Figure 6. Example for a context specification for the interior of a car.

```
Defense@OpponentOffense {
  double k, l;

  ∀player, opp ∈ MyPlayer × OppPlayer:
    distance(player.p, opp.p) <= 1.0[m];

  ∃player ∈ MyPlayer, ∀goal ∈ MyGoal, ∀ball ∈ Ball:
    goal.p + k * (goal.p − ball.p) == player.p;

  ∀ball ∈ Ball, ∀opp ∈ OppPlayer, ∃player ∈ MyPlayer:
    ball.p + l * (ball.p − opp.p) == player.p;
}
```

Figure 7. Examples of defensive positioning in robot soccer.

D. Application Context Specification

Depending on the present physical objects and their configuration (e.g., their positioning), the developer may desire to provide different target state descriptions. For example, in robot soccer, the programmer's team has to defend if the opponents possess the ball. Vice versa, if the developer's team possesses the ball it should attack to score a goal. Application contexts allow the programmer to describe such relations between physical objects of interest. They form constraints that allow the RTE to decide which target state description to follow at each point in time. Therefore, each target state description has to be bound to an application context (see Figure 7). Similarly to the target state description, the developer utilizes constraints to describe application contexts. Figure 8 shows an example of an application context that describes when defensive player behavior should be adopted in robot soccer. This occurs whenever an opponent possesses the ball, the ball moves toward the programmer team's goal, and an opponent moves toward the programmer team's goal.

VI. Runtime Environment

The RTE maintains a set of physical object descriptions provided by the programmer. It continuously utilizes interpretation methods to evaluate sensor measurements of the CPS environment to determine the state of the physical objects populating the physical system. Moreover, the RTE continuously evaluates the constraint system for the target state and application context specifications. In its evaluations, the RTE takes into account the actuator requirements in addition to the available actuators since they narrow down the possibilities for the available physical inputs.

Figure 9 depicts the architecture of the RTE. It consists of four modules, which are executed in a distributed fashion: the interpreter, the observer, the controller, and the constraint solver. Furthermore, it facilitates drivers for sensors and actuators. They provide an interface for utilizing the devices and supply information on their state (e.g., their positions and orientation) to the other modules. The following paragraphs describe the functionalities of the RTE.

A. Interpreter

The interpreter offers an interface to the programmer for registering class specifications for physical objects, target state constraints, as well as environmental and application context specifications. It extracts three basic types of information from the class descriptions for physical objects:

- (i) the state description of the physical object (i.e., what the properties of the object are and how it differs from other objects),
- (ii) the behavioral description (i.e., how the object's state changes, based on internal dynamics and external influences), and
- (iii) the actuator requirements for providing input signals (i.e., what conditions have to be met for an actuator to be able to supply a desired input to the physical system).

The interpreter creates a vector of state variables $\vec{z}_c$ from the state description of a given class c. Each state variable stands for a physical object property (i.e., a set of results from interpretation methods performed on sensor measurements). The state variables are utilized in the state equation of the physical object. This equation is created from the set of methods G_c belonging to the given class c. Each method $g \in G_c$ describes a change of state $\vec{z}'_{c,g}$ for an object of the given class. Such a method's parameters correspond to external influences caused by actuators. The interpreter converts them to a vector of input variables $\vec{u}_g$ for the method g. Each method describes a change of state, which depends on the state of the object, the specified internal dynamics, and reactions to external influences. The function f_g describes this change of state.

$$\vec{z}'_{c,g}(t) = f_g(\vec{z}_c, \vec{u}_g, t) \tag{11}$$

```
OpponentOffense {
  ∃opp ∈ OppPlayer, ∀ball ∈ Ball, ∀goal ∈ MyGoal :
    distance(ball.p, opp.p) <= 0.5[m];
    angle(ball.v, goal.p - ball.p) < 90[deg];
    angle(ball.v, goal.p - ball.p) > 180[deg];
    angle(opp.v, goal.p - opp.p) < 90[deg];
    angle(opp.v, goal.p - opp.p) > 180[deg];
}
```

Figure 8. Examples of an application context for defensive player behavior in robot soccer.

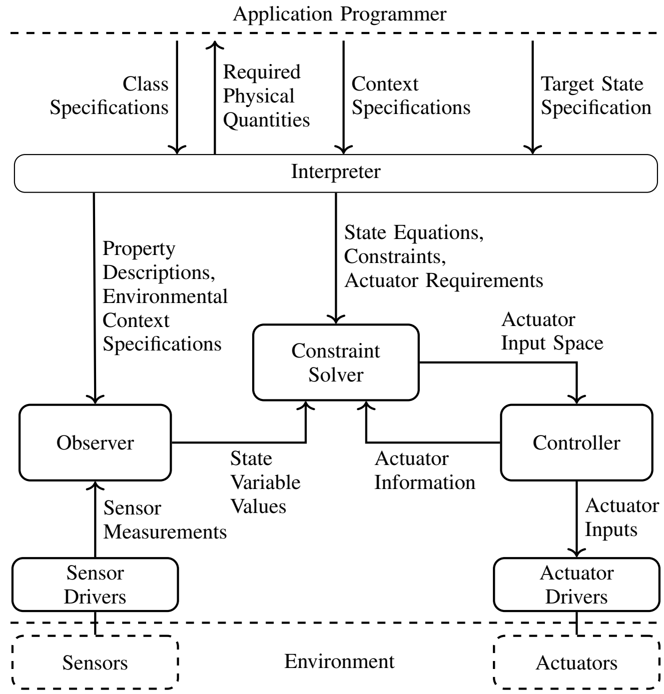


Figure 9. Architecture of the Runtime Environment.

If the function f_g is linear or linearized, the equation can be rewritten as a system of first-order differential equations.

$$\vec{z}'_{c,g}(t) = A_g \vec{z}_c(t) + B_g \vec{u}_g(t) \tag{12}$$

If the overall behavior of the class is linear or linearized, its state change can be described by the sum of all the methods' state changes, as the principle of superposition holds.

$$\vec{z}'_c(t) = \sum_{g \in G_c} \vec{z}'_{c,g}(t) = \sum_{g \in G_c} (A_g \vec{z}_c(t) + B_g \vec{u}_g(t)) \tag{13}$$

Since the constraint solver evaluates the constraints periodically in discrete steps, the interpreter converts the described equation into a time-discrete variant.

$$\vec{z}_c(k+1) = \sum_{g \in G_c} (A_g \vec{z}_c(k) + B_g \vec{u}_g(k)) \tag{14}$$

As the developer may provide multiple classes $c^{(i)}$ for different physical objects of interest, the interpreter creates such a state equation for each of the classes.

Figure 9 includes a depiction of the outputs of the interpreter module. For each method of a class, the interpreter creates constraints from the actuator requirements that are forwarded to the constraint solver. These constraints allow allocating the available actuator inputs to the corresponding input variables. For example, a mobile robot with a specified mass is able to provide the corresponding inputs to the `kick`-method in Figure 4. Additionally, the target state descriptions are added to the constraint system for determining the required actuator actions to reach the programmer's goals (e.g., moving soccer robots such that a defensive positioning is achieved, as described in Figure 7). The interpreter also forwards the application context specifications to the constraint solver. This allows the solver to decide which target state descriptions are in effect based on the current system state (e.g., choosing the defensive positioning constraints when the opponent is attacking, as described in Section V-D). From the given system of equations, requirements, and constraints, the constraint solver is able to compute a sequence of actuator inputs, which lead to a desired target state.

Furthermore, the interpreter module provides an interface to the programmer that supplies information on which physical quantities are possibly measured to observe the desired physical object properties. To achieve this, the interpreter utilizes information on the available interpretation methods in the system and the state descriptions of the physical objects. From that, the interpreter deduces which physical quantities have to be measured by the required sensor classes to perform each interpretation method for determining the different properties. The interpreter's information on which physical quantities may have to be measured by the system sensors allows the developer to examine the system space for contexts of interest that influence these physical quantities (see Section IV-B). Therefore, the programmer is able to precisely identify such contexts and create the corresponding specifications. He or she subsequently provides these specifications to the interpreter which forwards them to the observer module.

B. Observer

The observer module creates and maintains a digital representation of the state of the physical system. It gathers measurements from the available sensors of the system, similar to the data aggregation and dissemination process described in [11]. This allows for gathering and distributing data of the system based on given rules (i.e., according to the object specification).

These rules can be interpreted as the programmer's specifications for the properties of physical objects of interest. Sensor measurements may not always directly relate to these property descriptions, e.g., the shape of an object is not directly measured by a camera but can be deducted from its output pixel array. The observer achieves such deductions by executing appropriate interpretation methods (see Section IV). Therefore, it utilizes a dictionary of the available interpretation methods within the system. This dictionary maps object properties to the available interpretation methods that are able to measure the corresponding properties. Each interpretation method encompasses information on its required input types. These types refer to the sensor classes that provide corresponding outputs (e.g., the method of image recognition requires the outputs of cameras). The output of the methods themselves corresponds to the requested physical object property and may be valid for a region of space (instead of a single location). This depends on the chosen sensors (i.e., which regions of space they are measuring) and the method itself as it may enlarge or shrink the regions for which the sensor measurements are valid. An example of this is interpolation on temperature sensors. A temperature sensor measures the temperature for a single location in space. When a method like interpolation is performed on a set of temperature sensors, the result of the method is valid for a larger region in space. In contrast, when executing triangulation on a set of cameras the resulting region is smaller than the cameras' measured regions.

When considering the regions for which sensor measurements are valid the observer has to consider the environmental context specifications provided by the programmer. They restrict the interpretability of sensor measurements and allow to reason on which sensor measurements are related (i.e., if their context regions overlap, see [15]). For example, an interpolation between temperature sensors measuring the interior and exterior of a car is not feasible. Therefore, these context descriptions are necessary for the observer module to determine which groups of sensors are suitable as inputs for interpretation methods.

The observer has to consider the regions for which the results of interpretation methods are valid for identifying physical objects of interest. The state of an object can be seen as a set of properties (i.e., attributes) and rules that have to be fulfilled for the object to be present at a given location. the observer assesses whether a rule is fulfilled or not by analyzing the outputs of the corresponding interpretation methods. If the rules for all object properties are fulfilled for a region, the object is present there and the observer instantiates the corresponding state vector. The module may create multiple object instances if there are distinct regions in space in which objects are located. It creates a state vector for each of the regions as it interprets every region as a separate object for each of which the constraint solver maintains a state equation. The observer maintains all the created object instances by updating their states. These updates are applied whenever new results of the corresponding interpretation methods are available. After an update, the module forwards the new state vectors to the constraint system.

C. Constraint Solver

The constraint solver computes a set of sufficient actuator inputs to reach a state of the target state space. As inputs, it takes the system state equation, the measured current state, the actuator requirements, and information about the currently available actuators. Through the actuator requirements, the constraint solver is able to decide which actuators are able to influence the perceived physical objects. By this, location-aware control of the actuators is enabled without the programmer having to explicitly examine individual devices. Through the actuators' influence on the physical world and the internal dynamics of the objects, object states evolve over time. The solver evaluates the constraints periodically to check whether a target state is reached and to update the set of actuator inputs to react to environmental influences (i.e., disturbances) accordingly.

Mathematically, the constraint solver's task is to find a state trajectory for the system state. The trajectory depends on a set of actuator inputs between the current point in time t_0 and a chosen point in time t_1 before a deadline d, such that all constraints hold for the state at time t_1.

$$\vec{z}_\Sigma(t_1) = \vec{z}_\Sigma(t_0) + \int_{t_0}^{t_1} \vec{z}'_\Sigma(t)dt, \; t_1 \leq d \tag{15}$$

This allows to create a sequence of actions such that a target state is reached according to the programmer's intentions.

D. Controller

The controller module manages the set of available actuators. For each actuator, the controller module maintains information about the actuator's state (e.g., its position, orientation, reach, etc.) and which inputs it is able to provide. It offers this information to the constraint solver whenever an evaluation round starts. This enables the constraint solver to evaluate the actuator requirements for determining which actuators are able to provide the desired inputs.

The controller module uses the constraint solver's results (i.e., a sequence of sufficient inputs to reach a target state) and distributes it to the corresponding actuators. As the module is executed in a distributed fashion, a consistent view of the available actuators and their information has to be maintained and a consensus for distributing the required inputs has to be found.

VII. Conclusion and Future Work

The presented programming model allows the developer to focus on the description of a physical system and its target state. It allows him or her to specify explicitly what a desired state for a physical system is and how this state changes, based on possible actuator inputs and internal dynamics. This abstracts from the need to manage a changing set of actuators and sensors directly, as the information required of the programmer is reduced to defining the influences of actuators on the system and specifying properties of physical objects. Furthermore, the developer has to specify the physical contexts in which the system sensors may reside. This is necessary, as not all sensor measurements may relate to each other due to their capabilities, positioning, and spatial limitations. This necessitates a precise knowledge of the physical system and its characteristics by the programmer. In return, our programming model achieves virtualization of devices such that it provides distribution, motion, and location transparency to the developer.

To facilitate this, we present a RTE that links the programmer's view to the physical devices. It encompasses an interpreter, an observer module, a controller module, and a constraint solver. The observer module maintains a digital representation of the physical system state, based on the physical object descriptions. Additionally, it manages the available sensors, including information on their capabilities such that it is able to derive which sensors are able to observe physical objects of interest. The interpreter translates the programmer's system specification to a set of constraints and equations such that the constraint solver is able to utilize them. The constraint solver derives target states and required actuator inputs for the physical system from the programmer's specification and the current state of the system. The constraint solver's results are passed to the controller module. It utilizes this data to control the corresponding actuators in order to reach a target state. In conjunction, this allows the RTE the location-aware management of devices and physical objects of interest without the developer being directly involved.

Therefore, the presented programming model and RTE abstract from implicit conversions between digital computations and physical phenomena, which leads to the physical semantics of the program being made explicit. They are less complicated to understand and errors in the translation between digital and physical quantities are prevented. Additionally, the RTE transparently handles changing sets of devices as the programmer is concerned with the influences on the physical system of interest rather than their cause.

For future work, we intend to provide a formal description of actuator specifications, which allows deducing their properties with regard to how they influence their environment. Further research will be focused on describing the interactions between arbitrary physical objects, which are currently viewed as disturbances. To test the described approach, we will create a prototypical implementation of the RTE. In this regard, efficient data structures are necessary for the management of physical context information, sensor and actuator capabilities, as well as digital representations of physical objects. Furthermore, we intend to provide verifications of the real-time capabilities of the RTE. Additional research will concentrate on implementing consensus and consistency algorithms for the RTE, as a consistent view of the environment and optimal utilization of the devices have to be ensured.

References

[1] M. Richter, T. Werner, and M. Werner, "A Programming Model for Heterogeneous CPS from the Physical Point of View," in *The Sixteenth International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies*, 2022, pp. 1–6.

[2] L. D. Xu, W. He, and S. Li, "Internet of things in industries: A survey," *IEEE Trans. on Industrial Informatics*, vol. 10, no. 4, pp. 2233–2243, 2014.

[3] X. Yu and Y. Xue, "Smart grids: A cyber–physical systems perspective," in *Proc. of the IEEE*, vol. 104, 2016, pp. 1058–1070.

[4] F. Basile, P. Chiacchio, and J. Coppola, "A cyber-physical view of automated warehouse systems," in *2016 IEEE Int. Conf. on Automat. Science and Eng. (CASE)*, 2016, pp. 407–412.

[5] N. Jazdi, "Cyber Physical Systems in the Context of Industry 4.0," in *IEEE Int. Conf. on Automat., Quality and Testing, Robotics*, 2014, pp. 103–105.

[6] E. A. Lee, "Cyber physical systems: Design challenges," in *11th IEEE symposium on Object Oriented Real-Time Distributed Computing (ISORC)*, 2008, pp. 363–369.

[7] M. Viroli *et al.*, "From distributed coordination to field calculus and aggregate computing," *Journal of Logical and Algebraic Methods in Programming*, vol. 109, no. 100486, pp. 1–29, 2019.

[8] P. Fritzson, *Principles of Object-Oriented Modeling and Simulation with Modelica 3.3*, 2nd ed., 2014.

[9] E. Hossain, *MATLAB and Simulink Crash Course for Engineers*, 2022, ch. Introduction to Simulink, pp. 317–359.

[10] R. Newton, G. Morrisett, and M. Welsh, "The regiment macroprogramming system," in *2007 6th Int. Symp. on Inf. Process. in Sensor Networks*, 2007, pp. 489–498.

[11] S. Ebers *et al.*, "Hovering data clouds for organic computing," in *Organic Comput. — A Paradigm Shift for Complex Syst.*, 2011, pp. 221–234.

[12] C. Julien and G.-C. Roman, "Egocentric context-aware programming in ad hoc mobile environments," in *Proc. of the 10th ACM SIGSOFT Symp. on Found.s of Softw. Eng.*, 2002, pp. 21–30.

[13] Y. Ni, U. Kremer, and L. Iftode, "Spatial views: Space-aware programming for networks of embedded systems," in *Lang.s and Compilers for Parallel Comput.*, 2004, pp. 258–272.

[14] C. Borcea, C. Intanagonwiwat, P. Kang, U. Kremer, and L. Iftode, "Spatial programming using smart messages: design and implementation," in *24th Int. Conf. on Distrib. Comput. Syst.*, 2004, pp. 690–699.

[15] M. Richter, C. Jakobs, T. Werner, and M. Werner, "Using Environmental Contexts to Model Restrictions on Sensor Capabilities," in *The Seventeenth International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies*, 2023, to be published.

[16] J. Jaffar and M. J. Maher, "Constraint logic programming: A survey," in *The Journal of Logic Programming*, 1994, pp. 503–581.

Continuous Feature Networks: A Novel Method to Process Irregularly and Inconsistently Sampled Data With Position-Dependent Features

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***Abstract*—Continuous Kernels have been a recent development in convolutional neural networks. Such kernels are used to process data sampled at different resolutions as well as irregularly and inconsistently sampled data. Convolutional neural networks have the property of translational invariance (e.g., features are detected regardless of their position in the measurement domain), which is unsuitable if the position of detected features is relevant for the prediction task. However, the capabilities of continuous kernels to process irregularly sampled data are still desired. This article introduces the continuous feature network, a novel method utilizing continuous kernels, for detecting global features at absolute positions in the data domain. Through a use case in processing multiple spatially resolved reflection spectroscopy data, which is sampled irregularly and inconsistently, we show that the proposed method is capable of processing such data directly without additional preprocessing or augmentation as is needed using comparable methods. In addition, we show that the proposed method is able to achieve a higher prediction accuracy than a comparable network on a dataset with position-dependent features. Furthermore, a higher robustness to missing data compared to a benchmark network using data interpolation is observed, which allows the network to adapt to sensors with a failure of individual light emitters or detectors without the need for retraining. The article shows how these capabilities stem from the continuous kernels used and how the number of available kernels to be trained affects the model. Finally, the article proposes a method to utilize the introduced method as a base for an interpretable model usable for explainable AI.**

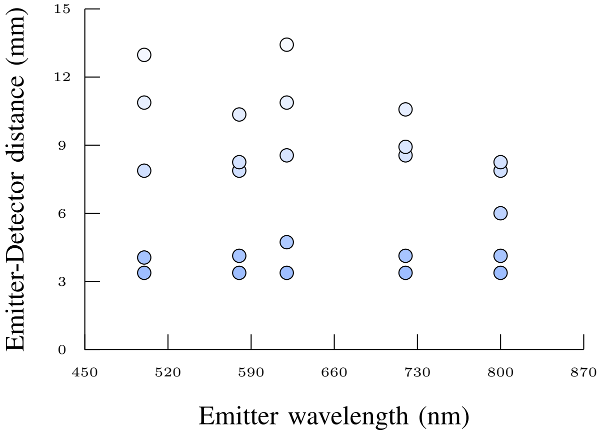
***Index Terms*—machine learning; neural nets; continuous kernel; irregularly sampled data; reflection spectroscopy**

I. Introduction

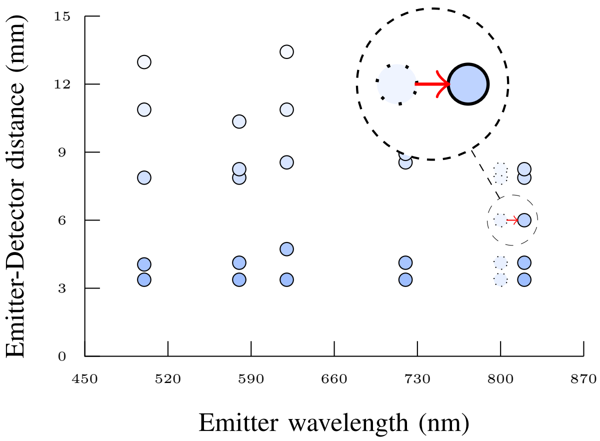
This article is an extended version of the conference paper "Utilizing Continuous Kernels for Processing Irregularly and Inconsistently Sampled Data With Position-Dependent Features" [1] presented at the ICAS 2023 conference. Common machine learning methods assume that data is sampled consistently. That is, each instance of sampled data has the same shape and each data point always represents the same value. However, in real-world applications, data might often be sampled inconsistently due to factors like production inaccuracies of sensors measuring the data. In some cases, certain data points may be missing from the measurement as well. To facilitate such incomplete data, imputation of missing data points can be used to reconstruct the data [2]. Some methods also employ neural networks to reconstruct or correct data [3]. For certain types of network architectures, such as convolutional neural networks (CNN) [4], continuous kernels have been utilized to circumvent the need for special preprocessing and to handle irregularly and inconsistently sampled data directly instead [5] [6] [7]. Convolutional neural networks have the property of translational invariance, which is ill-suited to data expected to exhibit features at consistent absolute positions within the data sampling domain. Common examples of this type of data include spectral data, both optical and acoustic, where the relevant features may be intensity peaks at specific, consistent wavelengths rather than a wavelength-invariant feature of the intensity curve's shape.

Certain types of spectrometry, such as multiple spatially resolved reflection spectroscopy (MSRRS, [8]), produce such data with position-dependant features, sampled both irregularly and inconsistently. An MSRRS-based sensor consists of several light emitters of different wavelengths, as well as several light detectors. These yield brightness values for all emitter-detector combinations, which have discrete emitter wavelengths and emitter-detector distance. An example of data from such a sensor can be seen in Figure 1. Figure 1a shows how such data is sampled irregularly due to the discrete nature of available emitters and detectors. Figure 1b shows one possible cause of inconsistently sampled data in MSRRS-based sensors. Due to production inaccuracies, it is possible that the wavelength of individual light emitters is slightly shifted, and the measured data points represent a different value in the measurement domain. Another possible cause of inconsistent data can be seen in Figure 1c, where data from one detector is unavailable.

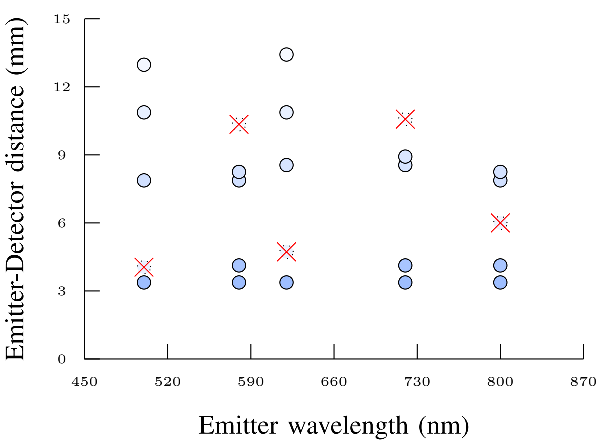
To process irregularly and inconsistently sampled data with



(a) Data from multiple spatially resolved reflection spectroscopy is only available at irregular intervals in the measurement domain.



(b) Production inaccuracies cause different emitter wavelengths for different devices.



(c) Individual detectors might fail, causing data to only be available inconsistently.

Fig. 1. Example of irregular and inconsistent data from a possible multiple spatially resolved reflection spectroscopy sensor arrangement. The data consists of relative brightness at discrete wavelengths and emitter-detector distances.

position-dependent features directly, a novel method is proposed in this paper. It has been shown that neural networks, such as sinusoidal representation networks (SIRENs) [9], can be used as functions parametrized through their learnable parameters, making them suitable for use as continuous kernels. These kernels are shown to be capable of modeling global, long-term dependencies [5]. By utilizing such continuous kernels outside of the context of convolutional neural networks, our method is capable of directly processing irregularly and inconsistently sampled data with position-dependent features.

The rest of the article is organized as follows. Section II details the current state-of-the-art regarding continuous kernels. Section III discusses the definition of a continuous kernel. Section IV introduces the new continuous feature networks utilizing continuous kernels. Section V introduces the experimental setup to evaluate the proposed method. The results are shown in Section VI, where the efficacy of the proposed method for processing spectroscopy data is discussed. Section VII discusses continuous feature networks as interpretable models for explainable AI. The conclusion closes the article.

II. Related Work

Previous work on continuous kernels focuses primarily on applications in CNNs to handle irregularly sampled data. In [5], continuous kernels are utilized to process various types of sequential data, including irregularly sampled sequences. The article contains an in-depth analysis of different types of continuous kernel parametrizations. [6] uses continuous kernels for convolutional neural networks to process non-grid bound data, such as representations of atoms in chemistry. In [7], continuous kernels are used to perform three-dimensional convolution on point clouds. However, as these articles all discuss the usage of continuous kernels for convolution in typical CNN architectures featuring certain degrees of translational invariance, the methods discussed are not well suited for use with data containing position-dependent features.

Using neural networks to represent a continuous function parametrized through the learnable parameters of the network, called implicit neural representation, has been previously analyzed by [10] [11] to model signed distance functions, which are required for shape representation of 3D geometry. In [9], a network architecture called SIREN is proposed as an implicit neural representation for generic data, including audio, images, and signed distance functions. Such implicit neural representations are useful to serve as continuous kernels [5].

III. Definition of Continuous Kernels

At its core, a continuous kernel is a function that assigns a weight to a data point at any given position [6]. Unlike in previous applications in CNNs, however, the position supplied to the kernel in our methods is an absolute position in the domain rather than a relative position to a convolution point.

To be able to represent continuous variants of typical weight kernels, the kernel function needs to be parametrizable with learnable parameters in such a way that the kernel function can ideally approximate any arbitrary function. It has been shown that multi-layer perceptrons (MPL) using sine nonlinearities, such as SIREN networks, can be used for such purposes.

Formalities

Small letters denote scalars, and small bold letters denote vectors. Capital letter variants of the former denote a set of the respective type. Subscripts on values indicate an index of the value within a containing set; superscripts indicate an index to the element of a vector.

Definition

Let $\mathbf{p}_i \in P \subset \mathbb{R}^n$ be the position of the value $d_i \in D \subset \mathbb{R}$ of the i-th data point of the set of data points D in an n-dimensional domain. A continuous kernel in the proposed architecture is now defined as a function

$$\psi : \mathbb{R}^n \mapsto \mathbb{R} \tag{1}$$

assigning a weight value to any position $\mathbf{p}_i$ in the domain. As shown in [5], such functions can be modeled and parameterized using implicit neural representations, such as MLPs using sine nonlinearities like SIREN [9]. In the proposed method, such an MLP serves as the function ψ. The MLP has n input neurons to input the absolute position $\mathbf{p}_i \in \mathbb{R}$ of a data point in the domain and one output neuron representing the assigned weight for the data point. The remaining model parameters of the kernel are the number and size of hidden layers in the MLP, which can be adjusted to the problem to be learned. The MLP serving as the weight function ψ of a continuous kernel is not trained separately but rather as part of the final network that the continuous kernel is used in.

IV. Continuous Feature Network

Figure 2 shows the general structure of the proposed architecture. Part I shows the set of input data points to the model, each representing a value at a specific position within the measurement domain. In the proposed method, the first layer of the architecture, called the continuous feature layer, contains multiple independent continuous kernels (see part II).

For each of the independent kernels, the input consisting of an arbitrary number of data points is weighed using the kernel. Additionally, the input data might be sampled unevenly. To compensate for an uneven distribution of samples, the local density of the sampled data points in the measurement domain is calculated (omitted in Figure 2). In the proposed method, kernel density estimation, where the kernel size is a learnable parameter, was used, but other methods for point density estimation can be used as well. Each data point is weighted by the inverse local density of data points at its position as proposed in [7]. The data points weighted by both the kernel and the inverse point density are shown in part III and are formally expressed in Equation (2).

For each kernel, the weighted data points are reduced to a single value as defined in Equations (3) and (4) and as shown in part IV. Here, a sum is used as the reduction operation, but other reductions, such as calculating the mean of the values, are also considerable. Combining the reduced value of each kernel into a vector results in an output feature vector of a fixed size depending on the number of independent kernels in the continuous feature layer.

Since the continuous feature layer reduces the input of arbitrary size to a latent vector of a fixed and predetermined size, the continuous feature layer can be followed with a typical neural network architecture, such as a multi-layer feed-forward network (see part V). The output of this MLP then serves as the output of the entire network as depicted in part VI. We call the proposed combination of a continuous feature layer followed by a multi-layer feed-forward network a continuous feature network. The continuous feature layer, as described, has three main model parameters: The number of kernels and the two parameters defining the shape of the kernels, being the number and the size of its hidden layers.

Formal Definition

Let the set Ψ be the set of multiple, independent continuous kernels ψ_k used in the continuous feature layer. In this set, each ψ_k represents one feature possibly present in the sampled data. Let $d_i \in D$ be the i-th data point in the input dataset D with the position $\mathbf{p}_i \in P$ in the measurement domain. Let $\rho(\mathbf{p}_i)$ denote the local density of sampled data at position $\mathbf{p}_i$ in the domain. Then we define the weighted data points for each kernel as

$$w_{i,k} := d_i \cdot \psi_k(\mathbf{p}_i) \cdot \frac{1}{\rho(\mathbf{p}_i)} \tag{2}$$

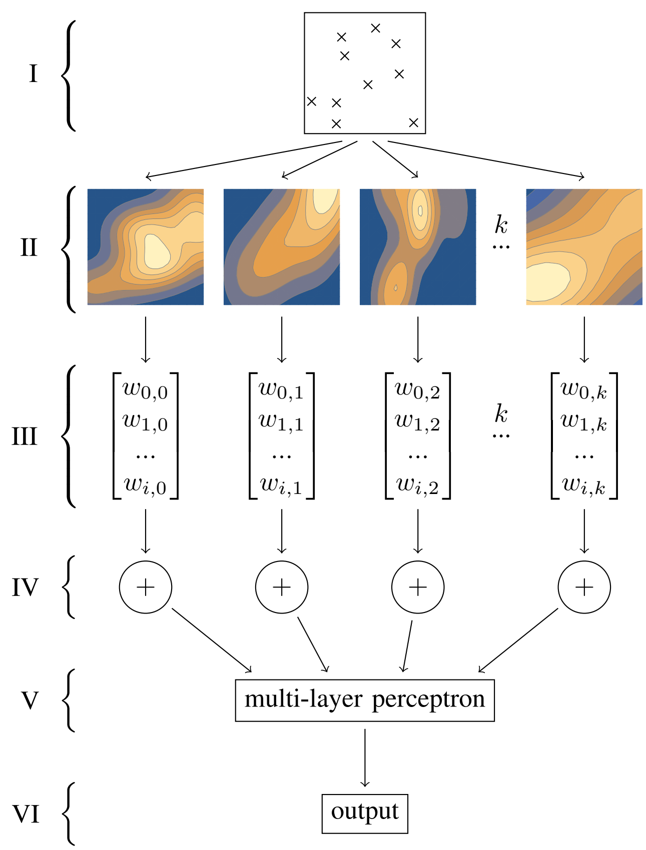


Fig. 2. Overview of a continuous feature network.

The components of the resulting fixed-size latent feature vector $\mathbf{v}$ are defined as follows:

$$\mathbf{v}^k(D,P) := \sum_i (w_{i,k}) \tag{3}$$

$$= \sum_i \left(d_i \cdot \psi_k(\mathbf{p}_i) \cdot \frac{1}{\rho(\mathbf{p}_i)} \right) \tag{4}$$

As the fixed size feature vector $\mathbf{v}$ is a function of the data points and their position, the feature vector can be expressed as a function of the following type:

$$\mathbf{v} : \mathbb{R}^i, \mathbb{R}^{i \times n} \mapsto \mathbb{R}^k \tag{5}$$

$\mathbf{v}$ describes the feature vector with a fixed size k as a reduction of an input of arbitrary size i for the data and $i \times n$ for the data's position for any i. Since the size of the feature vector $\mathbf{v}$ is fixed and does not depend on the input size i, the feature vector can be used as the input to a classical neural network architecture, such as a multi-layer feed-forward network, for an arbitrary input size i without the need to retrain the network.

V. Experimental Setup

The method is tested with a dataset from an MSRRS-based sensor as described in [8]. The data was measured in vivo, alongside a reference measurement of the carotenoid concentration in the skin on a scale ranging from 0 to 12. The datasets for training and testing are entirely distinct, having measured a different group of test subjects using a different set of MSRRS-based sensors.

The measured spectroscopic data is well suited for the use of continuous kernels and continuous feature networks as proposed in Section IV. This is because the MSRRS-based optical data is yielded in the shape of a relative brightness given for certain discrete wavelengths and certain discrete distances between light-emitter-detector pairs. These discrete wavelengths and distances are neither sampled at regular intervals nor always at the same exact wavelengths. Due to production inaccuracies for the sensors, slight differences in the wavelength of the emitters exist. However, the peak wavelengths are known for each sensor's emitters and can thus be accurately supplied as the position data for the continuous feature layer. In addition, it is expected that the relevant data in this type of spectral data is encoded in the position of the features (here, the absorption wavelengths of the carotenoids) rather than the shape of features to be detected, rendering the proposed method suitable.

Evaluation Architectures

To evaluate the method, a continuous feature network with a continuous feature layer containing 64 continuous kernels is used. Each kernel is made up of a SIREN network, containing three hidden layers of 48 nodes with sine nonlinearities each. The continuous feature layer is followed by a hidden feed-forward layer with 64 nodes, followed by an output layer with one output for the predicted carotenoid concentration. This network has approximately 320k parameters.

For a comparison network, we use a multi-layer feed-forward neural network using a similar amount of parameters. This feed-forward network has one input node for each emitter-detector pair, followed by a hidden layer of 256 nodes, followed by another hidden layer of 128 nodes, followed by an output layer with one output for the predicted carotenoid concentration for a total of approximately 375k parameters.

In addition, a continuous feature layer without any subsequent network was examined. Instead, a simple learned weighted sum of the components of the latent feature vector was used as the model output.

A convolution-based model was also investigated, but it has proved unable to produce meaningful predictions of the carotenoid concentration in human skin and is thus omitted from further analysis in this article.

All networks were trained using the ADAM optimizer [12] and implemented using the LibTorch bindings of the PyTorch framework [13].

VI. Experimental Results

Figure 3 shows the accuracy of the proposed continuous feature network architecture compared to the accuracy of the comparison network. To show the ability of the continuous feature network to handle inconsistently sampled data, the prediction accuracy of the network was measured with the data of certain detectors withheld during inference. For each sample of data in the test set the detectors whose data was withheld were picked randomly, according to the number of detectors disabled.

For the continuous feature network and continuous feature layer, the missing data points were simply removed from the input vector. Due to the nature of the continuous feature network, it is capable of processing the shorter input vector without the need to retrain the model. For the multi-layer feed-forward network, the data was interpolated from the data of other detectors with a similar wavelength and emitter-detector

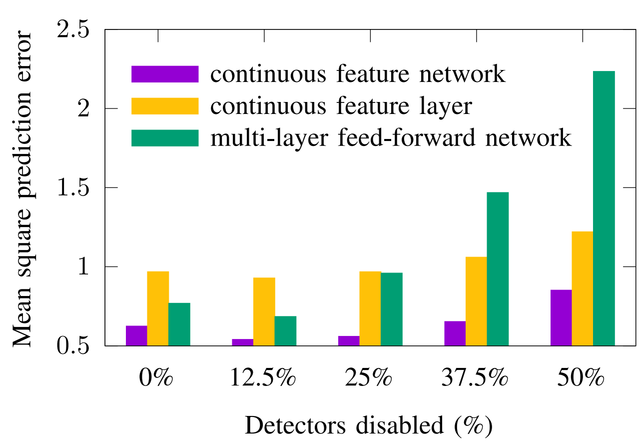


Fig. 3. The mean square prediction error (lower is better) of the continuous feature network, a continuous feature layer with no follow-up network, and the multi-layer feed-forward network with the data of a different number of detectors withheld.

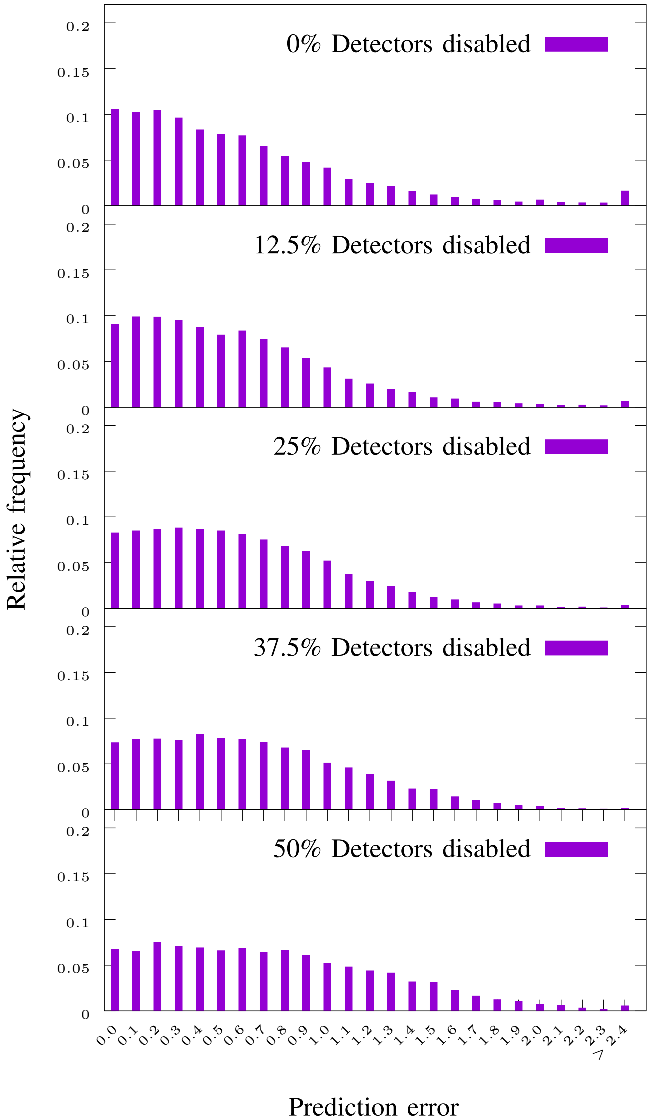


Fig. 4. A histogram of the prediction error of the **continuous feature network** at different numbers of light detectors whose data was withheld.

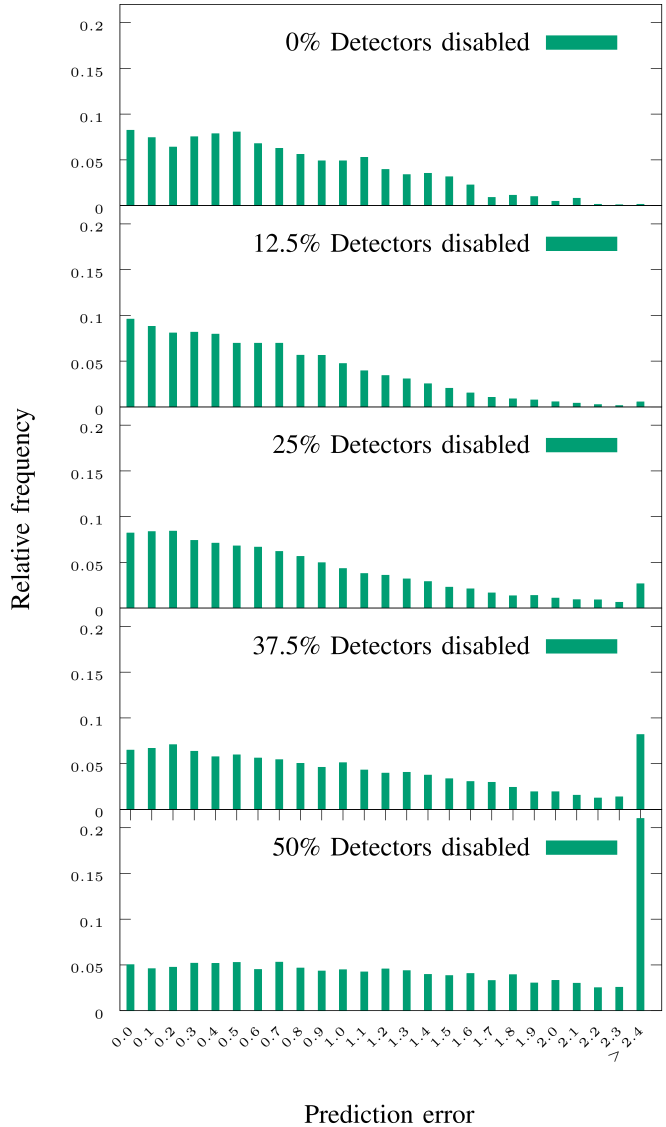


Fig. 5. A histogram of the prediction error of the **multi-layer feed-forward network** at different numbers of light detectors whose data was withheld.

distance. This is needed as the feed-forward network is incapable of handling the shorter input vector without retraining. If no other data was available with a similar wavelength and distance, the value was set to 0 for the feed-forward network.

The results show that the continuous feature network outperforms the similarly-sized multi-layer feed-forward network for all investigated numbers of detectors whose data was withheld. The continuous feature network is able to achieve a mean square error of 19% lower compared to the multi-layer feed-forward network for the full set of input data. The improved prediction accuracy can be explained both by the high suitability of continuous feature networks for MSRRS data allowing an improved abstraction of the relationship between optical data and the reference carotenoid concentration in human skin, as well as because the continuous feature network is able to incorporate the actual measured wavelengths of the light emitters for each sensor as the position of the input data points. In addition, we see that the continuous feature network is able to give a stable prediction with more data missing compared to the multi-layer feed-forward network. While the continuous feature layer without a subsequent network is unable to achieve a similar prediction accuracy compared to the full continuous feature network, it retains its resilience against missing data. The observed mean square error is only slightly increasing with 50% of the data missing. Compared to the multi-layer feed-forward network, the measurement results show that the resilience against missing data is yielded by the use of the continuous kernels in the continuous feature layer for initial data input. Built into a slightly deeper model architecture like the proposed continuous feature network, the continuous kernels in the continuous feature layer are a powerful tool for processing irregularly and inconsistently sampled data.

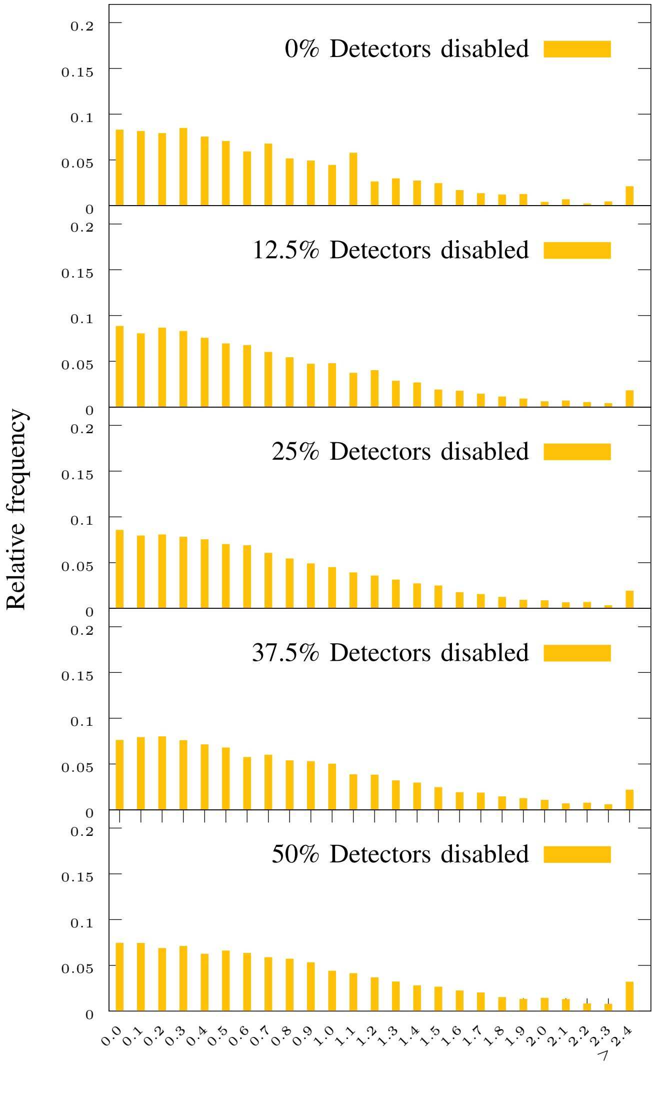
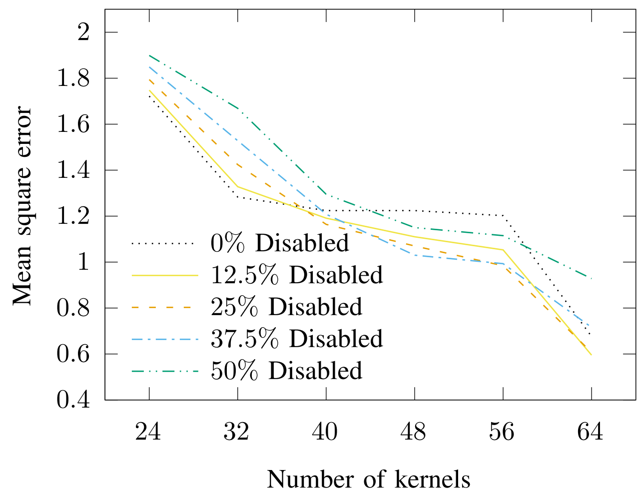


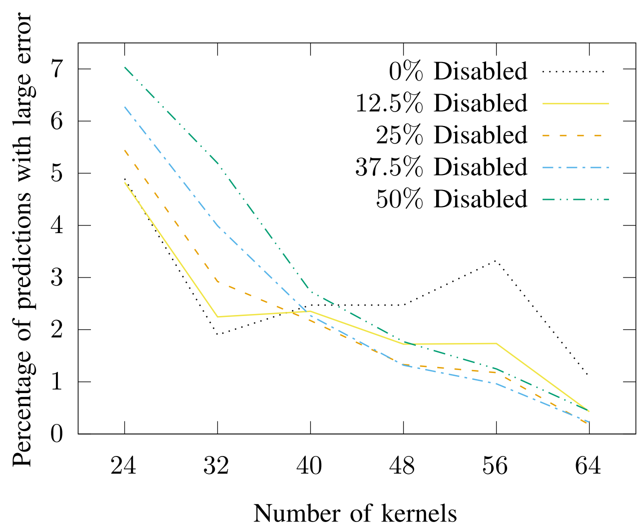
Fig. 6. A histogram of the prediction error of a **continuous feature layer** followed by a simple weighted sum instead of a fully trained follow-up network at different numbers of light detectors whose data was withheld.

The ability of the continuous feature layer and network to adapt to fewer data being available can be seen in more detail in Figures 4, 5, and 6. Figure 4 shows a histogram of the prediction error of the continuous feature network with a different amount of data being withheld. The detectors whose data was withheld from the continuous feature network were picked randomly. As the graph shows, while the amount of highly accurate precision lowers with more data being withheld, the amount of predictions with a large error (> 2.4) is not increasing significantly in contrast to the multi-layer feed-forward network. The multi-layer feed-forward network quickly encounters an increase in predictions with a large error (> 2.4) once the amount of withheld data from disabled detectors increases to or above 25%, in addition to a reduction in highly accurate predictions as seen in Figure 5. This contrast shows that the continuous feature network is capable of adapting to a lower amount of data being available without the need for retraining. The slight increase of predictions with a large error occurring for the continuous feature network when no data is withheld is presumed to be due to a combination of inaccurate input data point density estimation and slight overfitting and will be subject to further investigation.

Figure 6 shows a histogram of the prediction error for the continuous feature layer with no subsequent network. Compared to the full continuous feature network, the continuous feature layer only has less highly accurate predictions when the full amount of data is available. Instead, the number of



(a) The mean square error with predicting carotenoids in human skin using continuous feature networks of different sizes.



(b) The percentage of predictions with a large carotenoids in human skin using continuous feature networks of different sizes.

Fig. 7. The accuracy of continuous feature networks for predicting carotenoids in human skin from optical data, tested for continuous feature layers containing different amounts of continuous kernels and with the data of different percentages of detectors withheld from the continuous feature network.

moderately accurate predictions increases, while the number of predictions with a large error slightly increases as well. Similar to the full continuous network, the measurements show that with less and less data being available, the continuous feature layer without subsequent network is also capable of keeping the number of predictions with a large error low, with only a slight increase being observable, compared to the large increase of the multi-layer feed-forward network.

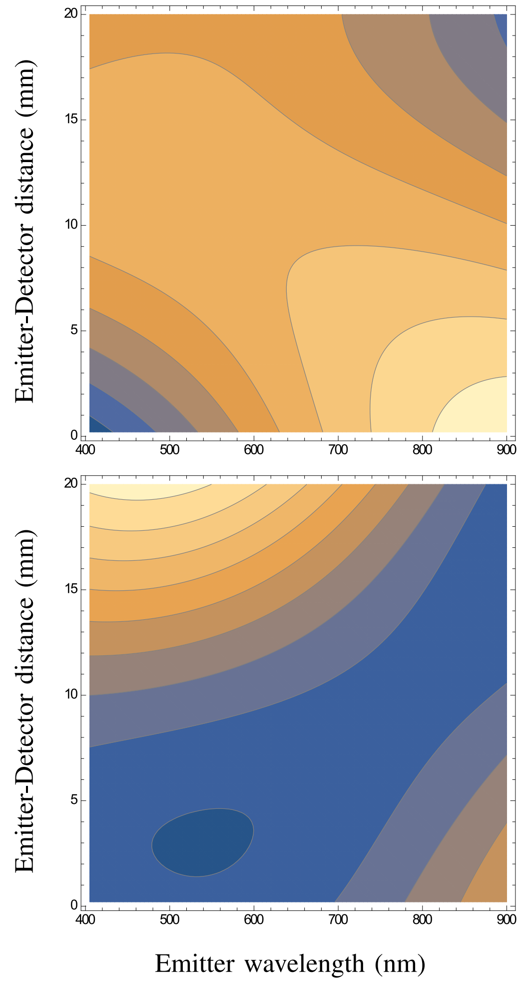
Influence of the Number of Kernels Used

One important parameter of the continuous feature network is the number of continuous kernels used in the continuous feature layer. As can be seen in Figure 7, a larger number of kernels will result in a better prediction of carotenoids in the test dataset. This is visible both in the reducing mean square error shown in Figure 7a, as well as in the reducing number of predictions with a large error (> 2.4) seen in Figure 7b. One interesting observation is that the number of predictions with a large error increases specifically for situations with many kernels used in the network as well as with few, especially no detectors having their data withheld. This supports the assumption that the slight increase in predictions with a large error, as observed before, may be caused by overfitting, especially in the larger networks. For this reason, analysis of the efficacy of anti-overfitting techniques such as dropout [14] for the use with continuous feature layers and continuous feature networks is interesting for future research. Once the network gets sufficiently large, the overall increase in prediction quality is able to outperform the increasing effect of overfitting when all data is available.

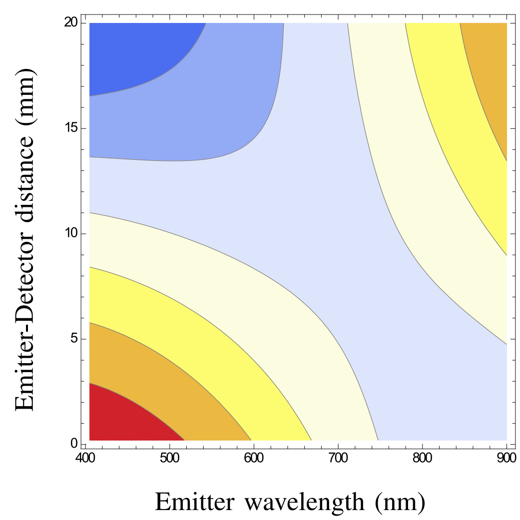
VII. Potential for Explainable AI

A side effect of the continuous feature layer is the resulting potential for explainable AI. As continuous kernels represent weights for each position in the measurement domain, we can deduct levels of importance of certain regions within the measurement domain from the encoded weights. The average of the absolute value of the weights over all kernels might be used as a measure of the importance of the data at certain points in the measurement domain. This may allow the use of the learned continuous kernels as an interpretable model [15].

Figure 8 shows three such kernels. They are taken from the continuous feature layer with no subsequent network, trained on predicting the carotenoid concentration in human skin, as presented in Figures 3 and 6 from Section VI. Figure 8a shows two kernels whose outputs have some of the highest weights in the learned network and thus have some of the highest influence. Figure 8b shows a kernel whose output has a negative weight with one of the highest absolute values. Since the output of this model is directly acquired from a weighted sum of the activated outputs of the continuous feature layer, it is possible to infer meaning directly from the learned kernels. In the positive kernels shown in Figure 8a, a high value in the kernel (here bright yellow/white) means that an emitter-detector pair with the corresponding wavelength and distance will have a high impact, and a high brightness will



(a) Two kernel whose outputs have a large **positive** weight. Yellow areas imply high weight, blue areas imply low weight.



(b) A kernel whose output has a large **negative** weight. Red areas imply high weight, blue areas imply low weight.

Fig. 8. Kernels from a continuous feature layer whose outputs are combined in a weighted sum, trained to predict carotenoids in human skin. High-weight areas in positively weighted kernels increase the final value when more light is detected, while high-weight areas in negatively weighted kernels decrease the final value when more light is detected.

thus increase the final value. At the same time, in the negative kernel Figure 8b, a high value (here red) means that an emitter-detector pair with the corresponding wavelength and distance will have a high impact, and a high brightness will thus decrease the final value. The positive kernels show that more light detected at various wavelengths will increase the final value, except for light at low distances and wavelengths around 400 nm to 600 nm. Similarly, the negative kernel shows that especially more light being detected at low distances and wavelengths between 400 nm to 500 nm will decrease the final value. This is plausible, as the main detection targets are carotenoids. It is known that carotenoids have a high absorption, especially between 450 nm and 500 nm [16]. It is thus expected that if more light in this absorption band is reaching the light detectors, fewer carotenoids seem to be present to absorb it, and thus the predicted carotenoid concentration is lowered, as the negative kernel shown in Figure 8b will cause.

This shows that kernel interpretability is an interesting feature of continuous feature layers. Combining kernel interpretability with more tools of explainable AI, especially to enable model interpretability for models with more complex networks following the continuous feature layer, are an interesting topic for future research.

VIII. Conclusion and Future Work

This paper proposes the continuous feature network, a novel method to process irregularly and inconsistently sampled data with position-dependent features, such as optical or acoustic spectra. In addition, the continuous feature network is shown to outperform a comparable multi-layer feed-forward network with a 19% lower mean square error on predicting carotenoid concentration in human skin from optical multiple spatially resolved reflection spectroscopy data. This shows that the continuous feature network performed better at abstracting the relationship between the optical MSRRS data and the reference carotenoid concentration. Furthermore, this paper shows that the continuous feature network is capable of making stable predictions of carotenoid concentration in human skin with up to 50% of the data from the optical detectors withheld, while a comparable multi-layer feed-forward network exhibits a significant increase in predictions with a large error from 25% of the data withheld. Furthermore, it is shown that this reliability is caused by the continuous feature layer itself instead of the subsequent network. Additionally, it is shown how the number of continuous kernels affects the model's resilience and adaptability against missing data, as well as its overall ability to perform accurate predictions of carotenoid concentrations from optical data. Other potential use cases include similar types of data where samples may be irregular and features are position-dependent in the measurement domain, including other types of spectra, such as audio. Additionally, an approach to utilize continuous feature networks as interpretable models for explainable AI is introduced and shown in the example of the prediction of carotenoids.

References

[1] B. M. Magnussen, C. Stern, and B. Sick, "Utilizing continuous kernels for processing irregularly and inconsistently sampled data with position-dependent features," in *Proceedings of The Nineteenth International Conference on Autonomic and Autonomous Systems*, ser. International Conference on Autonomic and Autonomous Systems, C. Behn, Ed., IARIA. ThinkMind, Mar 2023, pp. 49–53.

[2] A. R. T. Donders, G. J. van der Heijden, T. Stijnen, and K. G. Moons, "Review: A gentle introduction to imputation of missing values," *Journal of Clinical Epidemiology*, vol. 59, no. 10, pp. 1087–1091, 2006.

[3] P. K. Sharpe and R. J. Solly, "Dealing with missing values in neural network-based diagnostic systems," *Neural Computing & Applications*, vol. 3, no. 2, pp. 73–77, Jun 1995.

[4] Y. Lecun, L. Bottou, Y. Bengio, and P. Haffner, "Gradient-based learning applied to document recognition," *Proceedings of the IEEE*, vol. 86, no. 11, pp. 2278–2324, 1998.

[5] D. W. Romero, A. Kuzina, E. J. Bekkers, J. M. Tomczak, and M. Hoogendoorn, "Ckconv: Continuous kernel convolution for sequential data," *CoRR*, vol. abs/2102.02611, 2021.

[6] K. T. Schütt, P.-J. Kindermans, H. E. Sauceda, S. Chmiela, A. Tkatchenko, and K.-R. Müller, "Schnet: A continuous-filter convolutional neural network for modeling quantum interactions," in *Proceedings of the 31st International Conference on Neural Information Processing Systems*, 2017, p. 992–1002.

[7] W. Wu, Z. Qi, and L. Fuxin, "Pointconv: Deep convolutional networks on 3d point clouds," in *2019 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*, 2019, pp. 9613–9622.

[8] M. E. Darvin, B. Magnussen, J. Lademann, and W. Köcher, "Multiple spatially resolved reflection spectroscopy for in vivo determination of carotenoids in human skin and blood," *Laser Physics Letters*, vol. 13, no. 9, p. 095601, Aug 2016.

[9] V. Sitzmann, J. N. P. Martel, A. W. Bergman, D. B. Lindell, and G. Wetzstein, "Implicit neural representations with periodic activation functions," in *Proceedings of the 34th International Conference on Neural Information Processing Systems*, 2020.

[10] J. J. Park, P. Florence, J. Straub, R. Newcombe, and S. Lovegrove, "Deepsdf: Learning continuous signed distance functions for shape representation," in *2019 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*, 2019, pp. 165–174.

[11] K. Genova, F. Cole, A. Sud, A. Sarna, and T. Funkhouser, "Local deep implicit functions for 3d shape," in *2020 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*, Jun 2020, pp. 4856–4865.

[12] D. P. Kingma and J. Ba, "Adam: A method for stochastic optimization," in *3rd International Conference on Learning Representations, ICLR 2015, San Diego, CA, USA, May 7-9, 2015, Conference Track Proceedings*, Y. Bengio and Y. LeCun, Eds., 2015.

[13] A. Paszke, S. Gross, F. Massa, A. Lerer, J. Bradbury, G. Chanan, T. Killeen, Z. Lin, N. Gimelshein, L. Antiga, A. Desmaison, A. Kopf, E. Yang, Z. DeVito, M. Raison, A. Tejani, S. Chilamkurthy, B. Steiner, L. Fang, J. Bai, and S. Chintala, "Pytorch: An imperative style, high-performance deep learning library," in *Advances in Neural Information Processing Systems*, H. Wallach, H. Larochelle, A. Beygelzimer, F. d'Alché-Buc, E. Fox, and R. Garnett, Eds., vol. 32. Curran Associates, Inc., 2019.

[14] N. Srivastava, G. Hinton, A. Krizhevsky, I. Sutskever, and R. Salakhutdinov, "Dropout: A simple way to prevent neural networks from overfitting," *Journal of Machine Learning Research*, vol. 15, no. 56, pp. 1929–1958, 2014.

[15] O. Biran and C. V. Cotton, "Explanation and justification in machine learning: A survey," in *IJCAI-17 Workshop on Explainable AI (XAI) Proceedings*, 2017.

[16] E. S. Miller, G. Mackinney, and J. Zscheile, F. P., "Absorption spectra of alpha and beta carotenes and lycopene," *Plant Physiology*, vol. 10, no. 2, pp. 375–381, Apr 1935.

New Survey Results of Archaeological Settlement Infrastructures and Holocene-prehistoric Volcanological Features

Based on Methodological Conceptual Multi-disciplinary Contextualisation

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Abstract*—This paper presents the new survey and methodological analysis results of the research on coherent multi-disciplinary contextualisation and symbolic representation of worldwide Holocene-prehistoric volcanological features and discovery of archaeological settlement infrastructures, especially for prehistoric contexts and context discovery. The research is based on methodological contextualisation and targets flexible context representation, processing, and integration, which includes further development of knowledge resources, visualisation, and chorological and chronological views for analysis, interpretation, decision making, and new insight. The presented practical implementation employs the new Conceptual Knowledge Reference Implementation (CKRI) and the Component Reference Implementations (CRI) framework for conceptual knowledge-based context integration, complements knowledge processing, and geoscientific and spatial processing and visualisation. The goal of this research is the creation of practical knowledge-based methods and tool set components, which provide solid, standardised means for sustainable long-term research. Both, methods and components should enable further continuous development and adoption to future research questions and targets. This paper provides the specific context discovery results, references to all component implementations and realisations based on coherent multi-disciplinary conceptual knowledge and methodological and systematical component integration. Future research will address further, continuous developments of reference implementations and knowledge resources and the application for advanced large scale scenarios, site surveys, and campaigns in prehistory and archaeology.

Keywords*–*Prehistory; Holocene; Archaeological Settlement Infrastructures; Coherent Multi-disciplinary Conceptual Knowledge Contextualisation; CKRI and CRI Framework.

I. Introduction

This paper is an extended and updated presentation of new research results, based on the research, publication, and presentation at the GEOProcessing 2023 conference in Venice, Italy [1].

The theoretical and practical developments of this ongoing research are one group of six impactful research endeavors selected worldwide for the 2023 Hyperion Research special report on recent High-Performance Computing (HPC) centric AI success stories [2] (AI, "Artificial Intelligence"). The special report emphasises the epistemologically relevant methodological fundament 'The Conceptual Knowledge Reference Implementation' (CKRI) and 'The Component Reference Implementations framework' (CRI), providing sustainable standard component groups for implementation.

Due to the large number of inquiries and far-reaching interests from scientific disciplines and public regarding multi-disciplinary contextualisation cases employing the created inventory, we take the chance that this extended paper can concentrate on the practical application of the inventory, showing a wider range of new survey and on-site result groups of archaeological settlement infrastructures and insights based on practical conceptual facets used for on-demand contextualisation and symbolic representation. The entirety of provided methods enables an advanced, consistent multi-disciplinary conceptual knowledge contextualisation, especially universal knowledge facets, method integration, flexible workflow definition, and parallelisation on HPC resources.

Both, the ongoing research on the epistemological [3] and the components base [4] and its implementations were published and demonstrated at the Lawrence Livermore National Laboratory (LLNL) [5].

This publication includes the new survey results and references to on-site results of archaeological settlement infrastructures and Holocene-prehistoric volcanological features based on methodological contextualisation. The historico-cultural contexts span several continents.

The goal of contextualisation especially targets prehistoric contexts worldwide, identifying and integrating archaeological, prehistoric objects with objects from other scientific disciplines on equal footing, promoting a coherent multi-disciplinary conceptual methodological approach. The methodological goal of this research is the creation of practical and sustainable knowledge-based methods and tool sets, which provide solid means for sustainable long-term research. The methods and sets of tools should provide standardised components, which can be continuously further developed and adopted to future research questions and targets. The research targets flexible context processing, integration, and representation, which includes further development of knowledge resources, visualisation, and chorological and chronological views for analysis, interpretation, decision making, and new insight.

The rest of this paper is organised as follows. Sections II and III present the implementations of and conceptual knowledge with all required references including all technical aspects. Section IV provides the all respective components and references used for implementation. Section V delivers results for an excerpt of four scenarios. Sections VI and VII discuss case scenarios and summarise lessons learned, conclusions, and future work.

II. Knowledge and Component Implementations

Two major practical reference implementations were deployed for full implementations, realisations, and continuous further developments: the new versions of the prehistory-protohistory and archaeology CKRI [3] and the CRI framework [4] for conceptual knowledge-based context integration, complements processing, and geoscientific visualisation. CKRI provides the knowledge framework, including multi-disciplinary contexts of natural sciences and humanities [6]. CRI provides the required component groups and components for the implementation and realisation of all the procedural modules.

The reference implementations are based on the fundamental methodology of knowledge complements [7], considering that many facets of knowledge, including prehistory, need to be continuously acquired and reviewed [8]. Creating contextualisation requires to coherently integrate multi-disciplinary knowledge and to enable symbolic representations. Realisations need to integrate a wide range of components as required from participating disciplines, e.g., for dynamical processing, geoprocessing, spatial contextualisation. The capabilities and features of both reference implementations are huge. The individual characteristics and features of the components are explained in detail in the cited publications and the referenced documentation of the components. The materials also already include thousands of examples and applications. Here, we will assume these fundaments to be known and concentrate on the newly achieved survey results of archaeological settlement infrastructures and Holocene-prehistoric volcanological features.

III. Conceptual Knowledge Implementation

Implementations and realisations are based on the CKRI reference implementation [9], and respective contextualisation. References are capable to integrate required context. Besides the core scope of this knowledge-focussed research on prehistoric, archaeological, and geoscientific questions, procedural complements are employed and extended via the CRI frame reference implementations [10]. Both provide sustainable fundaments for highest levels of reproducibility and standardisation.

Many aspects of knowledge [11], including meaning, can be described using knowledge complements supporting a modern definition of knowledge [12] and subsequent component instrumentation, e.g., considering factual, conceptual, procedural, metacognitive, and structural knowledge. Complements are a means of understanding and targeting new insight, e.g., enabling advanced contextualisation, integration, analysis, synthesis, innovation, prospection, and documentation. Regarding knowledge, it should be taken for granted, that scientific members of any disciplines nowadays continuously practice and train themselves in development and practical employment of methods, algorithms, and components as required by their disciplines and keep track with how to integrate methods.

A. Coherent Conceptual Knowledge Implementation

Universally coherent multi-disciplinary conceptual knowledge is implemented via the CKRI [9], demonstrated with Universal Decimal Classification (UDC) [13] code references, spanning the main tables [14], based on science and knowledge organisation [15], [16], as shown in Table I. The verbal descriptions of the references are already available in more than fifty languages. Here, verbal descriptions are given in English language (en) as is. Any factual content in the verbal descriptions can be deliberately modified and re-assigned if descriptions should be used in a procedure. Consistent multi-disciplinary conceptual knowledge is demonstrated via UDC code references spanning auxiliary tables [16].

TABLE I. CKRI IMPLEMENTATION OF COHERENT CONCEPTUAL KNOWLEDGE CONTEXTUALISATION; MAIN TABLES (EXCERPT).

Code / Sign Ref.	*Verbal Description (en)*
UDC:0	Science and Knowledge. Organization. Computer Science. Information. Documentation. Librarianship. Institutions. Publications
UDC:1	Philosophy. Psychology
UDC:2	Religion. Theology
UDC:3	Social Sciences
UDC:5	Mathematics. Natural Sciences
UDC:52	Astronomy. Astrophysics. Space research. Geodesy
UDC:53	Physics
UDC:539	Physical nature of matter
UDC:54	Chemistry. Crystallography. Mineralogy
UDC:55	Earth Sciences. Geological sciences
UDC:550.3	Geophysics
UDC:550.7	Geobiology. Geological actions of organisms
UDC:550.8	Applied geology and geophysics. Geological prospecting and exploration. Interpretation of results
UDC:551	General geology. Meteorology. Climatology. Historical geology. Stratigraphy. Palaeogeography
UDC:551.2...	Fumaroles. Solfataras. Geysers. Hot springs. Mofettes. Carbon dioxide vents. Soffioni
UDC:551.21	Vulcanicity. Vulcanism. Volcanoes. Eruptive phenomena. Eruptions
UDC:551.24	Geotectonics
UDC:551.4	Geomorphology. Study of the Earth's physical forms
UDC:551.44	Speleology. Caves. Fissures. Underground waters
UDC:551.46	Physical oceanography. Submarine topography. Ocean floor
UDC:551.7	Historical geology. Stratigraphy
UDC:551.8	Palaeogeography
UDC:56	Palaeontology
UDC:6	Applied Sciences. Medicine, Technology
UDC:63	Agriculture and related sciences and techniques. Forestry. Farming. Wildlife exploitation
UDC:631	Agriculture in general
UDC:631.4	Soil science. Pedology. Soil research
UDC:692	Structural parts and elements of buildings
UDC:7	The Arts. Entertainment. Sport
UDC:711	Principles and practice of physical planning. Regional, town and country planning
UDC:8	Linguistics. Literature
UDC:9	Geography. Biography. History
UDC:902	Archaeology
UDC:903	Prehistory. Prehistoric remains, artefacts, antiquities
UDC:904	Cultural remains of historical times

The excerpts span all main tables, including relevant references required for this research. The CKRI is provided in development stage editions, prehistory-protohistory and archaeology E.0.4.8, natural sciences E.0.4.0.

B. Implementation of Auxiliaries and Operations

Tables II and III show CKRI excerpts of auxiliary tables and signs. Geological time ranges are in Million Years Before Present (MYBP).

TABLE II. CKRI IMPLEMENTATION OF COHERENT CONCEPTUAL KNOWLEDGE CONTEXTUALISATION; AUXILIARY TABLES (EXCERPT).

Code / Sign Ref.	*Verbal Description (en)*
UDC (1/9)	Common auxiliaries of place
UDC:(1)	Place and space in general. Localization. Orientation
UDC:(2)	Physiographic designation
UDC:(23)	Above sea level. Surface relief. Above ground generally. Mountains
UDC:(24)	Below sea level. Underground. Subterranean
UDC:(3)	Places of the ancient and mediaeval world
UDC:(4/9)	Countries and places of the modern world
UDC:"..."	Common auxiliaries of time.
UDC:"6"	Geological, archaeological and cultural time divisions
UDC:"61"	Precambrian (more than 542 MYBP) (supereon)
UDC:"62"	Phanerozoic (542 MYBP to present) (eon)
UDC:"621"	Palaeozoic / Paleozoic (542-251 MYBP) (era)
UDC:"622"	Mesozoic (251-65.5 MYBP) (era)
UDC:"628"	Cenozoic (65.5 MYBP to present) (era)
UDC:"63"	Archaeological, prehistoric, protohistoric periods and ages

Standardised operations (Table III) are employed for creation of reference listings and facetted knowledge, integrating UDC auxiliary signs [16].

TABLE III. CKRI OPERATION SIGNS EXCERPT, INTEGRATING UDC COMMON AUXILIARY SIGNS (ENGLISH COMMENTS VERSION).

Operation	*Symbol*	
Coordination. Addition	+	(plus sign)
Consecutive extension	/	(oblique stroke sign)
Simple relation	:	(colon sign)
Order-fixing	::	(double colon sign)
Subgrouping	[]	(square brackets)
Introduces non-UDC notation	*	(asterisk)
Direct alphabetical specification.	A/Z	(alphabetic characters)
[Reference listing, itemisation]	;	(semicolon)
[Reference listing, sub-itemisation]	,	(comma)

Conceptual knowledge in focus can be employed to provide references and facets to any universal knowledge context.

IV. COMPONENT IMPLEMENTATIONS

A. Resulting Methodological Component Integration

Integration components, reflecting standards and sustainable modules are based on the major groups of the CRI. The CRI framework is provided in development stage edition E.0.3.9. The ten major CRI component groups are:

1) Conceptual knowledge frameworks.
2) Conceptual knowledge base.
3) Integration of scientific reference frameworks.
4) Formalisation.
5) Methodologies and workflows integration.
6) Prehistory knowledge resources.
7) Natural sciences knowledge resources.
8) Inherent representation groups.
9) Scientific context parametrisation.
10) Structures and symbolic representation.

All parts were realised based on CRI components, with realisations fully referenced in the following sections. The groups are numbered for clearly addressing that these components and the understanding of their functional requirements and also their technical background are precondition for own knowledge-centric implementations and realisations.

1) The conceptual knowledge was realised for all disciplines via the CKRI conceptual knowledge framework [9] and operations (Table III). CKRI is demonstrated with UDC [13] references. For demonstration, CKRI references are illustrated via the multi-lingual UDC summary [13] released by the UDC Consortium, Creative Commons licence [17].
2) Relevant scientific practices, frameworks, and standards from disciplines and contexts are integrated with the Knowledge Resources (KR), e.g., here details regarding volcanological features, chronologies, spatial information, and Volcanic Explosivity Index (VEI) [18]. Corresponding coherent complementary results and details on faceting are available for a whole inventory of volcanological features groups [3].
3) All integration components, for all disciplines, require an explicit and continuous formalisation [19] process. The formalisation includes computation model support, e.g., parallelisation standards, OpenMP [20], Reg Exp patterns, e.g., Perl Compatible Regular Expressions (PCRE) [21]. Here, common scale of entities for primary objects is 10^3 and for secondary objects 10^4–10^5. Processing operations [22] were parallelised for primary (n_1) features groups with respective instances. For production, all components were implemented under Linux on multi-core systems and showed very efficient, both for OpenMP and GNU Parallel (GNU, Gnu's Not Unix).
4) Methodologies for creating and utilising methods include model processing, remote sensing, spatial mapping, high information densities, and visualisation. Respective contextualisation for scenarios in prehistory should be done under conditions especially reflecting state-of-the-art methods, e.g., spatial operations, triangulation, gradient computation, and projection.
5) The symbolic representation of the contextualisation can be done with a wide range of methods, algorithms, and available components, e.g., implemented here via LX Professional Scientific Content-Context-Suite (LX PSCC Suite) deploying the Generic Mapping Tools (GMT) [22] for visualisation.
6) Prehistoric objects and contexts are taken from The Prehistory and Archaeology Knowledge Archive (PAKA), which is in continuous development for more than three decades [23], released by DIMF [24]. Collaborative interfaces, e.g., The Archaeological Data Collector (ADC) [25], were developed and established for archaeological survey contributions and are used for ongoing data integration and analysis.

7) Several coherent systems of major natural sciences' context object groups from KR realisations have been implemented, especially KR focussing on volcanological features [18] deployed with in depth contextualisation and with a wide range [13] of contexts [26] and structures [27] [28].
8) The contextualisation solution can employ state-of-the-art results from many disciplines, e.g., context from the natural sciences resources, integrating their inherent representation and common utilisation, e.g., points, polygons, lines, and spatial techniques and standards. Here, resources are Digital Elevation Models (DEM), High Resolution (HR) (Space) Shuttle Radar Topography Mission (SRTM) [29] data fusion [30], HR Digital Chart of the World (DCW) [31], and Global Self-consistent Hierarchical High-resolution Geography (GSHHG) [32].
9) Scientific context parametrisation of prehistoric targets can use the overall insight from all disciplines, e.g., parametrising algorithms and creating palaeolandscapes.
10) Structure is an organisation of interrelated entities in a material or non-material object or system [27]. Here, relevant examples of sustainable implementations are NetCDF [33] based standards, including advanced features, hybrid structure integration, and parallel computing support (PnetCDF).

Overall, all parts of the solution were implemented and realised via these components. Especially, GMT modules were deployed for select procedures together with PCRE and Perl filters. Spatial distance dependencies of objects and conditional decision criteria were realised via GMT geodesic calculation, which is very accurate using the Vincenty algorithm [34].

V. Scenarios, Implementations and Results

The results for a multi-disciplinary case scenario from the current research with full practical implementations for four primary case instances were chosen, Holocene-prehistoric volcanological features of strato volcanoes, maars, subglacial volcanoes, and submarine volcanoes (CKRI: UDC:511.2…), with geospherical calculations on a global scale and context discovery with coherently classified archaeological settlement infrastructure instances (CKRI: UDC:711.…,692,903,902,…) in geospherical radii of 300 km spatial distance from primary objects.

A. Methodological Approach

The method can be summarised as follows.

- Selection of KR, components, primary and secondary object types, symbolic representation, …
- Conceptual knowledge assignment.
- Selection of chronological properties.
- Selection of primary objects.
- Selection of secondary objects.
- Calculation of secondary objects' geospherical spatial distances.
- Parallelisation of conceptual knowledge processing.
- Parametrisation of symbolic representation.
- Parallelisation of context data processing.
- Visualisation processing.
- (Further development of resources and implementations by the specific disciplines.)

In new applications, all steps and items should be carefully and intentionally addressed for any intelligent employment, depending on the research questions and contexts.

B. Resulting Context Groups

An excerpt of the four primary context groups and criteria ($\textcircled{\alpha}$, $\textcircled{\beta}$, $\textcircled{\gamma}$, and $\textcircled{\delta}$) and contextualisation of archaeological settlement infrastructures is shown in (Table IV). The primary decision criteria (n_1) include conceptual context, feature object type, chronology, and position. The secondary decision criteria (n_2) include conceptual context, prehistoric object type, chronology, position, and conditional geospherical spatial distance depending on respective primary objects.

TABLE IV. SCENARIO CONTEXT GROUPS AND CRITERIA: VOLC. FEATURES / ARCH. SETTLEMENT INFRASTRUCTURES (EXCERPT).

Context n_1		*Context n_2*
Geosciences		Archaeology / prehistory
Geoscientific features objects		Prehistoric object groups
Volc. features groups		Settlement infrastructures
• **Strato volcano**	$\textcircled{\alpha} \Rightarrow \{$	• **Viereckschanze**
• Shield volcano		• **Dwelling**
• **Maar**	$\textcircled{\beta} \Rightarrow \{$	• **Long house**
• Complex volcano		• **Midden context**
• Explosion crater		• **Farm hut**
• **Subglacial volcano**	$\textcircled{\gamma} \Rightarrow \{$	• **Enclosure**
• **Submarine volcano**	$\textcircled{\delta} \Rightarrow \{$	• **Roundhouse**
• Volcanic field		• **Siedlungsplatz**
• Cone		• **Homestead**
• Fissure vent		• **Hut circle**
• Dome		• **[individually named]**
• …		• …
[Type Instances …]		[Type instances …]
Decision Criteria (n_1)		*Decision Criteria (n_2)*
Conceptual context (CKRI)		Conceptual context (CKRI)
Feature object type		Prehistoric object type
Chronology conditions		Chronology conditions
Chorology / positional conditions		Chorology / positional conditions
Object attributes		Object attributes
…		Geospherical spatial distance (n_1-instance-conditional)
…		Parametrisation, …,
…		Calculation / analysis

Prehistoric object groups include all available language representations, e.g., 'en' and 'de'. Here, the first primary object group defines the spatial projection for consecutive primary groups. Each of these primary groups is contextualised for all of the secondary object groups.

C. Resulting Context Discovery Matrices

Table V shows an excerpt of the result matrix of Holocene-prehistoric volcanological features groups and respective facets, namely conceptual knowledge, chronology, and chorology for the four scenarios (ⓐ, ⓑ, ⓒ, and ⓓ in Table IV).

The result matrix includes conceptual knowledge view groups [13] based on CKRI references [9], factual knowledge from the KR objects, respective Country Codes (CC), and further Associated Context Data (ACD), e.g., symbolic representations of national flags.

Context example references for the features groups facets show Prehistoric Volcanic Activity (PVA), Historic Volcanic Activity (HVA), and Continued Volcanic Activity (CVA), e.g., latent volcanic activity. PVA are consequence of the Holocene-prehistoric chronological contextualisation for all objects in the resulting volcanological features groups. Cases for which further facts are holding true can also allow past-prehistoric contextualisation, e.g., with HVA and CVA.

Four instances each are further discussed for the primary scenarios. Contextualisation for instances is done regarding resulting settlement infrastructures. Instances are named ①, ②, ③, ④. Resulting context discovery matrices for primary case instances of the scenario for multi-disciplinary contextualisation of settlements are given in Tables VI and VII. Instances ⓐ, ⓑ, ⓒ, and ⓓ refer to Table IV. Figure 1 shows a corresponding visualisation of the calculation results of the context discovery for the first two instances.

The corresponding visualisation of the calculation results of the context discovery for consecutive instances three and four are given in Figure 2. Overall we have sixteen groups in this example as we select four primary with four secondary groups each. By consequently following the methodological approach does have the benefit of being consistent regarding multi-disciplinary conceptual knowledge, e.g., when integrating volcanological features and archaeological settlement infrastructures. The targets can also be modified by switching primary and secondary groups and by selecting different object groups. Applying such systematical implementations for the realisation of individual methods for case scenarios can deliver new factual answers to different research questions.

VI. Discussion of Case Scenario Results

The next sections discuss result we regard relevant from the methodological, historico-cultural, and educational domains.

A. Methodological Domain

Implementation and realisation provide a seamlessly coherent multi-disciplinary conceptual knowledge contextualisation for the case scenario and its instances. The context discovery result matrices (Tables VI, VII, VIII, and IX) for all instances ⓐ, ⓑ, ⓒ, and ⓓ refer to n_2 in Table IV. Especially, these secondary object groups include objects from Middle Neolithic (MN) to at least Late Iron Age (LIA), including ages in between, e.g., Bronze Age. Auxiliaries of time support various concepts and include geological, archaeological, and cultural time divisions, spanning from the Precambrian Supereon over the Archaean to the Palaeolithic over the Neolithic and to historical times. Mechanisms allow flexible extensions and facets, e.g., 'zoic' and 'phytic' references. Therefore, the Holocene-prehistoric scenarios, besides their high quantities and complexities, comprise just a small subset of cases.

The objects groups comprise all types of settlement infrastructures, e.g., Celtic ramparts, Viereckschanzen (VS), earthworks –commonly square, four corner ramparts–, and middens with settlement contexts.

The resulting group of strato volcanoes aligns along $0^\circ/360^\circ$ longitude (Figure 1). An appropriate Transverse Mercator projection was chosen in order to minimise the distortion along a respective meridian for the generation of the primary results of strato volcanoes and results for other consecutive, secondary, contextualised volcanological features, e.g., maars, subglacial and submarine volcanoes.

The CRI framework components were employed for all steps, including knowledge organisation, conceptual and spatial calculation, and visualisation. Primary objects, strato volcano (medium green volcano symbol), maars (light green volcano symbol), subglacial volcano (light cyan volcano symbol), and submarine volcano (cyan volcano symbol), are marked as well as resulting secondary objects, settlements (blue rectangular symbols), all in their precise georeferenced position. Resulting conceptual knowledge is given for these objects. Resulting sums of secondary discovery objects were calculated.

Each case scenario can be dynamically contextualised with coherent multi-disciplinary knowledge, as demonstrated for geosciences, prehistory, and archaeology, e.g., referring to prehistoric object properties and excavation results and targeting new insight from geoscientific and multi-disciplinary context integration.

Any resulting contextualisation matrices and coherent conceptual and facetted knowledge can further be input to consecutive contextualisation processes. The more, solutions with individual methods and workflows can be created for countless different questions and situations.

B. Historico-cultural Domain

The methodological approach to the cases delivers a series of new context-chorology results for our four scenarios:

Alpha-scenario: maximum numbers of archaeological settlement infrastructures in surrounding areas of strato volcanoes near the zero longitude are located in Japan, followed by Iceland, and the Azores, Portugal.

Beta-scenario: maximum numbers of archaeological settlement infrastructures in surrounding areas of maars under alpha-dependence conditions are located in the Eifel, Germany, followed by Chile, and Indonesia.

Gamma-scenario: maximum numbers of archaeological settlement infrastructures in surrounding areas of subglacial volcanoes under alpha-dependence conditions are located in Iceland and Canada.

Delta-scenario: maximum numbers of archaeological settlement infrastructures in surrounding areas of submarine volcanoes under alpha-dependence conditions are located in Italy and Iceland.

Integrated analysis: The methodological approach to the cases delivers further new results beyond the primary context groups, based on the large scale and on-site surveys. We see that the scenarios are interrelated on a knowledge level. The results form intermediate matrices from the KR, which can be used for further fact-based analysis, for which we just give some starting examples.

TABLE V. RESULT MATRIX OF HOLOCENE-PREHISTORIC VOLCANOLOGICAL FEATURES GROUPS FACETS (EXCERPT, Ⓐ, Ⓑ). IT INCLUDES CONCEPTUAL KNOWLEDGE VIEW GROUPS [13] (CKRI), VOLCANIC ACTIVITY, CONTEXTS, KNOWLEDGE RESOURCES OBJECTS, COUNTRY CODES (CC), AND FURTHER RESULTING ASSOCIATED CONTEXT DATA (ACD), E.G., SYMBOLIC REPRESENTATIONS (EXCERPT).

Multi-disciplinary Conceptual Knowledge Facets	*Chronology Facets*		*Chorology Facets*			*ACD*
Volcanological Features Conceptual Knowledge View / Facets Group	*Volcanic Activity*	*Context*	*KR Object & Ref.*		*CC*	*Flag*
CKRI: UDC:551.21,550.3,(23),STRATO_VOLCANO;“62”…	Holocene	PVA / HVA	**Agua de Pau**	①	PT	
CKRI: UDC:551.21,550.3,(23),STRATO_VOLCANO;“62”…	Holocene	PVA	**Alngey**	②	RU	
CKRI: UDC:551.21,550.3,(23),STRATO_VOLCANO;“62”…	Holocene	PVA / HVA	**Azuma**	③	JP	
CKRI: UDC:551.21,550.3,(23),STRATO_VOLCANO;“62”…	Holocene	PVA / HVA	**Hekla**	④	IS	
CKRI: UDC:551.21,550.3,(23),STRATO_VOLCANO;“62”…	Holocene	PVA	…		…	…
CKRI: UDC:551.21,550.3,(23),SHIELD_VOLCANO;“62”…	Holocene	PVA / (CVA)	Volcán Darwin		EC	
CKRI: UDC:551.21,550.3,(23),SHIELD_VOLCANO;“62”…	Holocene	PVA / HVA	Kilauea		US	
CKRI: UDC:551.21,550.3,(23),SHIELD_VOLCANO;“62”…	Holocene	PVA / HVA	Santorini		GR	
CKRI: UDC:551.21,550.3,(23),SHIELD_VOLCANO;“62”…	Holocene	PVA	Waesche		AQ	
CKRI: UDC:551.21,550.3,(23),SHIELD_VOLCANO;“62”…	Holocene	PVA	…		…	…
CKRI: UDC:551.2…,551.21,550.3,(23),…MAARS_FEATURES;“62”…	Holocene	PVA	**Cerro Tujle**	①	CL	
CKRI: UDC:551.2…,551.21,550.3,(23),…MAARS_FEATURES;“62”…	Holocene	PVA / HVA	**Suoh**	②	ID	
CKRI: UDC:551.2…,551.21,550.3,(23),…MAARS_FEATURES;“62”…	Holocene	PVA / HVA	**Ukinrek Maars**	③	US	
CKRI: UDC:551.2…,551.21,550.3,(23),…MAARS_FEATURES;“62”…	Holocene	PVA / (CVA)	**West Eifel Volcanic Field**	④	DE	
CKRI: UDC:551.2…,551.21,550.3,(23),…MAARS_FEATURES;“62”…	Holocene	PVA	…		…	…
CKRI: UDC:551.21,550.2...,550.3,(23),COMPLEX_VOLCANO;“62”…	Holocene	PVA / HVA	Marapi		ID	
CKRI: UDC:551.21,550.2...,550.3,(23),COMPLEX_VOLCANO;“62”…	Holocene	PVA / HVA	Soretimeat		VU	
CKRI: UDC:551.21/550.2...,550.3,(23),COMPLEX_VOLCANO;“62”…	Holocene	PVA / HVA	Unzen		JP	
CKRI: UDC:551.21,550.2...,550.3,(23),COMPLEX_VOLCANO;“62”…	Holocene	PVA / HVA	Vesuvius		IT	
CKRI: UDC:551.21,550.2...,550.3,(23),COMPLEX_VOLCANO;“62”…	Holocene	PVA	…		…	…
CKRI: UDC:551.21,550.3,(23),EXPLOSION_CRATER;“62”…	Holocene	PVA / (CVA)	Bunyaruguru Field		UG	
CKRI: UDC:551.21,550.3,(23),EXPLOSION_CRATER;“62”…	Holocene	PVA / HVA	Dallol		ET	
CKRI: UDC:551.21,550.3,(23),EXPLOSION_CRATER;“62”…	Holocene	PVA	Koranga		PG	
CKRI: UDC:551.21,550.3,(23),EXPLOSION_CRATER;“62”…	Holocene	PVA	San Luis Gonzaga, Isla		MX	
CKRI: UDC:551.21,550.3,(23),EXPLOSION_CRATER;“62”…	Holocene	PVA	…		…	…
CKRI: UDC:551.21,550.3,(24)::551.32,SUBGLACIAL_VOLC...;“62”…	Holocene	PVA	**Hoodoo Mountain**	①	CA	
CKRI: UDC:551.21,550.3,(24)::551.32,SUBGLACIAL_VOLC...;“62”…	Holocene	PVA / HVA	**Katla**	②	IS	
CKRI: UDC:551.21,550.3,(24)::551.32,SUBGLACIAL_VOLC...;“62”…	Holocene	PVA / HVA	**Loki-Fögrufjöll**	③	IS	
CKRI: UDC:551.21,550.3,(24)::551.32,SUBGLACIAL_VOLC...;“62”…	Holocene	PVA / HVA	**Volcan Viedma**	④	AR	
CKRI: UDC:551.21,550.3,(24)::551.32,SUBGLACIAL_VOLC...;“62”…	Holocene	PVA	…		…	…
CKRI: UDC:551.21,550.3,(24),SUBMARINE_VOLCANO;“62”…	Holocene	PVA / HVA	**Campi Flegrei Mar Sicilia**	①	IT	
CKRI: UDC:551.21,550.3,(24),SUBMARINE_VOLCANO;“62”…	Holocene	PVA / HVA	**Curacoa**	②	TO	
CKRI: UDC:551.21,550.3,(24),SUBMARINE_VOLCANO;“62”…	Holocene	PVA / HVA	**Shin-Iwo-Jima**	③	JP	
CKRI: UDC:551.21,550.3,(24),SUBMARINE_VOLCANO;“62”…	Holocene	PVA / HVA	**Vestmannaeyjar**	④	IS	
CKRI: UDC:551.21,550.3,(24),SUBMARINE_VOLCANO;“62”…	Holocene	PVA	…		…	…
CKRI: UDC:551.23,551.21,550.3,(23),VOLCANIC_FIELD;“62”…	Holocene	PVA	Four Craters Lava Field		US	
CKRI: UDC:551.23,551.21,550.3,(23),VOLCANIC_FIELD;“62”…	Holocene	PVA	Gallego		SB	
CKRI: UDC:551.23,551.21,550.3,(23),VOLCANIC_FIELD;“62”…	Holocene	PVA / HVA	Volcán de San Antonio		ES	
CKRI: UDC:551.23,551.21,550.3,(23),VOLCANIC_FIELD;“62”…	Holocene	PVA	Volcán de Flores		GT	
CKRI: UDC:551.23,551.21,550.3,(23),VOLCANIC_FIELD;“62”…	Holocene	PVA	…		…	…
CKRI: UDC:551.21,550.3,(23),CONES;“62”…	Holocene	PVA	Bus-Obo		MN	
CKRI: UDC:551.21,550.3,(23),CONES;“62”…	Holocene	PVA	Kabargin Oth Group		GE	
CKRI: UDC:551.21,550.3,(23),CONES;“62”…	Holocene	PVA	Tore		PG	
CKRI: UDC:551.21,550.3,(23),CONES;“62”…	Holocene	PVA	Tutuila		AS	
CKRI: UDC:551.21,550.3,(23),CONES;“62”…	Holocene	PVA	…		…	…
…	…	…	…		…	…

The density of archaeological settlement infrastructures in the Eifel, Germany, is far highest. This area marks the southern margin of the North European Plain. The prehistoric extension of the North European Plain was several times larger than today.

Nevertheless, the Eifel also marks the southern margin of known occurrences of volcanological features in the periphery of the North European Plain during human presence in the prehistoric North European Plain in at least more than the last 700,000 years [35].

The resulting findings also show prevalent concentrations of archaeologically relevant settlement infrastructures in close proximity of otherwise historico-culturally used areas with high concentrations of volcanological feature groups with a wide diversity of volcanological features.

This is especially relevant for the settlement infrastructure

TABLE VI. RESULTING SETTLEMENT INFRASTRUCTURES FROM CONTEXTUALISATION WITH HOLOCENE-PREHISTORIC STRATO VOLCANO @ VOLCANOLOGICAL FEATURES GROUP (EXCERPT), INCLUDING CONCEPTUAL KNOWLEDGE VIEW GROUPS [13] (CKRI).

Multi-disciplinary Conceptual Knowledge Facets	*Chronology Facets*		*Chorology Facets*		
Prehistorical Conceptual Knowledge View / Facets Group	*Dependency*	*Context*	*Knowledge Resources Object*	*Count*	*Ref. & Range*
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Grota do Medo	$\sum = 1$	① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	–	$\sum = 0$	② 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Goshono		③ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Hotta-no Saku		③ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Kanai Higashiura		③ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Kiwa-no Saku		③ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Sakiyama Kaizuka		③ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Togariishi		③ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Yaze		③ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	...	$\sum = 14$	③ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Flókatóftir		④ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Þjóðveldisbærinn		④ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Vogur		④ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Stöðvarfjörður	$\sum = 4$	④ 300 km

TABLE VII. RESULTING SETTLEMENT INFRASTRUCTURES FROM CONTEXTUALISATION WITH HOLOCENE-PREHISTORIC MAARS ⓑ VOLCANOLOGICAL FEATURES GROUP (EXCERPT), INCLUDING CONCEPTUAL KNOWLEDGE VIEW GROUPS [13] (CKRI).

Multi-disciplinary Conceptual Knowledge Facets	*Chronology Facets*		*Chorology Facets*		
Prehistorical Conceptual Knowledge View / Facets Group	*Dependency*	*Context*	*Knowledge Resources Object*	*Count*	*Ref. & Range*
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Bogatta		① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Coctaca		① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	La Huerta		① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Los Armarillos		① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Mariscal		① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Potrero de Payogasta		① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Pucará de Tilcara		① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Tulor	$\sum = 8$	① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Segayun megalithic site	$\sum = 1$	② 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	–	$\sum = 0$	③ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Benzenberg VS		④ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Bildechingen VS		④ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Burg Keltische VS		④ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Erbach VS		④ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Esslingen VS		④ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Federlesmahd VS		④ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Gelbrunn Wald VS		④ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Hardheim VS		④ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	...	$\sum = 180$	④ 300 km

results on Iceland, which show uniquely high concentration of settlement placements in a range of three volcanological feature groups, next to a diversity of strato volcanoes, subglacial volcanoes, and submarine volcanoes. The analysis results quantify and qualify the important role of these locations for ancient society, may it be have been for logistics, economy, and strategic purposes. The spatial density of the settlement can be suggested in this map scale but we have seen the detailed results in Tables VI, VIII, VII, and IX.

Further relevant context result from findings of prehistoric coast lines, especially for the prehistoric North European Plain. Factual prehistoric evidence in the prehistoric catchment ares of the North European Plain proves that findings concentrations date far back beyond Holocene, e.g., in England / Scotland so far 700,000 a to 500,000 a B.C.E (B.C.E., Before Common Era) for flint artefacts [35] and currently known 8,000 a to 7,800 a B.C.E. for post-built mesolithic houses [36] of post-glacial European societies. A large number of prehistoric settlements should still be waiting discovery and analysis in the prehistoric North European Plain, most of them in what are now submarine areas.

The results of the analysis in these scenarios enable us to further contextualise with physical and non-physical contexts supported by participating disciplines, e.g., targeting prehistoric use of resources and materials, ritual and symbolic correlations. Therefore, examples of object groups include findings of flint, obsidian, and basalt objects and material sources on the one hand and symbolic and mythological contexts on the other hand.

Regarding this long-term research, further findings from multi-disciplinary scientific endeavors are ongoing matter of research and contextualisation, especially pedology and soil condition results, bog and swamp related results, pre-modern mobility findings, findings on open field names and site names, coast lines, findings on materials of non-volcanic and volcanic origin, flint, obsidian, and basalt, and further volcanological

TABLE VIII. RESULTING SETTLEMENT INFRASTRUCTURES FROM CONTEXTUALISATION WITH HOLOCENE-PREHISTORIC SUBGLACIAL ⑦ VOLCANOLOGICAL FEATURES GROUP (EXCERPT), INCLUDING CONCEPTUAL KNOWLEDGE VIEW GROUPS [13] (CKRI).

Multi-disciplinary Conceptual Knowledge Facets	*Chronology Facets*		*Chorology Facets*		
Prehistorical Conceptual Knowledge View / Facets Group	*Dependency*	*Context*	*Knowledge Resources Object*	*Count*	*Ref. & Range*
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Lucy Islands		① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Hidden Falls	$\sum = 2$	① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Flókatóftir		② 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Þjóðveldisbærinn		② 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Vogur		② 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Stöðvarfjörður	$\sum = 4$	② 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Flókatóftir		③ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Þjóðveldisbærinn		③ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Vogur		③ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Stöðvarfjörður	$\sum = 4$	③ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	–	$\sum = 0$	④ 300 km

TABLE IX. RESULTING SETTLEMENT INFRASTRUCTURES FROM CONTEXTUALISATION WITH HOLOCENE-PREHISTORIC SUBMARINE ⑧ VOLCANOLOGICAL FEATURES GROUP (EXCERPT), INCLUDING CONCEPTUAL KNOWLEDGE VIEW GROUPS [13] (CKRI).

Multi-disciplinary Conceptual Knowledge Facets	*Chronology Facets*		*Chorology Facets*		
Prehistorical Conceptual Knowledge View / Facets Group	*Dependency*	*Context*	*Knowledge Resources Object*	*Count*	*Ref. & Range*
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Bagni Greci		① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Heraclea Minoa		① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Lampedusa		① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Megara Hyblaea		① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Segesta		① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Carthage Magon Quarter		① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Hadrumet		① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Kerkouane		① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Neapolis (Nabeul)		① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	...	$\sum = 57$	① 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	–	$\sum = 0$	② 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	–	$\sum = 0$	③ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Flókatóftir		④ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Þjóðveldisbærinn		④ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Vogur		④ 300 km
CKRI: UDC:711....,692,903,902,SETTLEMENT_INFRASTRUCTURE;...	Synchronous	MN-LIA	Stöðvarfjörður	$\sum = 4$	④ 300 km

results, seismological results, and evidences of earthquakes and natural disasters in prehistoric times.

The knowledge resources associate context, e.g., from the fact that obsidian formation is associated with felsic lava and contains higher percentages of lighter elements, especially, Si, Al, Na, K, O (silicon, aluminium, sodium, potassium, oxygen). This makes it distinct from flint and basalt and allows historico-cultural contextualisations, e.g., origins of resources, travel, transport, and trade.

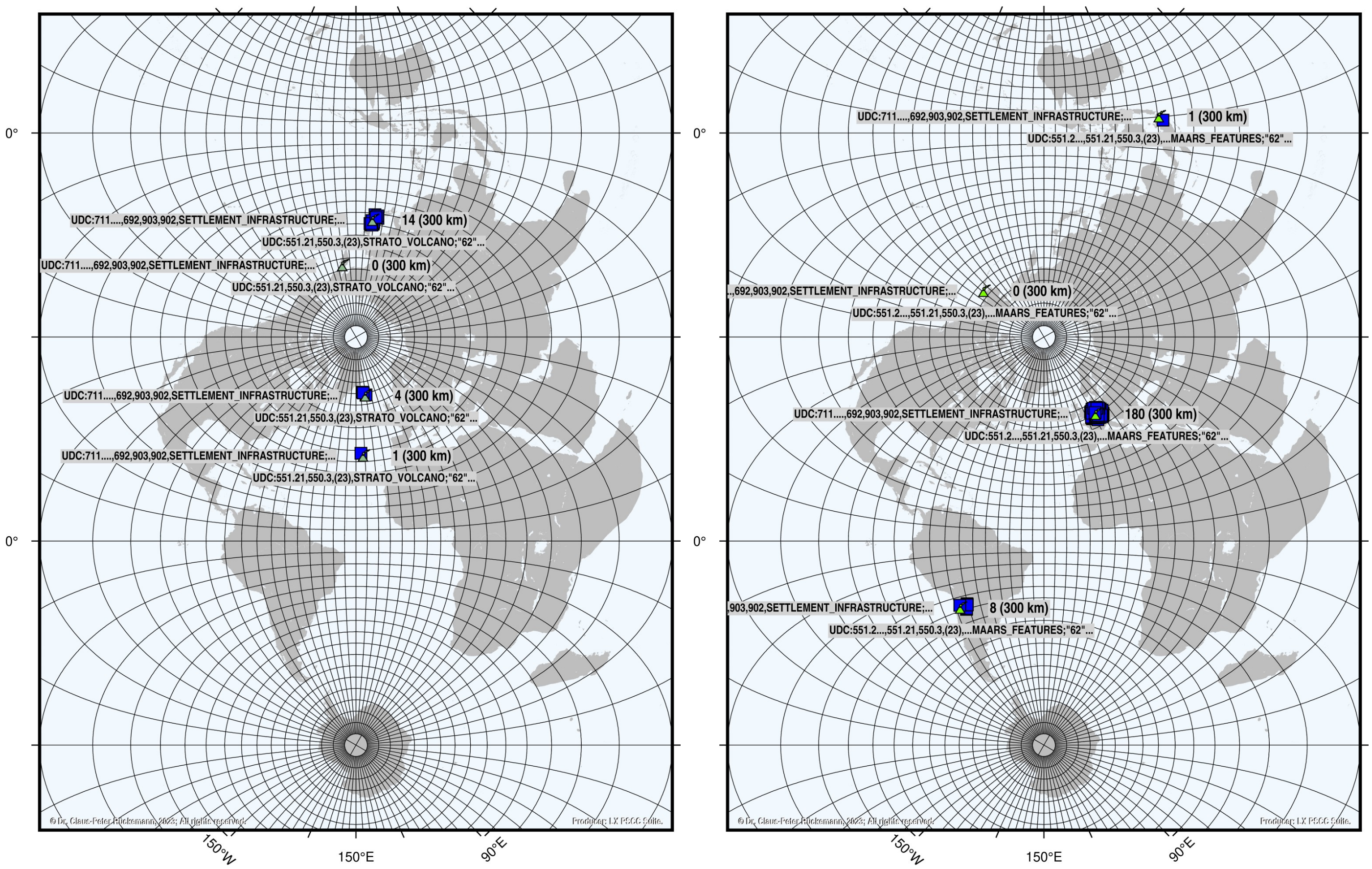
An example of multi-disciplinary contextualisation are factual results on pre-modern infrastructures, e.g., various pre-modern trackway systems, often wooden structures, are widely spread in several areas of interest, especially in the North European Plain, dating back older than 4,500 a B.C.E. [24], [37] [38] [39]. This is an example where results and insights –as often presented [40]– could benefit from a consequent scientific multi-disciplinary factual contextualisation in order to encounter non-factual approaches and perception.

C. Lessons Learned on Complexity and Educational Aspects

The methodology enables to manage a high grade of complexity and employ complexity for the creation of new insights. The methodological approach enables to even coherently contextualise symbolic, non-physical contexts of physical object groups by integrating new methods for procedural and conceptual knowledge complements, e.g., The Abydos Ships Method, a new insight-driven numeral systems approach for coherent multi-disciplinary analysis and contextualisation of object groups and their contexts [41].

The approach of methodological coherent multi-disciplinary contextualisation is what truly earns the term 'Artificial Instruments'. As all the 'technical' details are published and laid out in the given documentation of the components we have to explicitly emphasise that here a technical and unknowingly applied approach should not be considered a solution. This is just an optional consecutive stage of implementation and realisation as shown with the contextualisation here.

Contrary to an instrument approach, recently, researchers of some disciplines commented in personal communication that the motivation they use 'Artificial Intelligence' is that they do not want to lose the overview in their disciplines and respective contexts and because they want to get on in complex situations. This shows very limited engagements, shuffled views, and perspectives in some disciplines and is made an easy choice fostered by parts of the non-scientific world,



(a) Strato volcano group @: resulting archaeological settlement infrastructures.

(b) Maars group (β): resulting archaeological settlement infrastructures.

Figure 1. Contextualisation: Holocene-prehistoric volcanological features groups for case scenarios one and two and the resulting settlement infrastructures. Coherent multi-disciplinary context integration and results based on CKRI, chronological, and chorological criteria (excerpts, Transverse Mercator projections).

by legal visions, and industry focus and is clearly not what we should want, especially not in science. Besides unfunded claims and neologisms, relevant fundamental principles have not changed, e.g., Turing machines [42], Busy Beaver test [43], and machine unintelligence [44]. It is for sure, these principles, logic, and consequences will prevail true, even in future.

The given conditions for determination and analysis of this scenario are independent from the symbolic representation, e.g., the visualisation. For example, the specification of a radius inside which we analyse archaeological settlement infrastructures does not represent archaeological object distributions. It is a common premise that researchers understand how to specify their research questions and how to describe and use their methods, premises, and relevant logic.

Therefore, from our experiences, it is recommended to include information science fundaments, e.g., epistemology and logic, during all stages of educational processes of all disciplines and to practice multi-disciplinary approaches. Comprehensive studies of the works of the classical Organon [45] [46] [47] [48] [49] and understanding of logical fallacies [50] can be most beneficial as starting points. Further, a few years of practical experience in employing the component groups in complex scenarios will also be helpful.

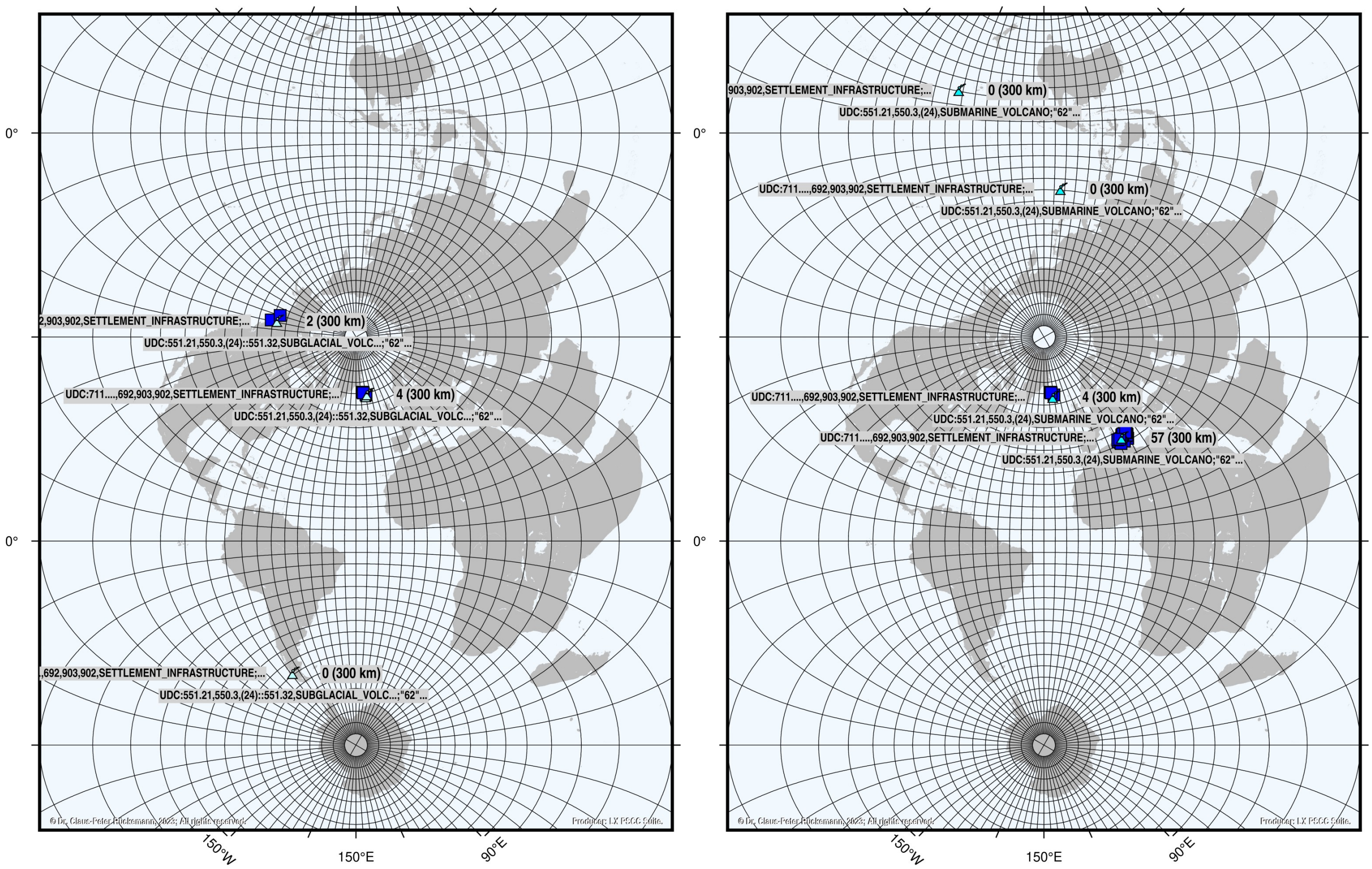
VII. Conclusion

This publication on extended research presented the new survey and methodological analysis results on coherent multi-disciplinary contextualisation and symbolic representation of worldwide Holocene-prehistoric volcanological features and discovery of archaeological settlement infrastructures, especially for prehistoric contexts and context discovery.

The research is based on the employment of contextualisation reference implementation and component frameworks for coherent multi-disciplinary conceptual knowledge-spatial context discovery, CKRI, which enable to implement conceptual multi-disciplinary coherency and a high level of consistency – keys for fact-based analysis and context correlation.

The practical realisations achieved their goals and proved efficient and sustainable over the long-term research and development of more than three decades. The case scenarios for context discovery of archaeological settlement infrastructures for Holocene-prehistoric volcanological features resulted in valuable contextualisation potential and possible new insight from on multi-disciplinary scenarios. The scenarios should have implicitly demonstrated that solely technical and procedural approaches are not sufficient.

The contextualisation integrates conceptual, factual, procedural, structural, and metacognitive knowledge complements. Based on the methodological approach, complements can be



(a) Subglacial volcano group ⓖ: resulting archaeol. settlement infrastructures. (b) Submarine volcano group ⓓ: resulting archaeol. settlement infrastructures.

Figure 2. Contextualisation: Holocene-prehistoric volcanological features groups for case scenarios three and four and the resulting settlement infrastructures. Coherent multi-disciplinary context integration and results based on CKRI, chronological, and chorological criteria (excerpts, Transverse Mercator projections).

identified and assigned during the contextualisation processes. An excerpt of complements relevant for this case scenario are CKRI classification, position data, calculation algorithms, content structures, and parametrisation experiences.

The methods and reference implementations can be efficiently and effectively employed for practical implementations and realisations for multi-disciplinary research, especially in prehistory, archaeology, natural sciences, and humanities. The solutions provide countless facilities and modules for adopting to individual solutions.

Future research will address archaeological settlement infrastructures and further object groups and new models for their coherent multi-disciplinary contextualisation based on continuous developments of the reference implementations and knowledge resources. Further, contextualisation and analysis of object groups will be matter of future advanced large scale scenarios, site surveys, and campaigns in prehistory and archaeology, targeting fact-based analysis and historico-cultural contexts. Projects will include ongoing multi-disciplinary investigations, e.g., context artefacts, pedological properties, soil characteristics, and pre-modern transport and mobility. The creation of new methods will include further integration and processing of knowledge complements, georeferencing, spatial and satellite data processing.

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REFERENCES

[1] C.-P. Rückemann, “Advanced Contextualisation Reference Implementation Frameworks in Practice: Coherent Multi-disciplinary Conceptual Knowledge-Spatial Context Discovery Results from the Holocene-prehistoric Volcanological Features and Archaeological Settlement Infrastructure Surveys,” in Proceedings of The Fifteenth International Conference on Advanced Geographic Information Systems, Applications, and Services (GEOProcessing 2023), April 24 – 28, 2023, Venice, Italy. Wilmington, Delaware, USA: XPS Press, 2023, pp. 98–103, ISSN: 2308-393X, ISBN-13: 978-1-68558-079-7, URL: https://www.thinkmind.org/index.php?view=article&articleid=geoprocessing_2023_2_150_30100 [accessed: 2023-11-26].

[2] T. Sorensen and E. Joseph, “Recent HPC-centric AI Success Stories,” Hyperion Research, St. Paul, MN 55102, USA, May 2023, URL: https://hyperionresearch.com/wp-content/uploads/2023/05/Hyperion-Research-HPC-AI-Success-Story-Report-May-2023.pdf [accessed: 2023-11-26] .

[3] C.-P. Rückemann, “Faceting the Holocene-prehistoric Inventory of Volcanological Features Groups Towards Sustainable Multi-disciplinary Context Integration in Prehistory and Archaeology Based on the Methodology of Coherent Conceptual Knowledge Contextualisation,” International Journal on Advances in Intelligent Systems, vol. 15, no. 3&4, 2022, pp. 115–129, ISSN: 1942-2679, LCCN: 2008212456 (Library of Congress), URL: http://www.iariajournals.org/intelligent_systems [accessed: 2023-11-26].

[4] C.-P. Rückemann, “Component Framework Implementation and Realisation for Development and Deployment of a Coherent Multi-disciplinary Conceptual Knowledge-based Holocene-prehistoric Inventory of Volcanological Features Groups and Faceting,” International Journal on Advances in Intelligent Systems, vol. 15, no. 3&4, 2022, pp. 103–114, ISSN: 1942-2679, LCCN: 2008212456 (Library of Congress), URL: http://www.iariajournals.org/intelligent_systems [accessed: 2023-11-26].

[5] C.-P. Rückemann, “Coherent Knowledge Solutions From Prehistory to Future – Towards Coherent Multi-disciplinary Knowledge Reference Implementation Blueprints for Industrial Learning: Insight from Consistent Coherent Conceptual Integration of Prehistory, Archaeology, Natural Sciences, and Humanities,” ML4I – Machine Learning for Industry Forum 2021; High-Performance Computing Innovation Center (HPCIC) and Data Science Institute (DSI), at Lawrence Livermore National Laboratory (LLNL), Aug. 10–12, 2021, Livermore, U.S.A., (Invited Speech), URL: http://www.llnl.gov [accessed: 2023-11-26], 2021.

[6] C.-P. Rückemann, “The Information Science Paragon: Allow Knowledge to Prevail, from Prehistory to Future – Approaches to Universality, Consistency, and Long-term Sustainability,” The International Journal “Information Models and Analyses” (IJ IMA), vol. 9, no. 3, 2020, pp. 203–226, Markov, K. (ed.), ISSN: 1314-6416 (print), Submitted accepted article: November 18, 2020, Publication date: August 17, 2021, URL: http://www.foibg.com/ijima/vol09/ijima09-03-p01.pdf [accessed: 2023-11-26].

[7] C.-P. Rückemann, “From Knowledge and Meaning Towards Knowledge Pattern Matching: Processing and Developing Knowledge Objects Targeting Geoscientific Context and Georeferencing,” in Proc. GEOProcessing 2020, November 21–25, 2020, Valencia, Spain, 2020, pp. 36–41, ISSN: 2308-393X, ISBN-13: 978-1-61208-762-7.

[8] R. Gleser, Zu den erkenntnistheoretischen Grundlagen der Prähistorischen Archäologie. Leiden, 2021, (title in English: On the Epistemological Fundaments of Prehistorical Archaeology), in: M. Renger, S.-M. Rothermund, S. Schreiber, and A. Veling (Eds.), Theorie, Archäologie, Reflexion. Kontroversen und Ansätze im deutschsprachigen Diskurs, (in print).

[9] C.-P. Rückemann, “Towards Conceptual Knowledge Reference Implementations for Context Integration and Contextualisation of Prehistory's and Natural Sciences' Multi-disciplinary Contexts,” International Journal on Advances in Systems and Measurements, vol. 14, no. 1&2, 2021, pp. 113–124, ISSN: 1942-261x, LCCN: 2008212470 (Library of Congress), URL: http://www.iariajournals.org/systems_and_measurements [accessed: 2023-11-26].

[10] C.-P. Rückemann, “Towards a Component Reference Implementations Frame for Achieving Multi-disciplinary Coherent Conceptual and Chorological Contextualisation in Prehistory and Prehistoric Archaeology,” International Journal on Advances in Systems and Measurements, vol. 14, no. 1&2, 2021, pp. 103–112, ISSN: 1942-261x, LCCN: 2008212470 (Library of Congress), URL: http://www.iariajournals.org/systems_and_measurements [accessed: 2023-11-26].

[11] L. W. Anderson and D. R. Krathwohl, Eds., A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives. Boston, MA (Pearson Education Group), USA: Allyn & Bacon, 2001, ISBN: 978-0801319037.

[12] C.-P. Rückemann, F. Hülsmann, B. Gersbeck-Schierholz, P. Skurowski, and M. Staniszewski, Knowledge and Computing. Post-Summit Results, Delegates' Summit: Best Practice and Definitions of Knowledge and Computing, Sept. 23, 2015, The Fifth Symp. on Adv. Comp. and Inf. in Natural and Applied Sciences (SACINAS), The 13th Int. Conf. of Num. Analysis and Appl. Math. (ICNAAM), Sept. 23–29, 2015, Rhodes, Greece, 2015, pp. 1–7, DOI: 10.15488/3409.

[13] “Multilingual Universal Decimal Classification Summary,” 2012, UDC Consortium, 2012, Web resource, v. 1.1. The Hague: UDC Consortium (UDCC Publication No. 088), URL: http://www.udcc.org/udcsummary/php/index.php [accessed: 2023-11-26].

[14] “UDC Summary Linked Data, Main Tables,” 2023, Universal Decimal Classification (UDC), UDC Consortium, URL: https://udcdata.info/078887 [accessed: 2023-11-26].

[15] “UDC 0: Science and knowledge. Organization. Computer science. Information. Documentation. Librarianship. Institution. Publications,” 2023, URL: http://udcdata.info/13358 [accessed: 2023-11-26].

[16] “UDC Summary Linked Data,” 2023, Universal Decimal Classification (UDC), UDC Consortium, URL: https://udcdata.info/ [accessed: 2023-11-26].

[17] “Creative Commons Attribution Share Alike 3.0 license,” 2012, URL: http://creativecommons.org/licenses/by-sa/3.0/ [accessed: 2023-11-26], (first release 2009, subsequent update 2012).

[18] C.-P. Rückemann, “Cognostics and Knowledge Used With Dynamical Processing,” International Journal on Advances in Software, vol. 8, no. 3&4, 2015, pp. 361–376, ISSN: 1942-2628, LCCN: 2008212462 (Library of Congress), URL: http://www.iariajournals.org/software/ [accessed: 2023-11-26].

[19] C.-P. Rückemann, R. Pavani, B. Gersbeck-Schierholz, A. Tsitsipas, L. Schubert, F. Hülsmann, O. Lau, and M. Hofmeister, Best Practice and Definitions of Formalisation and Formalism. Post-Summit Results, Delegates' Summit: The Ninth Symp. on Adv. Comp. and Inf. in Natural and Applied Sciences (SACINAS), The 17th Int. Conf. of Num. Analysis and Appl. Math. (ICNAAM), Sept. 23–28, 2019, Rhodes, Greece, 2019, DOI: 10.15488/5241.

[20] L. Dagum and R. Menon, “OpenMP: an industry standard API for shared-memory programming,” Computational Science & Engineering, (IEEE), vol. 5, no. 1, 1998, pp. 46–55.

[21] “Perl Compatible Regular Expressions (PCRE),” 2023, URL: https://www.pcre.org/ [accessed: 2023-11-26].

[22] P. Wessel, W. H. F. Smith, R. Scharroo, J. Luis, and F. Wobbe, “The Generic Mapping Tools (GMT),” 2020, URL: http://www.generic-mapping-tools.org/ [accessed: 2023-11-26], URL: http://gmt.soest.hawaii.edu/ [accessed: 2023-11-26].

[23] C.-P. Rückemann, “Information Science and Inter-disciplinary Long-term Strategies – Key to Insight, Consistency, and Sustainability: Conceptual Knowledge Reference Methodology Spanning Prehistory, Archaeology, Natural Sciences, and Humanities,” International Tutorial, DataSys Congress 2020, Sept. 27 – Oct. 1, 2020, Lisbon, Portugal, 2020, URL: http://www.iaria.org/conferences2020/ProgramINFOCOMP20.html [accessed: 2023-11-26].

[24] “The Prehistory and Archaeology Knowledge Archive (PAKA) Licence,” 2023, (release 2023), Unabhängiges Deutsches Institut für Multi-disziplinäre Forschung (DIMF): All rights reserved. Rights retain to the contributing creators.

[25] “The Archaeological Data Collector (ADC) Licence,” 2023, (release 2023), Unabhängiges Deutsches Institut für Multi-disziplinäre Forschung (DIMF): All rights reserved. Rights retain to the contributing creators.

[26] C.-P. Rückemann, “Prehistory's and Natural Sciences' Multi-

disciplinary Contexts: Contextualisation and Context Integration Based on Universal Conceptual Knowledge," in Proc. INFOCOMP 2021, May 30 – June 3, 2021, Valencia, Spain, 2021, ISSN: 2308-3484, ISBN: 978-1-61208-865-5.

[27] C.-P. Rückemann, "The Impact of Information Science Accompanied Structural Information on Computation of Knowledge Pattern Matching and Processing: A Prehistory, Archaeology, Natural Sciences, and Humanities Conceptual Integration Perspective," in Proc. INFOCOMP 2020, Sept. 27 – Oct. 1, 2020, Lisbon, Portugal, 2020, ISBN: 978-1-61208-807-5, URL: http://www.thinkmind.org/index.php?view=article&articleid=infocomp_2020_1_10_60015 [accessed: 2023-11-26].

[28] C.-P. Rückemann, "Coherent Knowledge Structures and Fusion Practice for Contextualisation Insight in Prehistory and Protohistory," in The Eleventh Symposium on Advanced Computation and Information in Natural and Applied Sciences, Proceedings of The 19th International Conference of Numerical Analysis and Applied Mathematics (ICNAAM), September 20–26, 2021, Rhodes, Greece, Proceedings of the American Institute of Physics (AIP), AIP Conference Proceedings 2849, Volume 2849, no. 1. AIP Press, American Institute of Physics, Melville, New York, USA, 2023, pp. 040 001 – 040 004, ISBN: 978-0-7354-4589-5, ISSN: 0094-243X, DOI: 10.1063/5.0162058.

[29] B. Tozer, D. T. Sandwell, W. H. F. Smith, C. Olson, J. R. Beale, and P. Wessel, "Global Bathymetry and Topography at 15 Arc Sec: SRTM15+," Earth and Space Science, vol. 6, no. 10, Oct. 2019, pp. 1847–1864, ISSN: 2333-5084, DOI: 10.1029/2019EA000658.

[30] C. L. Olson, J. J. Becker, and D. T. Sandwell, "SRTM15_PLUS: Data fusion of Shuttle Radar Topography Mission (SRTM) land topography with measured and estimated seafloor topography," (NCEI Accession 0150537), National Centers for Environmental Information (NCEI), NOAA, 2016.

[31] P. Wessel, "DCW for GMT 6 or later," 2022, URL: http://www.soest.hawaii.edu/pwessel/dcw/ [accessed: 2023-11-26].

[32] P. Wessel, "GSHHG," 2017, URL: http://www.soest.hawaii.edu/pwessel/gshhg/ [accessed: 2023-11-26].

[33] "Network Common Data Form (NetCDF)," 2021, DOI: 10.5065/D6H70CW6, URL: http://www.unidata.ucar.edu/software/netcdf/ [accessed: 2023-11-26].

[34] T. Vincenty, "Direct and inverse solutions of geodesics on the ellipsoid with application of nested equations," Surv. Rev., vol. XXII, no. 176, 1975, pp. 88–93.

[35] M. Pitts, "Early Humans," British Archaeology, Juli/August, 2023, pp. 23–23, ISSN: 1357-4442.

[36] M. Pitts, "Postglacial Hunters," British Archaeology, Juli/August 2023, 2023, pp. 24–24, ISSN: 1357-4442.

[37] H. Prejawa, Die Ergebnisse der Bohlwegsuntersuchungen in dem Grenzmoor zwischen Oldenburg und Preußen und in Mellinghausen im Kreise Sulingen. Osnabrück: Verlag und Druck von J. G. Kisling, 1897, Mittheilungen des Vereins für Geschichte und Landeskunde von Osnabrück („Historischer Verein“), Mit 10 Tafeln und Abbildungen im Texte, Einundzwanzigster Band, 1886.

[38] U. Dieckmann, "Paläoökologische Untersuchungen zur Entwicklung von Natur- und Kulturlandschaft am Nordrand des Wiehengebirges," Abhandlungen aus dem Westfälischen Museum für Naturkunde, vol. 60. Jahrgang, Heft 4, 1998, ISSN: 0175-3495.

[39] H. Hayen, "Bohlenwege in den großen Mooren am Dümmer," Heimatchronik des Kreises Vechta, vol. 45, 1977, pp. 33–48.

[40] A. Bauerochse and M. Heumüller, "Hölzerne Wege im Moor als Quellen der Siedlungs- und Verkehrsgeschichte," in Bewegte Zeiten. Archäologie in Deutschland., M. Wemhoff and M. M. Rind, Eds. Petersberg: Michael Imhof Verlag, 2018, pp. 47–54, ISBN: 978-3-7319-0723-7.

[41] C.-P. Rückemann, "The Abydos Ships Method: New-insight-driven Numeral Systems Approach for Coherent Multi-disciplinary Analysis and Contextualisation," in The Twelfth Symposium on Advanced Computation and Information in Natural and Applied Sciences (SACINAS), Proceedings of The 20th International Conference of Numerical Analysis and Applied Mathematics (ICNAAM), September 19–25, 2022, Heraklion, Crete, Greece. Melville, New York, USA: AIP Press, American Institute of Physics, 2023, ISSN: 0094-243X (American Institute of Physics Conference Proceedings, print), URL: http://icnaam.org/ [accessed: 2023-11-26], (to appear).

[42] A. M. Turing, "On Computable Numbers, with an Application to the Entscheidungsproblem," in Proceedings of the London Mathematical Society, vol. s2-42, no. 1, 1937, pp. 230–265, DOI: 10.1112/plms/s2-42.1.230.

[43] T. Radó, "On non-computable functions," Bell System Technical Journal, vol. 41, no. 3, 1962, pp. 877–884, ISSN: 0005-8580, DOI: 10.1002/j.1538-7305.1962.tb00480.x.

[44] M. Broussard, Artificial Unintelligence, How Computers Misunderstand the World. Cambridge - Massachusetts, London - England: The MIT Press, 2018, ISBN: 978-0-262-03800-3.

[45] Aristotle, On Interpretation, 2008, Peri Hermeneias, Organon, (Written 350 B.C.E.), Translated by E. M. Edghill Provided by The Internet Classics Archive, URL: http://classics.mit.edu/Aristotle/interpretation.html [accessed: 2023-11-26].

[46] Aristotle, Categories, 2008, Organon, (Written 350 B.C.E.), Translated by E. M. Edghill Provided by The Internet Classics Archive, URL: http://classics.mit.edu/Aristotle/categories.html [accessed: 2023-11-26].

[47] Aristotle, Prior Analytics, 2008, Organon, (Written 350 B.C.E.), Translated by A. J. Jenkinson Provided by The Internet Classics Archive, URL: http://classics.mit.edu/Aristotle/prior.html [accessed: 2023-11-26].

[48] Aristotle, Posterior Analytics, 2008, Organon, (Written 350 B.C.E.), Translated by G. R. G. Mure Provided by The Internet Classics Archive, URL: http://classics.mit.edu/Aristotle/posterior.html [accessed: 2023-11-26].

[49] Aristotle, On Sophistical Refutations, 2008, (Written 350 B.C.E.), Translated by W. A. Pickard-Cambridge Provided by The Internet Classics Archive, URL: http://classics.mit.edu/Aristotle/sophist_refut.html [accessed: 2023-11-26].

[50] B. Bennett, Logically Fallacious: The Ultimate Collection of Over 300 Logical Fallacies, 1st ed. eBookIt, 2012, ISBN: 978-1-4566-0737-1.

Development of Household Members' Behavior Model in Urban Scale Using Dynamic Time Warping and Particle Swarm Optimization Algorithms Based on National Time Use Survey

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***Abstract*—For the target of energy demand estimation of residential buildings in urban scale, occupants' behavior model has been paid much attention. In this paper, a new model for simulating occupants' behavior schedules in urban scale has been proposed using only public stochastic data (national lifetime survey) combined with Dynamic Time Warping and Particle Swarm Optimization algorithms. We use this proposed model to generate the 5 type occupant behavior schedules with 5-minutes interval in working and resting day. The generated results - percentages of occupants adopt the given behavior at specific moments are calculated and compared with public stochastic data to verify the accuracy. Also, based on the mutual influence of household members, the generated schedules are filtered and combined into a group of behavior schedules, which is suitable for a household. By the proposed model in this paper, behavior schedule combinations of family members are generated and prepared for residential energy demand calculations in urban scale.**

Keywords*—*occupants' behavior model; household members; public stochastic data; particle swarm optimization; dynamic time warping.

I. INTRODUCTION

This paper is an extended research considering family member based on the publication on Energy 2023 [1]. To get the target of decarbonized society in 2050 [2], the Japanese government is promoting the introduction of decentralized renewable energy devices in urban area to reduce carbon emissions. However, without a suitable introduction plan the surplus electricity generated at times by various devices would disturb the balance between the supply and demand of power system. There is also a prospect of failing to reach the decarbonization target because of insufficient devices. Thus, it is essential to develop a decentralized energy introduction plan based on the energy demands of buildings in urban areas The renewable energy is limited to natural condition (e.g., solar energy) and outpower changes dramatically over time. Therefore, the energy demand of buildings should be estimated with high temporal resolution. Non-residential buildings (e.g., office) have temporal characteristics of energy demand because of fixed schedule of users. However, the energy demand of residential building is decided by appliances' operation, which is influenced by the behavior of the occupants with significantly personal characteristics. In previous studies about energy demand estimation for residential buildings, the behavior schedules of occupants had been set to several cases. This assumption would significantly affect the accuracy of results. The reason is that even the same type occupants in urban scale would have numerous kind behaviors at the same time, but there are only a few cases in these few schedules that would overlay the peak or trough energy demand amount. Thereby, the demand results and the amount of renewable energy devices need to be introduced would be a departure from reality. Thus, a method to simulate the occupants' behavior schedules in urban scale is very essential for the plan of introduction of decentralized renewable energy in urban scale.

In this paper, a new occupants' behavior model generating behavior schedules of occupants in one household with only public stochastic data has been proposed. Compared with existing models in previous research, this model has the following characteristics of innovation:

- No need to analysis of raw Time Use Data (*TUD*)
- Without classification of behaviors.
- Without prior assumptions about the number of occurrences of behavior.
- Consider the mutual influence of household members and generate behavior schedule combinations of household members.

Section II introduces the related work of this study. Section III introduces the detailed procedures of the proposed model. Section IV corrects the simulation processes based on the simulation results. In Section V, the final generated results of each type occupant in working and resting day are shown. In Section VI, a model has been proposed to combine generated behavior schedules considering the interactions among household members. In Section VII， the conclusions about features and weaknesses of proposed model are introduced. Based on that, the directions of improving model in future are also introduced.

II. Related Research

There is much previous research about the occupants' behavior model in urban scale [3]. The models could be divided into two types based on whether to use *TUD*, which describes occupants' behavior by time.

For the first type without *TUD*, Tanimoto et al. [4] developed a model using only public stochastic data of *TUD* include mean and standard deviation of behaviors' duration time in a day and percentages of occupants adopt the behavior at special moments by 15-minutes interval of a day. They firstly selected the behaviors according to probabilities and arranged their total duration time into 24 hours. Next, they placed the first behavior into the slot in timeline according to random number and placed the next behavior into the end of previous behavior one by one. As one merit, this method could generate the occupants' behavior schedules with only public stochastic data. But the accuracy of the simulation results was greatly influenced by the randomly decided slot for the first behavior, which was inserted. Additionally, the results had not been validated.

For the type of models using *TUD*, Richardson et al. [5] developed a model using the Markov Chain, which is a stochastic model to determine the transition of behavior from another only depend on the condition at the previous time step. They collected the *TUD* from a great number of households and analysis the transition probability between behaviors. But the behavior items were limited in at room or not.

Widén et al. [6] proposed a Markov Chain model and expanded analysis of the number of behavior items. They simulated the household's members independently. These Markov Chain models considered and simulated the transitions probability between the behaviors precisely, but the accuracy of behavior duration time was dependent on the timing and number of behavior transitions. This could be a weakness for simulating the occupants' behavior schedules. Yamaguchi et al. [7] developed a occupants' behavior model dealing with above problems. They divided behaviors into routine and non-routine and considered them separately. The behaviors' duration time and transition probabilities between them were acquired by analyzing the *TUD* from the national time-use survey conducted by Statistics Japan in 2006 and been utilized for placing the behaviors into the timeline. They firstly placed the routine behaviors (including sleeping, commuting to work & school, dining and bathing) into timeline, then selected the non-routine behaviors according to the probabilities and placed them in the gap between the routine behaviors until all gaps had been filled. They improved the model in [8] considering the interaction among household members (e.g., household members always have dining together at one time and bathing one by one) and time-dependent characteristics of the specific behaviors (e.g., for a single person, bathing often happens immediately after waking up or breakfast, but it's not shown in *TUD* because it was originated from a wide range of people.). In [9], they explored several machine learning methods to pre-process the *TUD* to improve the accuracy of behavior model. Although the duration time and transition probabilities of behaviors were detailed considered in their model, predetermining the number of behavior occurrences with a subjective assumption was made. For example, three meals over a day, one sleeping at night with long period were considered in their model. But according to the public stochastic data, there are also sleeping at the daytime for many type people), this might be a weakness of their model for ignoring these specific cases. On the other hand, raw *TUD* are required to make this kind of model while only public stochastic data are available in many countries.

As mentioned above, until now there are many developed occupants' behavior models in urban scale with own strengths and weaknesses. But there is still no precise occupants' behavior model that considering the interaction among household members, without prior analysis of large amount of raw *TUD*, pre-classification of behaviors according to routinely or not and predetermined number of occurrences with subjective assumption.

III. Proposed Behavior Model

In Section III, we will discuss the processes model.

A. Parameters of purposed occupants' behavior model

The proposed model simulates the occupants' behavior schedules with 5-min interval based on the public stochastic data called National Lifetime Survey in 2020 from Japan Broadcast Institution (*NHK*) [10]. It should be noted that target of simulating behavior schedules is to estimate energy demand of residential building, so the behaviors that have no relationship with energy demand in residential building (e.g., working outside, commuting to work, school) have not been simulated in this paper. This assumption, which is one of the differences between the previous studies, can greatly simplify the model. Table I shows the classification result of behaviors on public stochastic data. These behaviors have been simplified into 24 types and divided into interior and exterior. According to whether using appliances, the interior behaviors are further divided into two categories.

TABLE I. Classification of Behaviors

Interior Behavior (lighting & HVAC used)		**Exterior Behavior**
Appliance used	***Non-appliance used***	
eating	children care	shopping
bath	leisure	conversation personal relationships
sleeping	newspaper	work
hobbies, entertainment and culture (with Internet)	magazines comics	leisure and exercise
hobbies, entertainment and culture (without Internet)		class and lecture
cooking, cleaning, laundry		commuting
radio		sporting
household chores		

To make the model, the public stochastic data would be utilized include:

- ***PM***: probabilities of adopting given behavior by 15-minutes interval (the data has been processed into 5-minutes interval by liner interpolation).
- ***PA***: probabilities of adopting given behavior over a day.
- ***MTB***: average duration time of adopting given behavior.
- ***SDTB***: standard deviation of duration time of given behavior.

Some samples of public stochastic data are shown in Table II.

During the process of simulation, a blank timeline with 288 time slots (time of a day with 5-minutes interval) is generated firstly and prepares for filling up with behaviors separately. The given behavior's occurrences will span corresponding time slots in the timeline depend on its duration time length. The detail steps are explained as:

1) Iterates over all given behaviors in order of the ***PA***'s values and determines whether to adopt based on its ***PA***.

2) Once the given behavior has been adopted, the duration time (***DT***) is determined according to the Gaussian Distribution defined by ***MTB*** and ***SDTB***.

3) To insert these given behaviors into the timeline, it is critical to decide several parameters' solution of the given behavior including:

a) ***n***: number of behavior occurrences. (***n*** =1~4 randomly)

b) *sm*: start moment of each behavior occurrence.

SMN: $\left[sm_1, sm_2, \cdots sm_n\right]$

c) *pn****:*** probability of each number of behavior occurrences**.**

(e.g., pn_2 : probability of behavior occurring twice)

PNN: $\left[pn_1, pn_2, \cdots pn_n\right]$

d) *pt*: each occurrence's duration time as percentage of ***DT*** in a large number of schedules**.**

PTN: $\left[pt_1, pt_2, \cdots, pt_n\right]$

(e.g., Fig. 1 shows the difference between ***PTN₁***: $[\frac{1}{3}, \frac{1}{3}, \frac{1}{3}]$ and ***PTN₂***: $[\frac{1}{6}, \frac{1}{3}, \frac{1}{2}]$)

B. Start moments of behavior occurances

It is necessary to decide ***SMN*** 's solution to determine the positions of timeline where the behavior occurrences are going to be inserted.

Fig. 2 shows the process of deciding the start moment of each behavior occurrence by the cumulative distribution of ***PM***. In detail, one day is divided into ***n*** time regions which have the same sum of ***PM***. The start moment of splitting time region is generated randomly (e.g., 6:30). It is assumed that object behavior occurs once in each time region. Based on that assumption, the cumulative distribution function of ***PM*** in each time region has been calculated to determine the start moment of each occurrence.

TABLE II. SAMPLE OF PUBILC STOCHASTIC DATA OF WORK-MALE IN SUNDAY AND TARGET BEHAVIOR - SLEEPING

Behavior	*PA*	*MTB*	*SDTB*	*Time*	*PM*
sleeping	99.20%	8:25	2:07	0:00	70.20%
eating	97.60%	1:38	0:52	0:05	71.27%
bath	96.00%	1:04	0:34	0:10	72.33%

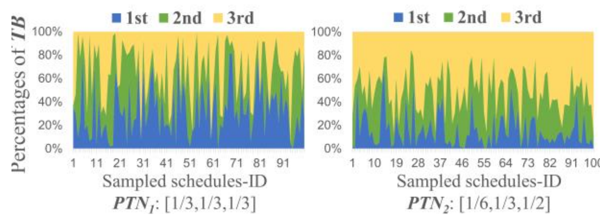

Figure. 1 Percentages of each occurrence's duration time in sampled schedule

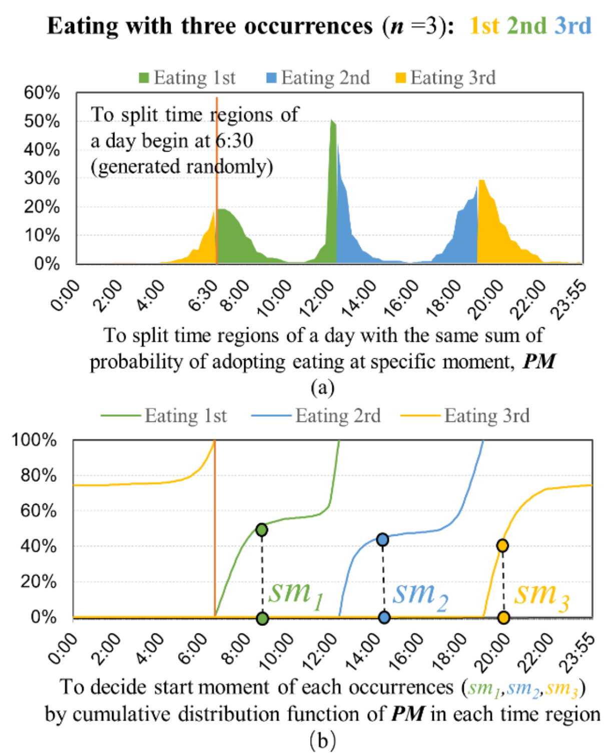

Figure 2. Processes of determining start moment of each occurrence of eating

C. Process of proposed model

Fig. 3 shows the proposed model's all processes for generating the behavior schedules. The process of searching the optimal solution is as follows.

D. Dynamic Time Warping

Different from ***SMN***, it is impossible to get ***PNN***&***PTN*** solution based on the existing public stochastic data merely. Therefore, it is necessary to introduce parameter optimization method to obtain the optimal ***PNN***&***PTN*** solution.

To verify the fitness of ***PNN***&***PTN*** candidate solution, we introduce the objective function to compare ***PM*** and probability of adopting given behavior at 5-min interval, which is calculated by schedules generated using ***PNN***&***PTN*** candidate solution (***PM'***). For ***PM*** and ***PM'*** are both time series data, Dynamic Time Warping (*DTW*) introduced in [10] is used as objective function to measure their similarity. *DTW* of ***PM*** and ***PM'*** is calculated by (1):

$$DTW(\boldsymbol{PM}, \boldsymbol{PM'}) = \min \sqrt{\sum (x_i - y_j)^2} \quad (i, j) \in L \qquad (1)$$

$$\boldsymbol{PM} = [x_1, x_2, \cdots, x_{287}],\ \boldsymbol{PM'} = [y_1, y_2, \cdots, y_{287}]$$

The list of index pairs $L = [l_0, l_1, \cdots, l_{287}]$ shows the matching pairs of the elements of ***PM*** and ***PM'*** (e.g., $l_k = (i_k, j_k)$ shows the x_{i_k} and y_{j_k} would be matched) that satisfies the following properties are shown in (2) (3) (4):

$$0 \le i_k, j_k \le 287 \qquad (2)$$

$$l_0 = (0,0),\ l_{287} = (287, 287) \qquad (3)$$

$$l = (i_k - 1, j_k) \text{ or } (i_k, j_k - 1) \text{ or } (i_k - 1, j_k - 1) \qquad (4)$$

Different from the traditional matching method which would match PM and PM' at the same index pairs ((x_1, y_1), (x_2, y_2) ,…, (x_{287}, y_{287})). In DTW, based on the above properties, there is a large number (T) of possible matching solutions as candidates, which is shown in (5):

$$T[l_0, l_1, \cdots, l_{287}] = \begin{bmatrix} (x_0, y_0) & (x_1, y_0) & (x_1, y_1) & \cdots & (x_{287}, y_{287}) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ (x_0, y_0) & (x_0, y_1) & (x_0, y_2) & \cdots & (x_{287}, y_{287}) \end{bmatrix} \qquad (5)$$

all matching solutions' distances between ***PM*** and ***PM'*** would be compared and the smallest one would be called *DTW*. By calculating the *DTW* obtained from different ***PNN***&***PTN*** candidate solutions, the most suitable solution would be decided with the minimal *DTW*.

E. Patricle Swarm Optimization

As mentioned above, the best ***PNN***&***PTN*** solution can be found by finding the minimal *DTW*. In this paper, we use

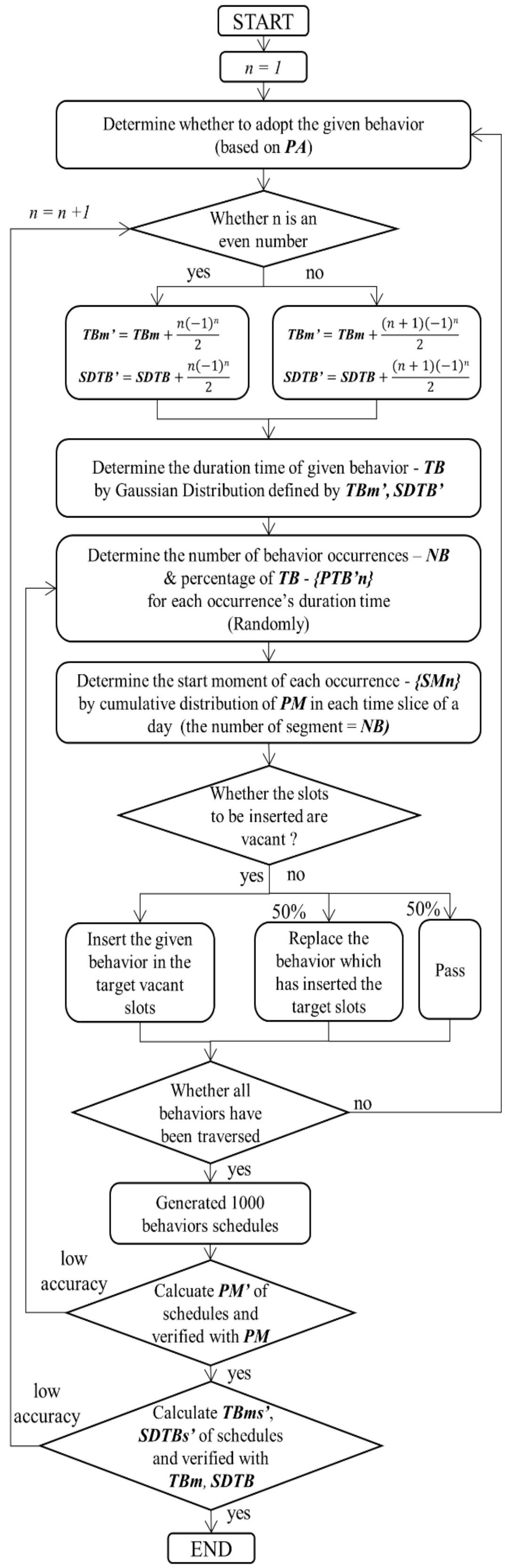

Figure 3. Simulation processes of proposed model

Particle Swarm Optimization (*PSO*) algorithm to find the minimal *DTW*. *PSO* is an evolutionary algorithm introduced in [12] that could optimize a problem by iteratively trying to improve a candidate parameters' solution to get the better position in a D-dimensional space (D is the number of parameters).

In the process of the *PSO* algorithm, firstly, a large number of particles have been generated and each particle is a candidate solution of ***PNN***&***PTN*** with different *DTW* result. At 1st iteration, particle' initial position (p_1) and velocity (v_1) are randomly generated. p_1 means ***PNN***&***PTN*** solution and v_1 means the distance between p_1 and p_2 (position at 2nd iteration) as showed in (6). These particles make up a cloud that covers the entire space, then the *DTW* of all particles are calculated to decide their fitness. Based on fitness values, the globally best particle position (pg_1) and locally best particle position (pl_1) are determined. As showed in (7), according to pg_1, pl_1 and p_1, v_1 would be updated to v_2, which would continue to update p_2 to p_3.

$$p_{k+1} = p_k + v_k \tag{6}$$

$$v_{k+1} = wv_k + \varphi_1(pg_k - p_k) + \varphi_2(pl_k + p_k) \tag{7}$$

k:	k^{th} iteration	pl_k:	locally best particle's position at kth iteration
w:	inertia weight	φ_1, φ_2:	$\varphi_1 = c_1 r_1$, $\varphi_2 = c_2 r_2$
v_k:	particle's velocity at kth iteration	r_1, r_2:	random numbers in the range [0,1]
p_k:	particle's position at kth iteration	c_1, c_2:	$c_1 = c_2 = 2$
pg_k:	globally best particle's position at kth iteration		

With the iteration advancing, the cloud contracts gradually and performs the exploration for best ***PNN***&***PTN*** solution with minimal *DTW.*

IV. Correction of Simulation Process

According to the schedule results, there are two significant errors include:

1) Fig. 4 shows the results of sleeping are inaccurate thoroughly.
2) Fig. 5 shows the delaying of start moments of ***PM'*** compared with ***PM***.

The above errors would be dealt with as follows:

A. Correction of sleep simulation process

The error 1) can be attributed to the inaccurate determination of start moments of sleeping. Different from other behaviors, people always have a long period sleeping in the evening and add a short period sleeping during the daytime. For this type of behavior with a clear temporal characteristic, the method deciding behavior start moments based on sum of ***PM*** is not suitable any longer. To solve this problem, we revise the model to simulate sleeping behavior in the following process:

a) The number of sleeping occurrence (***n***) is set to 1~2. If sleeping occurs once, it occurs at night; if sleep occurs twice, the first and longer sleeping occurs in the evening and second one occurs at daytime.

b) For sleeping in the evening, people wake up at a more concentrated time than when they fall asleep. Therefore, we use the moments of waking up (ending of sleeping) to decide the position of sleeping in timeline where being inserted into.

c) The range of end moments of first sleeping in the evening is set as 0:00-12:00, the range of start

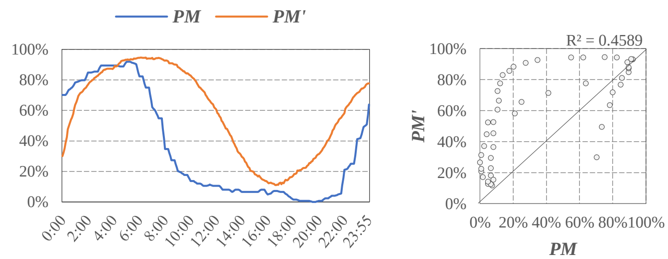

Figure 4. Comparation of simulated stochastic data -***PM'*** and public stochastic data -***PM*** (sleeping)

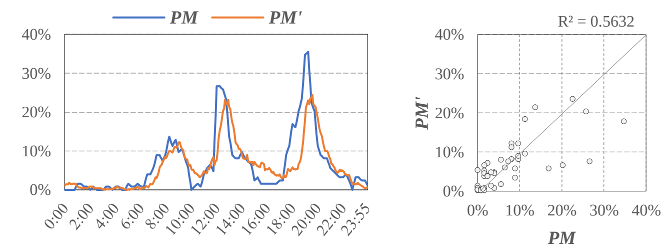

Figure 5. Comparation of simulated stochastic data-***PM'*** and public stochastic data -***PM*** (eating)

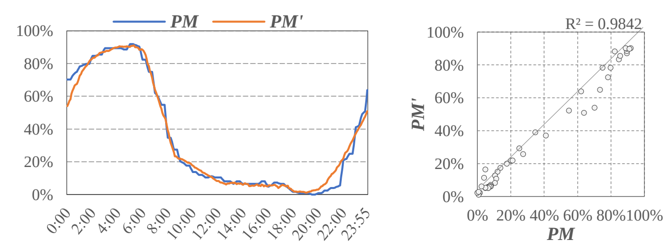

Figure 6. Comparation of simulated stochastic data -***PM'*** after corrected and public stochastic data -***PM*** (sleeping)

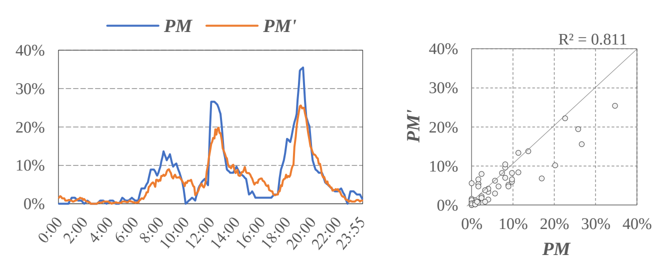

Figure 7. Comparation of simulated stochastic data -***PM'*** after corrected and public stochastic data -***PM*** (eating)

moments of second sleep is set as 12:00-18:00. The specific moments in the range are searched by *PSO* method too.

To sum up, the parameters of sleeping for *PSO* method are reset showed as (8):

$$\boldsymbol{SMN} = [sm_1, sm_2] \ \boldsymbol{PNN} = [pn_1, pn_2] \ \boldsymbol{PTN} = [pt_1, pt_2] \quad (8)$$

After the calculation by *PSO*, Fig. 6 shows the results of sleeping's ***PM*** and ***PM'*** by this revised process, which is better than original one.

B. Correction of start moment

For the error 2), the reason being considered is that the decision of start moment based on cumulative distribution function of ***PM*** always drop behind actual situation. To solve this issue, the new parameter *ad* is introduced to adjust the $\boldsymbol{SMN}: [sm_1 + ad, sm_2 + ad, \cdots, sm_n + ad]$. The decision of *ad* is also calculated by *PSO* method. Therefore, the solution of ***PNN&PTN,*** *ad* would be decided together by minimal *DTW*. Fig. 7 shows the simulation results of ***PM*** and ***PM'*** after the adjustment of behavior start moments and it demonstrates higher accuracy than before.

V. Simulation Results

In Figs. 8-12, comparation of simulated stochastic data - ***PM'*** and public stochastic data-***PM*** of 5 type occupants include working-male, housewife, child, teenager and elder are shown, each color block shows the probability that a behavior is undertaken at corresponding period of day. The result shows that ***PM'*** agreed well with ***PM*** and it confirms our model's accuracy.

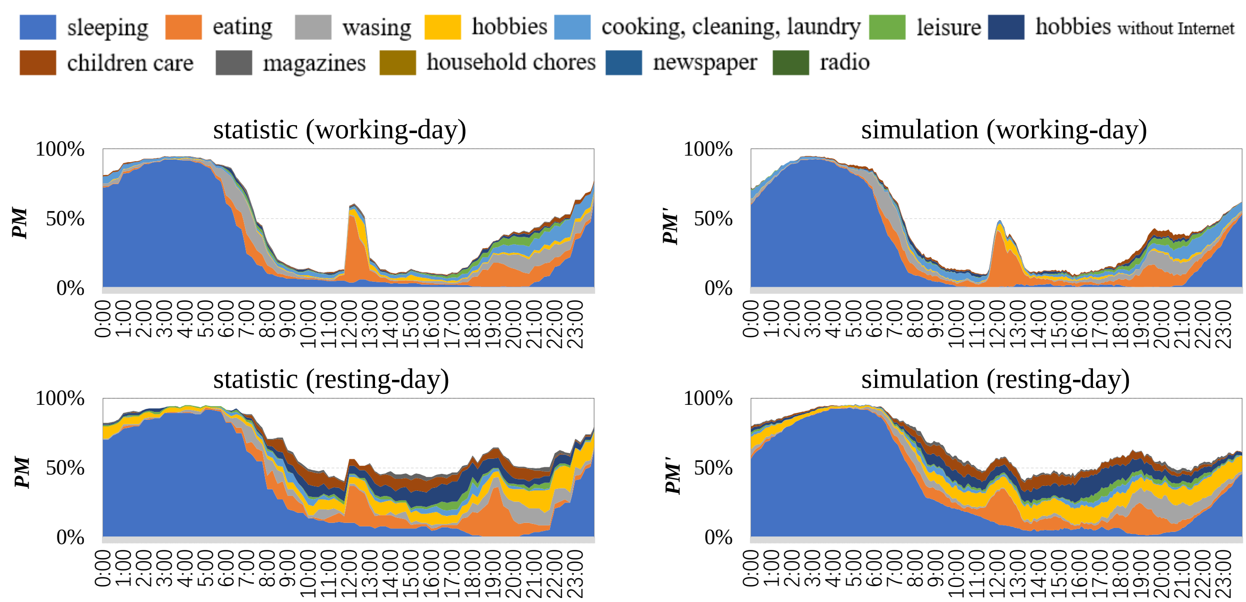

Figure 8. Comparation of simulated stochastic data - PM' and public stochastic data-PM (working-male)

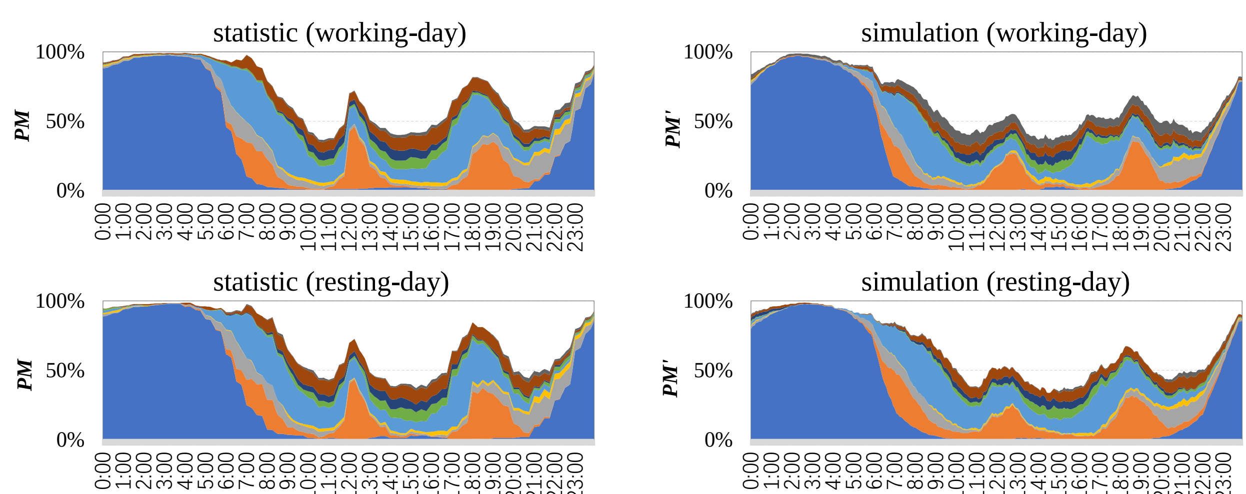

Figure 9. Comparation of simulated stochastic data - ***PM'*** and public stochastic data-***PM*** (housewife)

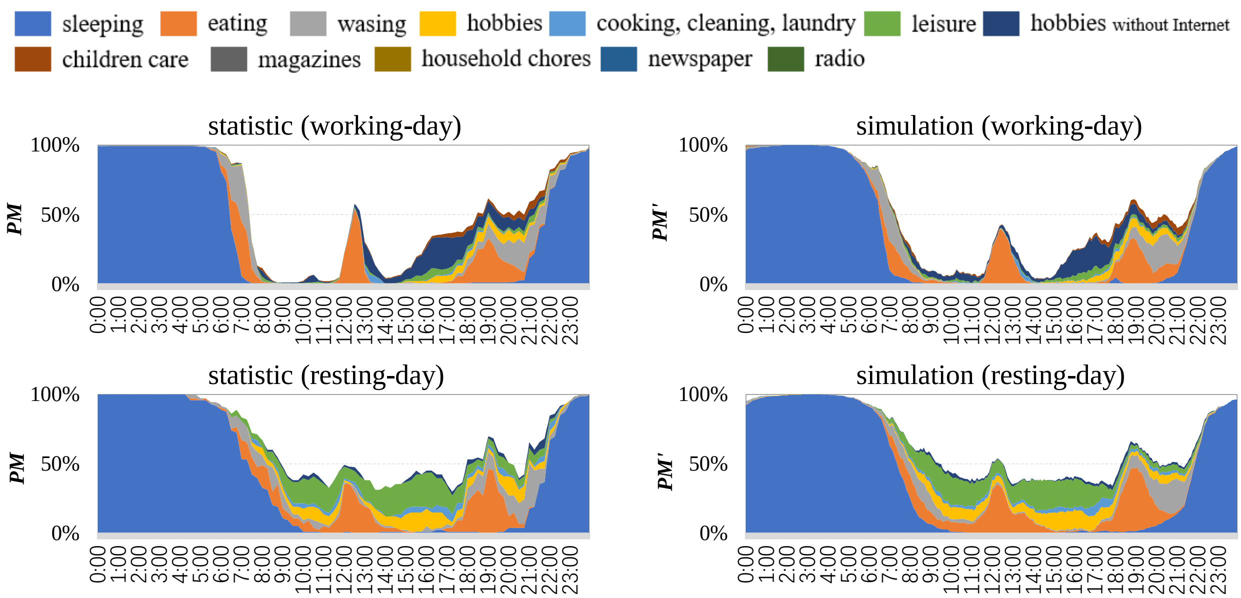

Figure 10. Comparation of simulated stochastic data - ***PM'*** and public stochastic data-***PM*** (child)

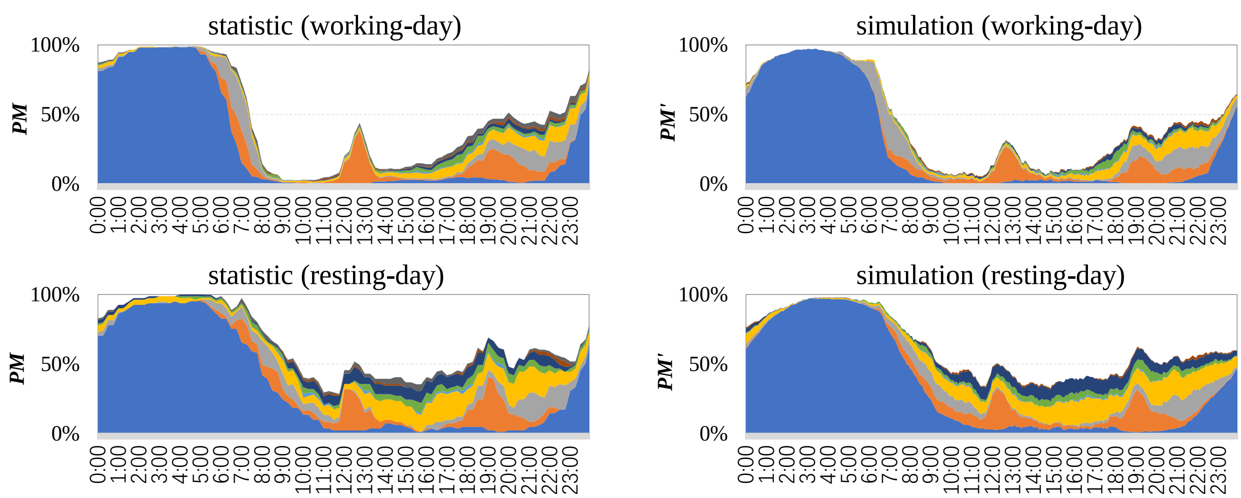

Figure 11. Comparation of simulated stochastic data - ***PM'*** and public stochastic data-***PM*** (teenager)

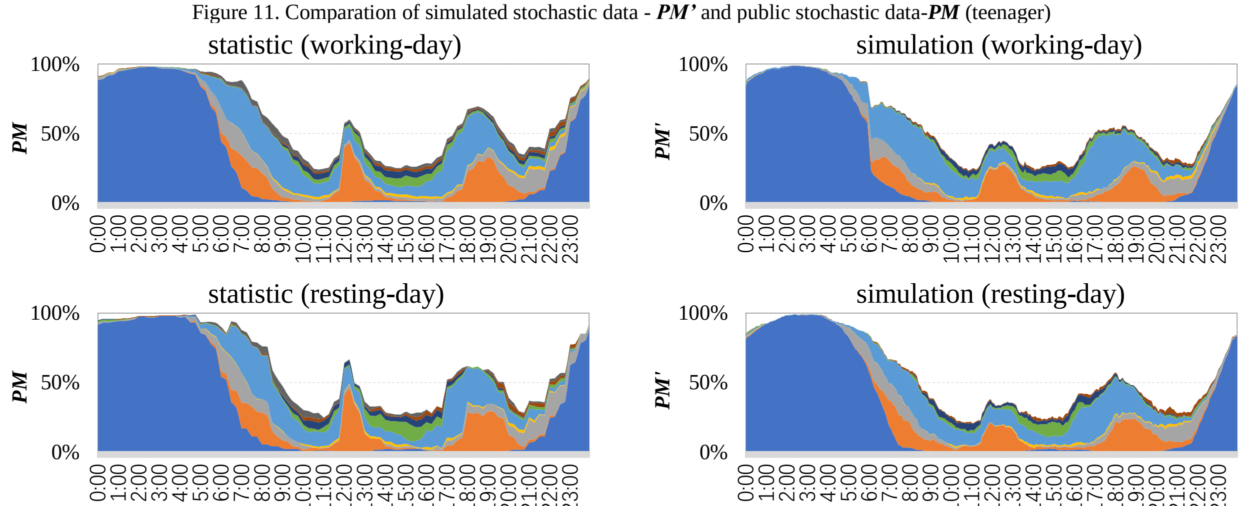

Figure 12. Comparation of simulated stochastic data - ***PM'*** and public stochastic data-***PM*** (elder)

VI. SIMULATION RESULTS OF HOUSEHOLD

Considering the energy demand simulation of residential building, the behavior schedules of household members are necessary. Although the model could simulate each type occupant behavior schedules properly, there is no connections among these results, which could not be used directly because behaviors of household members are always related. Therefore, a model for filtering and matching generated results is proposed.

According to [8], the Japanese household members tend to eat together and take a bath one by one. Based on this assumption, among the above generated results of each type occupants with a large number, the schedules of eating at the same time and bathing at different time would be filtered and matched into behavior schedules of a household. It should be pointed out that the start moment, duration time of eating, bathing by each household member is not the same or different exactly.

The detail process of the proposed model is explained as follow:

The target is to select suitable behavior schedules from above 1000 simulation results of each occupants to form the behavior schedule combination of a household. Therefore, *PSO* algorithm is used again to search the suitable solutions. The candidate solution of behavior schedules-ID of each member is set as $[x_1, x_2, ..., x_n]$ ($1 \le x_1, x_2, ..., x_n \le 1000$, n=household member number) and the objective function is set as (8)

$$y = T_{bath} - T_{eating} \quad (8)$$

T_{bath} : Duration time that more than two members are bathing at the same time by candidate solution.

T_{eating} : Duration time that more than two members are eating at the same time by candidate solution.

According to (8), among each member, less overlap of bathing behaviors and more overlap of eating behaviors at the same time means the better fitness of candidate solution. It should be pointed out that this process is not to search the best solution but to find a group of appropriate solutions with certain number.

As two examples, the behavior schedules of three members (working-male, housewife and one child) and five members (two elders, working-male, housewife and one child) of two households in working day and resting day are Figs. 13-16 show 5 behavior schedule combinations of

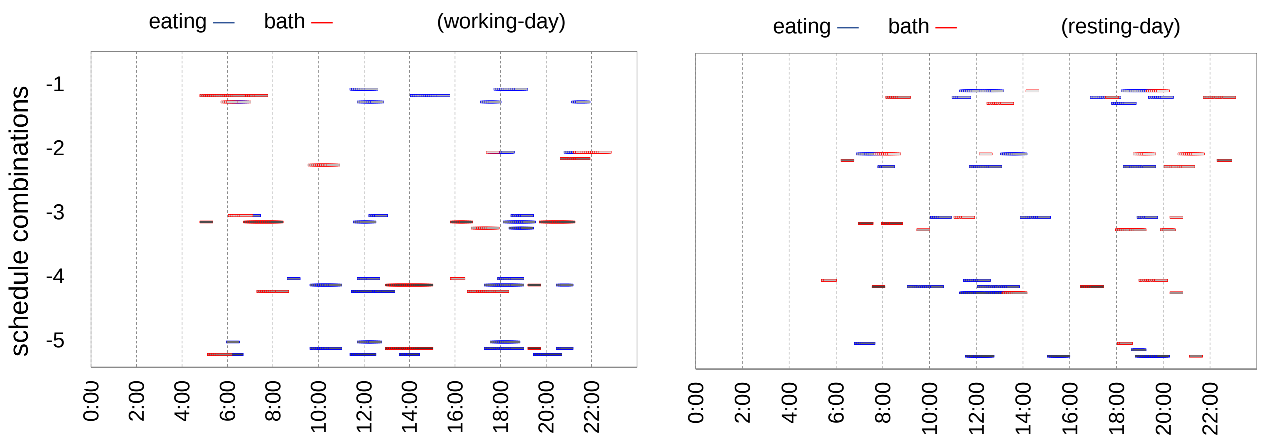

Figure 13. Behavior (eating and bath) schedule combination of a household (working-male, housewife, one child) (selected randomly)

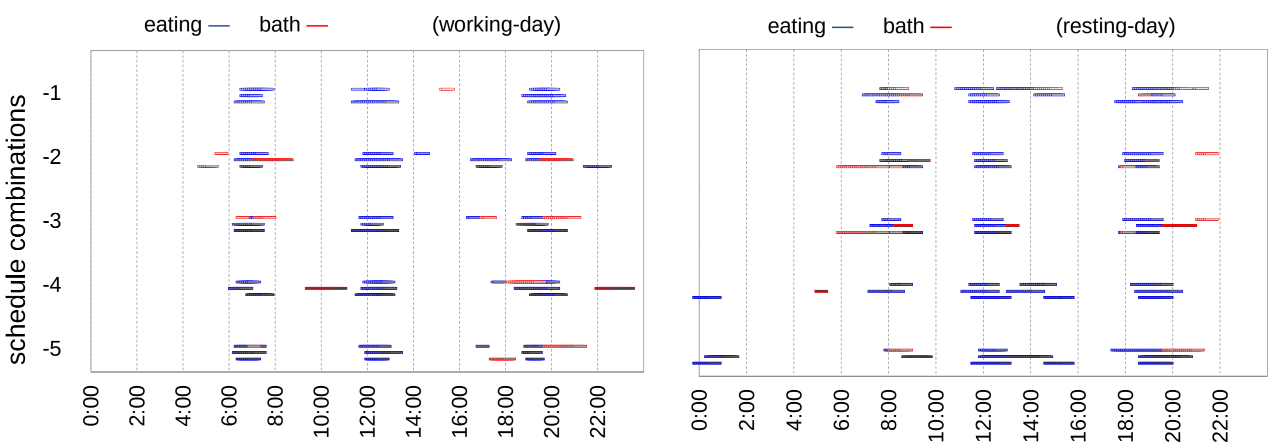

Figure 14. Behavior (eating and bath) schedule combination of a household (working-male, housewife, one child) (selected by *PSO* algorithm)

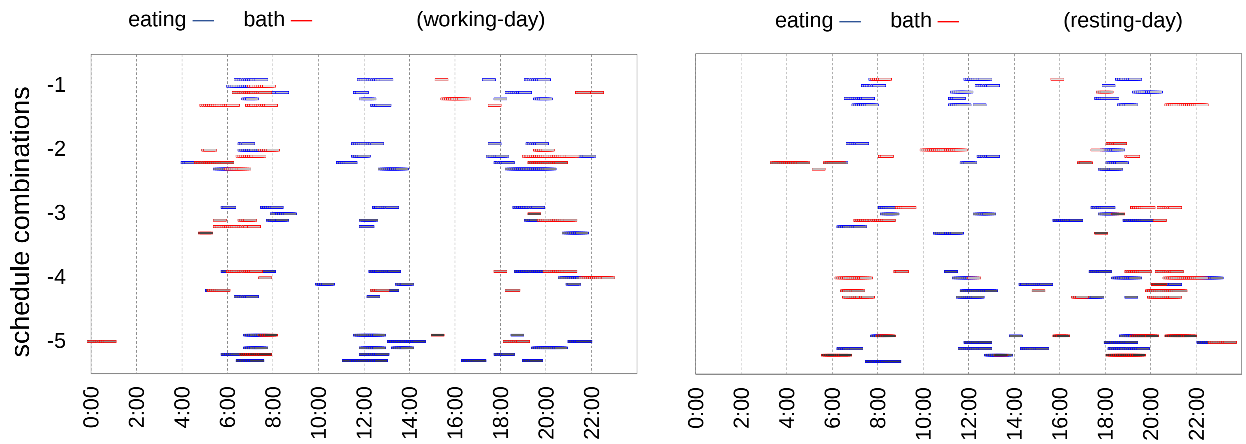

Figure 15. Behavior (eating and bath) schedule combination of a household (two elders, working-male, housewife, one child) (selected randomly)

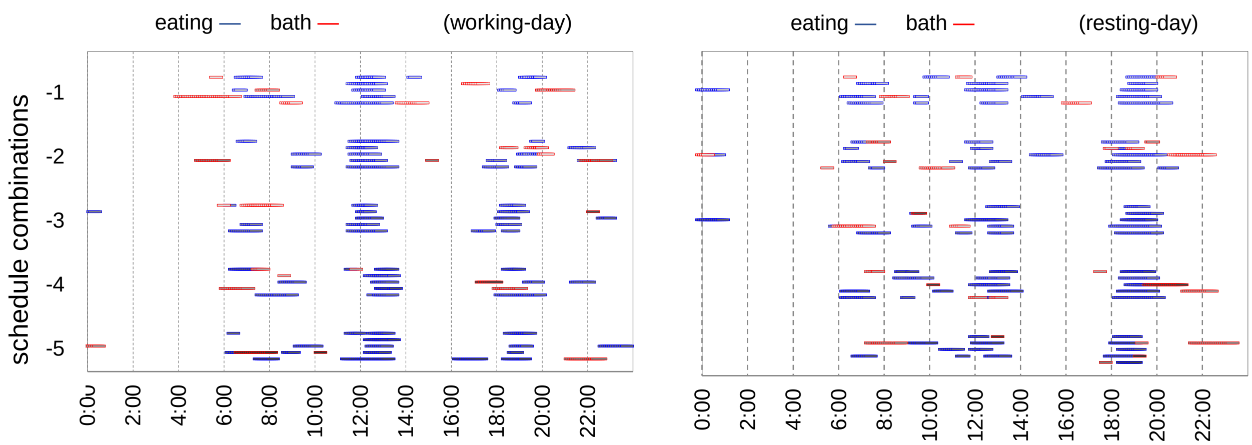

Figure 16. Behavior (eating and bath) schedule combination of a household (two elders, working-male, housewife, one child) (selected by *PSO* algorithm)

selected randomly and with assistant of *PSO* algorithm. each situation. To compare the results precisely, average R_{eating} and R_{bath} (ratios of time by more than two members performing the same behavior to the sum time of this behavior) of 5 schedule combinations are calculated and shown in Table III. It could be concluded that compared with random selection, by *PSO* algorithm, eating behaviors of each member are gathered at the same periods with larger R_{eating}, while the bathing behaviors are scattered at different periods with smaller R_{bath}. This is consistent with the basic characteristics of household members' lives and proved our model's merit in generating household member behavior schedules.

TABLE III. R_{EATING} AND R_{BATH} OF EACH RASULTS BY RANDOM OR *PSO* IN WORKING DAY AND RESTING DAY

Household	Day-type	Method	R_{eating}	R_{bath}
household-3 people	working-day	random	0.13	0.06
		PSO	0.24	0.005
	resting-day	random	0.17	0.07
		PSO	0.31	0.02
household-5 people	working-day	random	0.17	0.11
		PSO	0.22	0.002
	resting-day	random	0.19	0.06
		PSO	0.22	0.001

VII. Conclusion and Future Work

This paper proposes a model based on public stochastic data to generate occupants' behavior schedules and form behavior schedules of household members. This model could be used in energy demand estimation of residential buildings in urban scale. Compared with existing behavior model's research, the proposed model has the following features:

- Generating occupants' behavior schedules based on
- public stochastic data only. Without statistical analysis of large amounts of raw *Time Use Data* (*TUD*), which is not available in many countries, making the behavior model simpler and more efficient.
- No classifying the behaviors or setting the specific number and duration time of behavior occurrences. This feature could exclude the errors from subjective assumptions.
- Utilizing the *Dynamic Time Warping* (*DTW*) and *Particle Swarm Optimization* (*PSO*) algorithms to search the suitable number of behavior occurrences and percentages of occurrences' duration time. It would make the simulation results match the public stochastic data as closely as possible.

- Deciding the start moments of behavior based on cumulative distribution of public stochastic data. As the simulation results do not agree with the public stochastic data, the start moments calculated by the above method have been corrected using *PSO* algorithm.
- Considering the behaviors connection among the household members. By *PSO* algorithm, the suitable combination of generated behavior schedules from each occupant would be searched as the household members' behavior schedules.

For single occupant, 5 type occupant's behavior schedules in two type days have been generated with the proposed model. The result shows that our model has a good accuracy. But there are also several drawbacks:

a) In public stochastic data, during some periods (12:00~12:30 and 22:00~22:30, probabilities of adopting eating, sleeping by 5-minutes interval increase rapidly, but the simulation results fail to reflect such phenomenon.

b) No consideration of interaction between behaviors (e.g., people are likely to wash themselves when they wake up, but behavior transition between sleeping and bath can't be simulated in a single schedule).

For household, an example household with three members has been searched with suitable behavior schedule combination. The result shows that the behavior schedules of each member tend to eat together and wash at different period and this is the purpose of the model. However, some limitations are still need to be solved:

c) Only behaviors include eating and bath are considered in our model, other behaviors like watching TV are still need to be considered. As the number of considered behaviors increases, the difficulty of matching the suitable behavior schedules is also increasing.

d) As shown in results, household members tend to have lunch together in working day, which is inconsistent with reality. The reason is that the records of public data about behavior eating do not distinguish between being at home and going out. Therefore, this problem needs to be considered in the energy simulation of residential buildings.

There are also some details need to be explained. Firstly, by *PSO* algorithm merely, the start moment of each behavior occurrence (***SMN***) could be determined without using cumulative distribution of probabilities of adopting given behavior by 15-minutes interval (***PM***). But with the assistance of cumulative distribution, the *PSO* algorithm could narrow the search range and get solution quickly. Secondly, more than just simulation for behavior schedules based on past public stochastic data, it might be useful for assuming the future people behavior change by altering the inputting public stochastic data (e.g., the working time at home increased because of covid-19). Finally, compared with similar studies with *TUD* in other country such as UK [5] and US [13], the simulation results show the uniqueness of Japanese occupant behaviors.

In future, we are going to deal with mentioned drawbacks to improve the model. About drawback *a)*, more in depth analysis of public stochastic data especially in specific period will be done so that different weights will be given during these time intervals in simulation process. For *b)*, which had been raised in much previous research, analysis the raw *TUD* to get the results of behavior transition probabilities is a feasible option. About last *c)*, more behaviors and more efficient algorithms will be considered. For last *d)*, the classification of indoor behaviors needs to be more detailed based on the types of occupant and target days. Also, it should be noted that the behavior schedules could not be used directly in the energy demand estimation model without appliance operation possibilities based on behaviors. More work about the relationship between behavior and appliance operation is also necessary in future.

REFERENCES

[1] H.Wang and D.Sumiyoshi, "Development of Occupants' Behavior Model in Urban Scale Using Dynamic Time Warping and Particle Swarm Optimization Algorithms Based on National Lifetime Survey," ENERGY 2023, The Thirteenth International Conference on Smart Grids, Green Communications and IT Energy-aware Technologies, pp. 17-22, Mar. 2023.

[2] Ministry of the Environment, Japan, Outlines of Japan's Long-term Strategy under the Paris Agreement, 2019.

[3] G. Happle, J. A. Fonseca, and A. Schlueter, "A review on occupant behavior in urban building energy models," Energy & Buildings, vol. 174, pp. 276-292, Sept. 2018, doi: 10.1016/j.enbuild.2018.06.030.

[4] J. Tanimoto, A. Hagishima, and H. Sagara, "Validation of methodology for utility demand prediction considering actual variations in inhabitant behavior schedules," Journal of Building Performance Simulation, vol. 1, no. 1, pp. 31-42, Mar. 2008, doi:10.1080/19401490701868471.

[5] I. Richardson, M. Thomson, and D. Infield, "A high-resolution domestic building occupancy model for energy demand simulations," Energy and Building, vol. 40, no. 8, pp. 1560-1566, Feb. 2018, doi:10.1016/j.enbuild.2008.02.006.

[6] J. Widén, M. Lundh, I. Vassileva, E. Dahlquist, K. Ellegård, and E.Wäckelgård, "Constructing Load Profiles for Household Electricity and Hot Water from Time-Use Data – Modelling Approach and Validation," Energy and Building, vol. 41, no. 7, pp. 753-768, Mar. 2009, doi:10.1016/j.enbuild.2009.02.013.

[7] Y. Yamaguchi and Y. Shimoda, "Evaluation of behavior model of occupants in home based on Japanese national time use survey," Proceedings of Building Simulation 2015: 14th Conference of IBPSA, Dec. 2015, pp. 2897-2904, doi: 10.26868/25222708.2015.2520.

[8] Y. Yamaguchi and Y. Shimoda, "A stochastic model to predict occupants' activities at home for community-/urban-scale energy demand modelling," Journal of Building Performance Simulation, vol. 10, no. 5-6, pp. 565-581, Jun. 2017, doi: 10.1080/19401493.2017.1336255.

[9] Y. Li, Y. Yamaguchi, and Y. Shimoda, "Impact of the pre-simulation process of occupant behavior modelling for residential energy demand simulations," Journal of Building Performance Simulation, vol. 15, no. 3, pp. 287-306, Mar. 2021, doi:10.1080/19401493.2021.2022759.

[10] Japan Broadcast Institution (*NHK*), National Lifetime Survey in 2020, Japan.

[11] H. Sakoe and S. Chiba, "Dynamic programming algorithm optimization for spoken word recognition," IEEE Transactions on Acoustics, Speech, and Signal Processing, vol. 26, no. 1, pp. 43-49, Feb. 1978, doi:10.1109/TASSP.1978.1163055.

[12] J. Kennedy and R. Eberhart, "Particle swarm optimization," Proceedings of ICNN'95 – International Conference on Neural Networks, Nov. 1995, pp. 1942-1948, doi: 10.1109/ICNN.1995.488968.

[13] L. Diao, Y. Sun, Z. Chen, and J. Chen, "Modeling energy consumption in residential buildings: A bottom-up analysis based on occupant behavior pattern clustering and stochastic simulation," Energy and Building, vol. 147, pp. 47-66, July 2017, doi:org/10.1016/j.enbuild.2017.04.072

Identification of Workflow in Construction Projects in Cambodia

With and Without Building Information Modeling/ Models/ Management Approaches

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***Abstract*—Cambodia's construction industry is overgrowing but faces challenges like cost overruns and delays. This study explores collaboration in construction projects involving project owners, designers, and contractors, including architecture, structure, mechanical, electrical, and plumbing disciplines. The semi-structured interviews were conducted with 16 participants, focusing on coordination, communication, and co-production. Two construction projects with and without Building Information Modeling (BIM) approaches were also observed. Our findings identified four workflow scenarios linked to different interaction actors' categories. The study demonstrated that the degree and timing of collaboration among project owners, designers, and contractors were the primary factors influencing the workflow scenarios in the Cambodian construction sector. Most participants were unfamiliar with BIM and did not apply it to their projects. Traditional project delivery methods remained prevalent, even in large-scale projects. Participants lacked a common language regarding BIM, hindering effective collaboration. It became evident that there was a lack of willingness to align knowledge and practices to enhance project value. To promote BIM collaboration within Cambodia's construction sector, we recommend the development of a centralized collaboration guideline tailored to architects, engineers, contractors, and project owners.**

Keywords-collaboration; workflow; construction; Cambodia; BIM.

I. Introduction

This paper is an extension version of the COLLA 2023 conference paper [1], which added a research question: "How can we facilitate and support Building Information Modeling (BIM) enabled collaboration in Cambodia's construction sector?" To answer this, we extended experiments by observing two construction projects in Cambodia: one that BIM has not been used and one that BIM has been used. Moreover, we specifically explained our protocol.

The construction industry is pivotal in driving Cambodia's economic growth, contributing 9.1% to the country's total Gross Domestic Product (GDP) in 2018 [2]. Over the past few decades, the number of foreign investors, including those from China, South Korea, Japan, Europe, and America, has increased [3]. These investments have primarily targeted infrastructure development and urbanization, resulting in a remarkable construction sector expansion over the last [4][5].

However, despite this significant growth, many construction projects in Cambodia have grappled with poor cost management and project schedule performance [6]. It's worth noting that these challenges are not unique to Cambodia but are prevalent in contemporary construction projects worldwide [7]. The construction sector needs to improve its efficiency, which leads to decreased cost and improved project performance at various stages of the project life cycle.

Previous research has underscored the critical role of collaboration in ensuring the success of construction projects [8]. Meanwhile, effectively managing collaboration among various specialized actors involved in construction project development remains challenging [7]. To address these issues and improve the project performance, it is imperative to ascertain the current state of the collaborative process within the sector.

The three main parties driving construction development are the project owner, the designer, and the contractor, with a legal framework governing their interactions stated in the contract [9]. Architectural, civil, structural, mechanical, and electrical design are five essential disciplines in building design [10].

This study is geared towards the collaborative process among project owners, designers, and contractors, focusing on the architectural, structural, and MEP disciplines across various phases of the construction project life cycle. Within the context of Cambodia's construction, this study aims to answer the following questions:

- What characterizes the interaction among Cambodian construction project owners, designers, and contractors?
- How do collaborative workflows and processes of these actors evolve throughout different phases of construction projects in Cambodia?
- Is BIM perceived by industry professionals as an alternative to overcome poor cost and schedule performance in the future?
- How can we facilitate and support BIM-enabled collaboration in Cambodia's construction sector?

Interviews and observations have been conducted to answer these multifaced questions. This article is structured into six parts. First, we introduce the Cambodian context, problem statement, research questions, and an outline of the article's content. The second section presents the specificity of the construction sector in Cambodia. The second section also delves into the existing literature, outlining the definitions and tools of collaboration, and the three components of collaborative work. The third section explains our data collection protocol, which encompasses semi-structured interviews and observation case studies. The fourth section presents results, including insights into the relationship among project owners, designers, and contractors, the four workflow scenarios, the balance of collaboration, problem-solving, and BIM experiences and perspectives. The fifth section discusses the results. We finish this paper with the conclusion of our research findings and further work in the last section.

II. Literature Review

This section demonstrates the existing knowledge, i.e., the specifics of Cambodia's construction context, including the construction contract, the project lifecycle phases, and the importance of adopting BIM. Moreover, this section presents the definition and components of collaboration.

A. *Specificity of the construction sector in Cambodia*

Bellowing is the information specific to the construction in Cambodia. However, finding this information is challenging due to limited resources and research gaps within this field.

1) *Construction contract in Cambodia*

The interaction, roles, and responsibilities of the owner, the designer, and the contractor are typically stated in the contract [9]. According to the contract agreement, the owners should expect the result, payment, and oversee the progress of the work. The structure of a construction contract in Cambodia is as follows:

Within the Cambodian context, the legal framework governing construction activities includes the adoption of a sub-decree on construction permits in 1997, as well as the Civil Code in 2007; and land law in 2001. However, it needs more explicit regulations of construction law and the establishment of a standardized construction contract. Without a locally standardized contract, Cambodian construction projects frequently turn to the International Federation of Consulting Engineers (FIDIC) standard, which was established by Belgium, France, and Switzerland [11].

FIDIC standards published in 1999 have four standard forms of contracts:

- Conditions of Contract for Construction recommended (1) for the project designed by the owner or engineer. The contractor builds the building following the design provided by the owner [12].
- Conditions of Contract for Plant and Design-build recommended (2) for "the provision of electrical and/or mechanical plants, and for the design and execution of building or engineering works" on a design/build basis. The contractor designs most or all the work [13].
- Conditions of Contract for EPC/Turnkey projects recommended for "a process or power plant, a factory or similar facility, an infrastructure project, or other types of development [14]."
  (i) a higher degree of certainty of final price and time is required.
  (ii) the contractor takes total responsibility for the design and execution of the project, with little involvement from the employer.
- Short form of Contract (3) recommended for building or engineering works, which is a small value (less than US$500,000) or short-term work (less than six months) [15][16].

In our study, we are interested in only the conditions of the contract for construction, conditions of the contract for plant and design-building, and the short form of the contract, which are recommended for building or engineering works. The definition of the contractual relationship between actors is the aim of these standards [17].

All contract standards have identified the tasks and responsibilities of three actors: employer (owner), engineer (designer), and contractor. We compare those contract standards based on the duties of actors, as shown in Table I.

- Contractors in (1) and (3) design only for extent specification. Otherwise, they design almost all the projects in (2).
- The requests for construction and environmental permits are the owners' responsibility.
- Providing instructions and requesting any requirement to the contractor is the owner's

designer's responsibility in (1).

- There is the owner's representative who acts on behalf of the owners in (2) and (3)—otherwise, the designers who work on the owner's behalf in (1). On behalf of the owner, the owner's representative and designers have the authority to check, inspect the site, join decision-making, and make requests to the contractor on behalf of the owner.
- The contractor also executes and completes the project.

2) Construction project life cycle phase

In Cambodia, there is not a standardized national framework for delineating the phases of construction life cycle. Instead, individual companies, institutions, and universities often adopt the standard from United States (US) or Europe as a reference. Based on the interviews conducted (which will be discussed in the following section), we indicated that construction projects in Cambodia are typically structured into eight phases: initial, conceptual design, schematic design, permitting, tender, BID, construction, and post-construction. Thus, this part, we will illustrate the difference in nomenclature and the structure of the primary phase of the construction project life cycle between US, Europe, and Cambodia (Table II).

In traditional design-bid-build projects, the life cycle phases generally include project initiation, design, permitting, BID and award, construction, and commissioning and operation phase. In the initiation phase, they study the funding, environmental impact, and the potential of the project. The design phase is about conceptual design. Preliminary engineering is also a part of the design phase. It helps analyze and validate the project. From this phase, the owner can choose the option that meets their budget and requirements. Then, they detail the final design to request the permit. The detailed drawing and specifications are also submitted to the contractors' companies to bid. The selected contractor must complete the project as stated in the contract. The contractor must join in operation activities and commissioning when the construction phase is completed [18].

Naming these phrases may differ between countries, but the principal remains the same. For example, in Belgium, the design and construction phase of the project is divided into eight main sub-phases: preliminary studies (PRE), summary pre-project (APS), detailed pre-project (APD), construction of urban planning permit (PDU), construction of the contractor consultation (DCE), suit, development of works contracts (MDT), work execution (EXE), suit, and additional assignments phase (MSU) [19].

In the PRE phase, the owners gather information about their project and define the requirements, including the project's characteristics, budget, etc. All that information must be provided to the architect to study. Then, the architect sketches three proposals to the owner. In APS phase, they summarize and search for more information from the PRE phase and develop the selected sketch. They also study energy performance choice, technical security, ventilation, and acoustics. APD is the phase of coordination structure and technical design. They choose the material, ventilation, etc., and calculate the PEB. The PDU phase is the registration for the environment, construction permit, and Energy Performance of Building (PEB) certificate. The DCE phase is the phase of preparing documents for contracts. MDT is a phase of analysis, choosing the contractor company, and signing the contract. In EXE phase, the site works start and follow the plans in the agreement. There are regular meetings and report submissions in the phase. The MSU phase is the final step to be completed [19].

TABLE I. COMPARISON OF THE RESPONSIBILITIES OF ACTORS IN STANDARD FORM: CONDITION CONTRACT FOR CONSTRUCTION, CONDITION CONTRACT FOR PLANT AND DESIGN-BUILD, AND SHORT FORM OF CONTRACT

Task	**Condition contract for construction** [12]	**Condition contract for plant and design-build** [13]	**Short form of contract** [15]
Designing the project	Owner/ designer	Contractor	Owner/ designer
Requesting construction and environmental permits	Owner	Owner	Owner
Giving the instruction	Designer	Owner	Owner
Designing to the extent specified in the contract	Contractor	Contractor	Contractor
Execution plan	Contractor	Contractor	Contractor
Completing the work (building)	Contractor	Contractor	Contractor
Submitting details of the arrangements and method, which the contractor proposes to adopt for the execution of the work	Contractor	Contractor	
Requesting details of the arrangements and method	Designer	Owner's representative	Owner's representative
Action on the owner's behalf under the contract: approval, check, certificate, consent, examination, inspection, instruction, notice, proposal, request, test	Designer	Owner's representative	Owner's representative

3) For construction 4.0 in Cambodia: towards Building Information Modeling, Models, Management (BIM)

In the 21st century, industrials have a remarkable evolution with the advent of Industries 4.0, driven by digital technology. This transformation has had a profonde impact across various industrial sectors. In the construction industry, often referred to as Construction 4.0, the goal is to promote the integration of advanced information and communication technologies into construction services. The aim is to enhance collaboration, productivity, and overall quality while minimizing project delays and costs. This approach also involve effectively managing complex construction projects their life cycle [20].

TABLE II. THE DIFFERENCE BETWEEN US, EUROPE, AND CAMBODIA PROJECT LIFE CYCLES PHASE NOMEMCLATURE

	US	Belgium	Cambodia
Phase	Initial	PRE	Initial
	Design	APS	Conceptual design
		APD	Schematic design
	Permitting	PDU	Permitting & Tender
	BID & award	DCE	BID
		MDT	
	Construction	EXE	Construction
	Post-construction	MSU	Post-construction

Moreover, Royal Government of Cambodia has issued the Rectangle Strategy-Phase IV for Growth, Employment, Equity, and Efficiency: Building the Foundation Toward Realizing the Cambodia Vision 2050. Within rectangle 2 (Economic Diversification) and slide 3 (preparing for the digital economy and the Industrial 4.0 revolution) express the purpose of the government developing forward the Industrial 4.0 as stated below [21]:

- "Developing and implementing a long-term strategic framework for digital economics.
- Further updating and implementing the Telecommunication and ICT Development Policy, the Master Plan for Information and Communication Technology, the Law on Telecommunications, and other relevant regulations, along with developing and implementing a long-term ICT strategic framework.
- Further strengthening and expanding the development of necessary supporting infrastructures.
- Promoting the establishment of a legal framework to support development.
- Developing education and training programs
- Developing entrepreneurship and digital ecosystem."

Towards the Construction 4.0, BIM is presented as the most appropriate solution to enable the change and as the potential tool/method for solving the problems in the architecture, engineering, and construction industry [22]. It profoundly impacts how project stakeholders collaborate and share information throughout a building's lifecycle [23].

Numerous sources define BIM. The National BIM Standard-United States defines Building Information Modeling as "a digital representation of physical and functional characteristics of a facility forming a reliable basis for decisions during its life-cycle; defined as an existing from earliest conception to demolition [24]." International standard (ISO 19650-1: 2018) defines BIM as the "use of a shared digital representation of a built asset to facilitate design, construction, and operation processes to form a reliable basis for decisions [25]."

The letters "B" and "I" represent the civil construction or infrastructures (Building) and the information, respectively, which represents the real added value of this methodology in the context of 3D modeling. Otherwise, "M" has been given many definitions. BIM (modeling) is a process of creating models; BIM (models) is the model, which obtains the data and information for building; BIM (management) is the process of information management on the one hand and collaboration management on the other [26]. These three Ms complete the meaning of BIM and reflect the complexity of the resulting collaborative process and data sharing between the various actors and protagonists of the project throughout the life cycle of the building.

Rezaei and Sistani [27] found that professionals in the construction sector are confidential with hand drawing and 2D/3D CAD software, especially AutoCAD software. Otherwise, they lack BIM-based skills and knowledge [27][28], even as most companies in the United States and Europe actively promote BIM adoption.

Meanwhile, there remains a lack of studies on the factor facilitating or hindering BIM adoption within Cambodia's Architecture, Engineering, and Construction (AEC) sector. Previous study demonstrated that project visualization and schedule performance are the most significant drivers factors, while significant industry resistance to change remains a considerable challenge [29].

In the broader Asian context, studies focusing the key barriers of BIM adoption, including those in China, Vietnam, and Malaysia, have highlighted the importance of BIM legal, regulation, and standards [30][31][32][33][34][35][36][37][38]. Additionally, the important BIM guideline encompass technology, return on investment, and implementation [31][37][39][40]. A study by Liu, 2022 presents the hierarchical structure and level partitioning of BIM adoption barriers for small and medium-sized fire protection enterprise in China [33]. This study highlights root barriers, including lack of external support from local government and a deficiency of BIM laws and regulations applicable to the fire protection industry. It also identifies a lack of client demand, and internal issues (i.e., training culture), software and technology-based barriers, insufficient knowledge and experience in applying BIM, and external guidance barriers such as pilot and standard. Remarkably, in China, the BIM adoption rate has surged from 5% in 2014 to 23.6% in 2019, following the government's promoted BIM policies in 2015 [41]. This rate is expected to further rise if BIM becomes mandatory for national construction projects, increasing client demand.

Many countries have conducted extensive research to customize guidelines or references for their national setting. As previously mentioned, fostering collaborative culture among project teams is vital for successful BIM implementation [28]. Therefore, imperative for us to gain a comprehensive understanding of the collaborative processes within Cambodia's construction sector. This knowledge will enable us to better prepare for change, overcome significant inertia, and promote the adoption of Construction 4.0.

B. "Collaboration": Many defenition and tools

Several definitions are given for Collaboration. Some speak of collective activity in general, and others propose differentiating them in terms of collaboration or cooperation. Both collaboration and cooperation are inter-organizational. Nevertheless, we refer to the definition of collaboration as the relationship with a common goal. In contrast, cooperation refers to "relationship among participants in a project, which does not commonly relate by vision or mission, resulting in separated project organization with independent structures, where the project culture is based on control and coordination to solve problems independently to maximize the value of the own organization [42]."

In our case, we borrow the definition of Wood and Gray (1991), who describe collaboration as an interactive process of a group of actors that work together to make joint decision-making on a problem domain [43] by sharing their vision, information, and process via interacting, communicating, exchanging, coordinating, and approving in order to meet their common goal [44]. In the construction management domain, "collaboration" is defined as "a central element of success throughout the lifecycle of construction project [45][46]." Schöttle et al. [42] stated that the factors to reaching a successful collaboration are "trust, communication, commitment, knowledge, sharing, and information exchange [42]." Moreover, "the project-based nature of the Architect, Engineer, and construction industry requires collaboration, or at a minimum some form of negotiated interaction [47]."

Table III shows the supported system variant of place and time which was originally presented by DeSanctis and Gallupe [48].

TABLE III. GROUP DECISION-SUPPORTED SYSTEM [48]

	Synchronous	**Asynchronous**
Same place	Face-to-face meetings and discussion aids	Team meeting rooms and discussion areas
Different place	Voice/ video conferences, virtual meeting rooms, shared applications	Messaging systems, e.g., e-mail, multi-user editors and collaborative writing tools, workflow systems

C. Three components of collaborative work

We base ourselves on Ellis's model [49], which is also used by many researchers [50][51] because it permits us to understand collaborative works through three components: "Coordination", "Communication", and "Co-production".

Coordination is how the work is structured [52]. The coordinative activities manage the task for actors to perform and the relationship between the actors to complete the tasks [53].

Communication is about exchanging information and sharing knowledge [54] to ensure that all actors get a common referential [46]. The information can be transmitted in different forms, e.g., verbal, written [54]. However, the development of technologies has supported communication, including "the electronic communication system (mail systems, facsimile transfer, voice and video conferencing) and shared workspace systems (virtual meeting rooms, remote screen sharing and electronically aided intelligent whiteboards (shared application) [54]."

Co-production is the action related to creating or realizing the project design or building [53][55]. Those actions can be an action of a single actor or multi actors [55]. This concept also includes the decision-making of problem-solving.

BIM capability supports all three components of collaboration. BIM actively facilities co-productive activities. For example, it enables actors to collaborate closely with other disciplinary actors. Model-based collaboration within BIM includes the interchange of models or part-models through both proprietary formats "(e.g., between Revit Architecture and Revit Structure through the .RVT file format) and non-proprietary formats (e.g., between ArchiCAD and Tekla using the IFC file format) [23]."

Furthermore, BIM enhances coordination through software tools like Navisworks and BIM collab, etc. These tools streamline the coordination of various project aspects.

BIM also supports communication activities, both asynchronous and synchronous. Actors can leave the comments, highlight issues, and engage in discussions based on information shared through software platforms, i.e., BIM collab, etc., thus fostering effective communication among project stakeholders, regardless of geographical distance.

Hence, the Cambodian construction context needs national common references, including standard contracts, a clear workflow of the project lifecycle, and BIM implantation guidelines. Moreover, the research on these references needs to be improved; a few studies demonstrate the current construction situation. Our research aims to fill this gap and significantly contribute to knowledge in this field.

III. PROTOCOL

This section provides how the study was successfully conducted through interviews and observations. The semi-structured interviews process encompassed two steps approach. The first step involved interviewing employees to establish the relation of actor's categories, while the second step aimed to validate the collaborative activities and workflow within each project phase. Additionally, observation of construction project/company in Cambodia were conducted to identify practical issues.

A. Semi-structured interviewing

We employed qualitative research via semi-structured interviews to gather participants' thoughts, feelings, and perspectives. This data allowed us to collect detailed problems in the participants' practice. The framework for these interview were based on the Ellis's model: coordination, communication, and co-production (Cf. II.C.) [49].

We structured the semi-structured interviews around five themes:

- Presentation project and company: participants described the projects they have been involved in and their company's role in those projects.
- Coordination: participants answered questions about their roles and responsibilities in the project. We defined the participants' tasks (individual and overlapping tasks) and participants' roles. They mentioned how the work was structured and their interactions with other actors to complete the tasks.
- Communication: participants explained the communication methods and tools for teams. Participants described the procedure of sharing understanding, knowledge, and information.
- Co-production: we focused on the action that actors produced tasks or projects, especially the method and tools they used.
- BIM experience and perspective: we asked the participants a straightforward question to see their first expression. The question is "Have you ever heard of BIM?" If so, participants explained their experiences and perspective.

In total, we conducted semi-structured interviews with sixteen participants for approximately fourteen hours, divided into two steps.

In the first step, we interviewed eight participants from three disciplines: architecture, structure, and MEP. These participants work in different companies and play various roles, including MEP engineers, architects, and structural engineers (Table IV).

In the second step is the interviews of an additional eight participants (Table IV). The section of participants in the 2nd step were based on the outcome of the initial interview, aimed at gaining a more understanding of workflow scenarios. These eight participants were selected from management level, including free-lancer architects, MEP manager, CEO of contractor company, general manager, CEO of architecture company, BIM modeler and coordinator. These participants addressed the same five thematic areas but were required to provide a holistic account of the entire process, from design to construction phase.

The number of participants is indeed restricted. However, qualitative research typically required a sample size of five to twenty-five samples are sufficient [56], and our sample of 16 participants is considered acceptable. We know that this size could limit our research, but our work has allowed us to trace specific trends in the collaboration sector, illuminate the collaboration process and the workflow, and address the specificity of the construction sector in Cambodia, all with the aim of preparing for the BIM implementation.

TABLE IV. PARTICIPANTS' INFORMATION OF SEMI-STRUCTURED INTERVIEWS

No	Role	Company
		1st step
1	MEP engineer 1	Contractor
2	MEP engineer 2	Contractor
3	Architect 1	Owner
4	Architect 2	Designer
		Sub-contractor (finishing)
5	Architect 3	Contractor
6	Architect 4	Owner
7	Structural Engineer 1	Owner
8	Structural Engineer 2	Owner
		2nd step
9	Architect 5	Free lancer
10	Architect 6	Free lancer
11	Architect 7	BIM modeler & coordinator
12	MEP engineer 3	MEP manager
13	Structural engineer 3	CEO of contractor company
14	Structure engineer 4	General manager
15	Architect 8	Involved both local and standard project
16	Architect 9	CEO of Architecture company

B. Case study: Observation the construction projects in Cambodia

In addition to our interview data, we complemented our research with field observations of construction project/company in Cambodia. These observations cover both projects without and with BIM deliverables.

1) Construction project without BIM deliverables

We received permission from Panhchaksela Construction company to conduct site visits to the Ly Vouch Leng Condo project in Phnom Penh, Cambodia. This high-rise condominium building consists of 30 floors and covers an area of 1 150m2. The stakeholder structure during our observation is illustrated in Fig. 1, which included project manager, site manager, MEP contractor, and structural consultant teams. At the time of our observation, the construction phase has been ongoing for two months with an expected completion date in 2024.

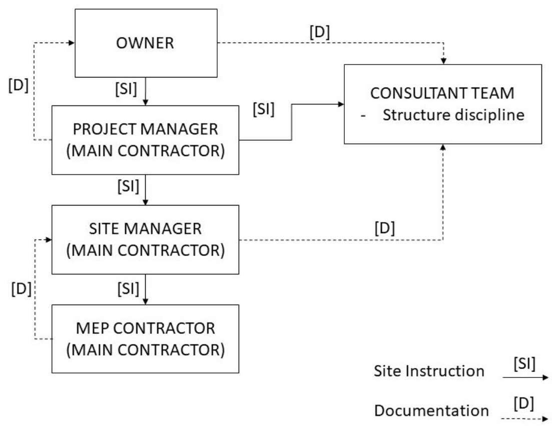

Figure 1. Stakeholder's structure.

2) Construction project with BIM deliverables

Our study concerning BIM implementation in construction project aims to address the question of how we facilitate and support BIM-enabled collaboration in Cambodia's construction sector. To gather insights into this aspect, we engaged with Shanghai Baoye (Cambodia) CO., LTD (SBCC), a Chinese construction company that has been established in Cambodia since 2016. SBCC has an extensive experience, having participated in high-rise construction more than 25 projects in Cambodia, including those in Phnom Penh, Sihanoukville, Siem Reap, Kampot, Koh Kong, and other locations.

The presence of a company utilizing BIM in Cambodia is a positive indication. We conducted a questionnaire survey with a BIM engineer from SBCC, who was part of the project management team. The question covered various aspects, including information about the respondent, the company's details, project specifics, BIM standards and protocols, BIM deliverables method, roles and responsibilities within the BIM process, workflow, dataflow, communication methods, BIM software usage at different project stages, and the engineer's perspectives. To overcome language barriers, interviews were conducted following a questionnaire.

IV. Results

The research results are demonstrated in the following.

A. Actor relationship

The findings from first step semi-structured interviews indicated a clear correlation between project tasks and roles actors. Subsequently, we categorized the participants into four distinct categories, each contingent on the relationship among project owners, designers, and contractors. These categories are summarized as follows:

1) Category 1

The owner separated the contract between the designer and the contractor. Participants who were involved with this project said that "[…] the foreign company provided the architectural plan […]"; and a local architect provided the finishing plan.

2) Category 2

The owner owned a company that has a full-package team: designer and constructor. He could be a real estate agent or own a company with many campuses. Thus, the owner used the same design for his many projects. The architect participant stated, "I design […], but I had to respect the previous project reference or guideline"; "I kept its style, function, similar size, and then I suited it in the new terrain." Projects could be banks, coffee shops, stores, factories, or a uniform residential building like Borey. The architect proposed and discussed the new architectural plan with the owner. The architectural plan must respect the standard of the previous project.

3) Category 3

The owner owned the full package of the design team. The contractor company built the project by follow up and participating in discussions from owner or his representative in construction phase.

4) Category 4

The owner hired a design-build company to oversee the project.

B. Workflow

Based on the data gathered from both step of semi-structured interviews, we have identified four workflow scenarios that defined in eight phases (referred to as phase in Cambodia). These phases are initial, conceptual design, schematic design, tender design, permitting, BID, construction, and post-construction (Fig. 2).

We illustrated Fig. 2 to provide a visual comparison of these four workflow scenarios across the project life cycle. Additionally, the tools and methods employed for communication, coordination, and co-production are depicted.

1) Scenario 1

In this scenario, the architect proposed the concept design corresponding to the owner's requirements. The structural and MEP consultants also supported and advised on the design. They here had a role in giving ideas, critiquing, and predicting future technical problems. As the owner's representatives, they also participated in accepting or rejecting the architect's proposal. If the owner requests, the architect modifies his proposal until the owner approves it. Otherwise, the presence of consultants here was only in some cases. They did not participate in the conceptual design phase for some projects presented as shown in Fig. 3.

Schematic design phase, structural and MEP designers proposed the structural and MEP design, respectively. Then, they submitted those plans to the architect, who overlayed them and identified the clashes. The architect, structural engineer, and MEP engineer discussed solving those clashes. They modified those plans until these three parties, and the owner approved.

Then, the architect, structural engineer, and MEP engineer detailed their plans. They also must list material quantities in detail and submit them to the owner. The owner gave these tender documents to many contractors for studies. Those contractors' companies applied their proposal attached with cost estimates, build method, schedule, etc. Then, the owner chose a company to be a contractor.

In the construction phase, the contractor submitted the progress report to the owner or consultant and completed the work mentioned in the contract.

2) Scenario 2

The architect proposed the conceptual architecture under the support of the structure and MEP engineer. If the owner rejects the proposal, it must repeat it. If the owner accepts the proposal, it moves to schematic design.

Structure and MEP engineers designed the structure and MEP plan, respectively. The architect had a role in overlapping the three plans. Then, the architect, owner, structure, and MEP engineer discussed solving the clashes or technical problems between those three discipline plans.

After the approval of the schematic design, the architect, structural, and MEP engineer provided detailed drawings for the building.

3) Scenario C

The workflow in the conceptual and schematic design phase is the same as in scenario B. The difference is the designer from the owner teams. The tender, construction, and post-construction workflow is the same as in scenario A.

4) Scenario D

An architect designs conceptual design. The Schematic Design phase is the same as in scenario A. The workflow of the tender, construction and post-construction phases is the same as in scenario B. But the contractors who designed and built the structure and MEP.

C. Collaborative work: a balance between communication, coordination, and co-production

The participant stated, "architect is remote, and we do the videoconference. The participant added, "[…] we sent questions via e-mail and got a response one week later." In Cambodia, actors mostly communicate via social media in routine work, such as Telegram, WhatsApp, WeChat, etc., and in the form of voices, text, videos, and pictures. The architect shared all plans in Dropbox. If there were any updates, he sent us an e-mail with the link for access to a modified plan.

They discussed it face-to-face. It can be a formal or informal meeting. A face-to-face meeting is better than a distant meeting to solve the critical situation [54]. Not only Computer-Aided (CAD) but actors also printed to make a discussion during the meetings. Workers preferred hard copies compared to soft copies. After getting the agreement, they updated the plan. The participant said, "[…] after discussion, I made a cloud in red color on layout and made a note, e.g., 3rd-floor modification on the layout plan." Other actors received the updated information.

In the construction phase, they discussed daily with the internal team (MEP management team, subcontractor) and finishing team, rarely with an architect. The structure team works more often with an architect. One participant mentioned using DWG Fast view application to demonstrate 2D plans. It also allows him to use AutoCAD to verify its dimensions and take notes by smartphone.

D. Problem-solving

The issues on-site have been resolved through stakeholder discussions, which encompass both formal and informal meetings. These regular meetings are held bi-weekly and are attended by key participants, including the project manager, site manager, MEP contractor, and structural consultant teams. The project management team represents the owner's interests and is responsible for guiding the project towards meeting its planning and cost targets. The site manager plays a pivotal role in troubleshooting and ensuring the progress of the work aligns with the project's success criteria. The consultant teams act as proxies for the owner to ensure the contractor adheres to the owner's requirements.

The primary objective of these meetings is to provide progress reports on the work, address challenges related to retaining wall installation, and seek solutions. The meetings typically last for approximately 35 minutes.

This process is depicted as a recurring cycle in Fig. 4. The meetings commence with progress reports and the introduction of challenges. The project manager and site manager propose solutions, initiating discussions. As the highest-ranking authority in the cooperative hierarchy, the project manager makes final decisions. Participants with specialized knowledge share their expertise with others. The information disseminated after each meeting includes proposals, opinions, and problem-solving strategies.

Verbal communication serves as the primary method of interaction during these meetings, complemented by hand-drawn diagrams and hard copies of plans to facilitate discussions.

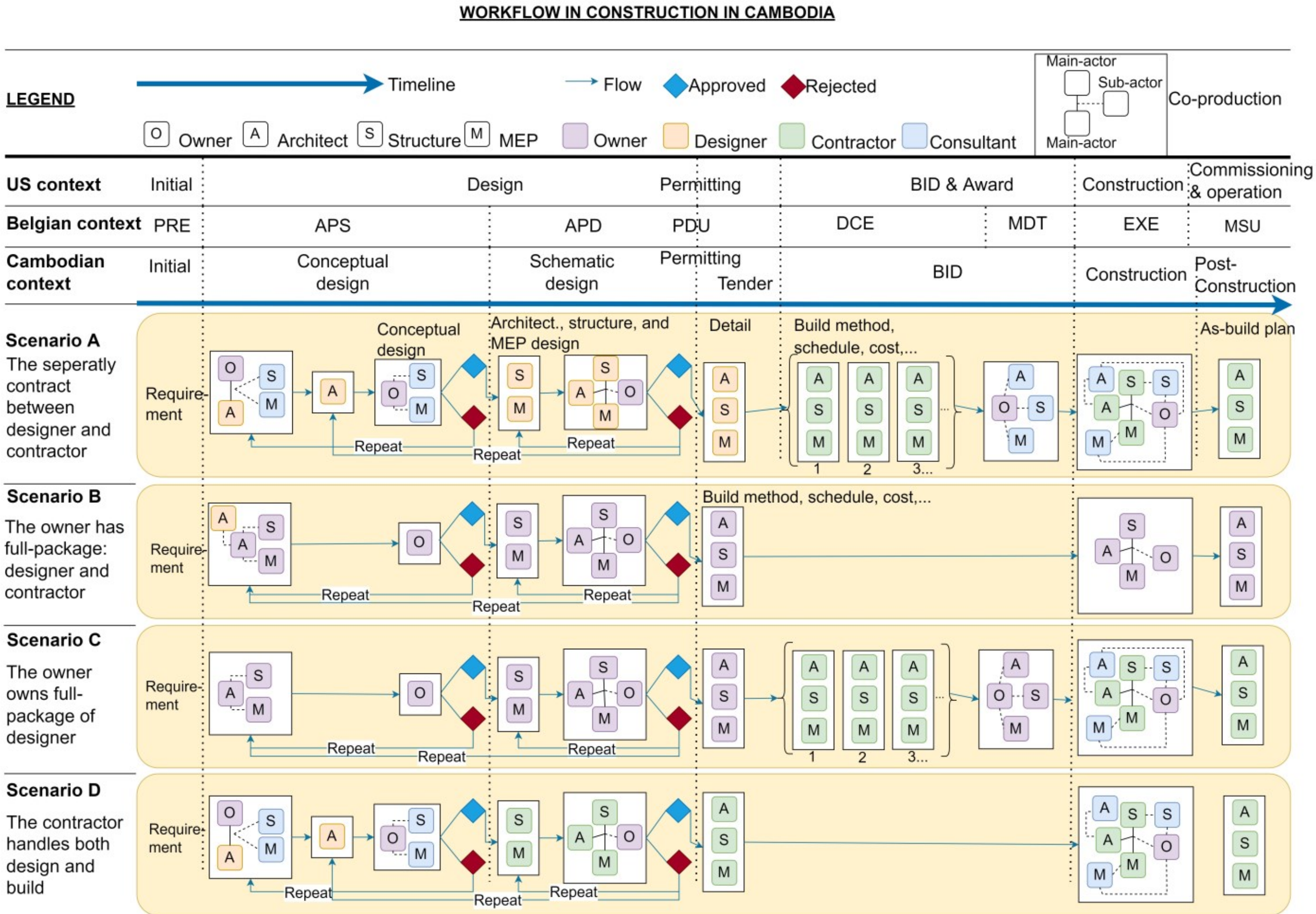

Figure 2. Four workflow scenarios in construction in Cambodia [1].

E. BIM experiences and perspectives

From semi-structured interviews conducted with a sample of sixteen participants, it emerged that eleven of them used to hear or know BIM. Among these, two individuals had received formal BIM training provided by their companies, while an additional four had acquired their knowledge through online or self-guided learning resources such as YouTube. These findings underscore the existing limitations in BIM training, highlighting a potential area for improvement, particularly within the context of universities and educational institutions.

Interestingly, only one participant reported having practical experience with BIM in real application, indicating a lack of BIM implementation within the Cambodian construction industry. One stated, “Our team utilized BIM for quantity and cost estimation, design planification during in Bidding phase.” Furthermore, among the sixteen participants, one was engaged in BIM modeling (architecture) and served as a BIM coordinator. This individual had undergone company-sponsored BIM training and emphasized the considerable benefits of BIM, particularly in terms of reducing rework and minimizing wastage of time. They also acknowledged the challenges associated with transitioning from traditional software to BIM, emphasizing the need for additional expertise to address the difficulties encountered.

One architecture company expressed an interest in adopting BIM but voiced concerns about the associated expenses and time required to train their staff. Additionally, they indicated that their decision would be contingent upon project owner requirements. Another participant acknowledged the advantages of BIM in construction but admitted to needing more time for learning. Due to the limited familiarity with BIM among collaborators, this individual found it necessary to export BIM models to DWG format each time they shared documents with their partners.

Shanghai Baoye (Cambodia) CO., LTD stands as a pioneering entity in the widespread adoption of Building Information Modeling (BIM) across numerous projects in Cambodia, contributing significantly to developing professionals in this field. SBCC has been actively engaged in these endeavors, assuming roles as bidders, general contractors, and sub-contractors.

A BIM engineer affiliated with SBCC has diligently provided insights through our questionnaires. She/he outlined the utilization of several standards, including BS1192 (collaborative production, management & exchange of AEC information), PAS1192-2 (information management using BIM - capital delivery phase), PAS1192-3 (information management using BIM - operational phase), BS8536 (soft landing - handover & post occupancy evaluation), and PAS 1192-2:2013 (information management).

BIM engineer has specified that BIM has been used for tasks such as building performance analysis and design/draw MEP coordinate. It is important to clarify that the reference to "Building Performance Analysis" does not exclusively entail the analysis, evaluation, or simulation of building performance parameters, which encompass aspects like energy efficiency, occupant comfort, and environmental impact. To eliminate any ambiguity, we conducted an in-depth interview to extract more precise information.

She/he described the communication question in general. Effective communication within the team is characterized by several principals:

- Team members prioritize communication by ensuring that everyone has an opportunity to both speak and listen simultaneously during discussions. This fosters inclusivity and active engagement.
- Communication is primarily conducted through face-to-face interactions, emphasizing the use of both verbal expressions and gestures to convey information. This robust approach enhances clarity and mutual understanding.
- Team members establish direct links with one another, promoting open communication channels not solely reliant on communication through a team leader. This reflects a culture of respect and equality within the team.
- Team communication goals encompass both formal and informal interactions, allowing team members to engage in discussions not limited to official team meetings. This flexibility encourages diverse forms of collaboration and knowledge exchange.
- Team members regularly venture outside the team to explore external resources and gather information. This information is subsequently shared with the team, avoiding unnecessary duplication of efforts and promoting resourcefulness.

In summary, these communication practices underscore the importance of inclusive, clear, respectful, and resourceful communication within the team, contributing to effective collaboration and knowledge sharing.

The software tools are employed for various purposes within the project workflow. These software tools can be categorized as follows:

- Programing: Microsoft office, WPS (Writer, Presentation, Spreadsheets), Adobe Photoshop.
- Designing: Revit (Architect, Structural, MEP Template), AutoCAD, 3D studio max, CAD MEP, ArchiCAD, Lumion,
- Analysis: AutoCAD Civil 3D, Autodesk, Steps software.
- Management: Microsoft Project, Synchro, Asite, BIM technologies, Autodesk Naviworks, Takeoff Cubicost (QS), Review: AutoCAD, Autodesk Design Review, PDF, Second life.
- Review: AutoCAD, Autodesk Design Review, PDF, Second life.

Fig. 5 illustrates the BIM workflow implemented by Shanghai Baoye (Cambodia), as outlined below:

The project owner provided 2D plans to the contractor company. The BIM team's responsibility generated geometrically precise 3D models from 2D Computer-Aided Design (CAD) plans. The primary software utilized for modeling is Revit. Within the SBCC BIM modeling workflow, modeling tasks are distributed among BIM team members based on floor levels or towers; the partial models are then combined.

A team member assumes the role of clash detection overseer. This individual exports architectural, structural, and MEP models from .rvt to .nwd format for clash detection purposes.. All identified clashes are screenshotted and reported in .doc format. This report is then submitted to the project owner for review and feedback. Subsequently, the BIM team undertakes corrective actions and revises the information or models as deemed necessary after discussion.

The BIM models serve various purposes, including utilization in the bidding and/or construction phase. The BIM models are subject to two distinct modes of export:

- Quantitative analysis and cost estimation: BIM models play an integral role in conducting meticulous quantity and cost estimations pertinent to the construction endeavor. To facilitate this process, BIM models are exported from the .rvt (Revit) format to the Industry Foundation Classes (IFC) format. These IFC-formatted models are subsequently imported into the Take-off Cubicost software. The utilization of Take-off Cubicost software allows for precise cost estimations, thus aiding in financial planning and budgeting for the project.
- Construction planning and execution: the BIM models are pivotal in orchestrating comprehensive construction planning and execution strategies. Furthermore, BIM technology extends to the creation of various visual assets (e.g., video, image, etc.) and generation comprehensive documentation pertinent to on-site construction.

Based on the questionnaire and interview, the following conclusion can be drawn:

- **Roles in the BIM process:** the BIM process at SBCC involves two distinct roles: BIM modelers and BIM coordinators. BIM modelers are responsible for creating precise geometrically accurate models. BIM coordinators are responsible for supervising the BIM modelers, ensuring model accuracy, and conducting clash detection checks.

- **BIM utilization at SBCC**: SBCC leverages BIM for various purposes, encompassing 3D BIM for modeling and documentation, 4D BIM for planification, and 5D BIM for cost estimation.
- **Lack of BIM procedure protocol:** notably, there is currently no documented BIM procedure protocol in place at SBCC. This suggests a potential area for improvement in formalizing and standardizing their BIM processes.
- **Challenges in BIM questionnaire:** the effectiveness of BIM-related questionnaires appears to be hampered by language and comprehension gaps among the participants. This highlights the importance of clear communication and common understanding when collecting BIM-related information.
- **BIM workflow:** the BIM workflow was drawn and submitted to Shanghai Baoye (Cambodia) company, and after review, it received approval.

This conclusion provides insights into the organizational structure and BIM practices, emphasizing the need for formalized procedures and improved communication strategies for BIM-related activities.

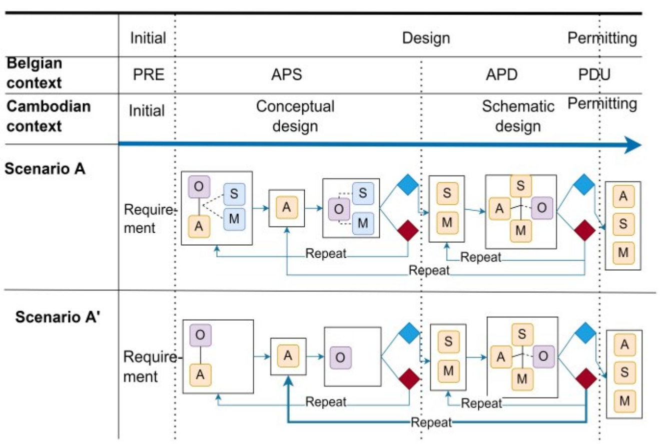

Figure 3. Scenario A in the conceptual design phase [1].

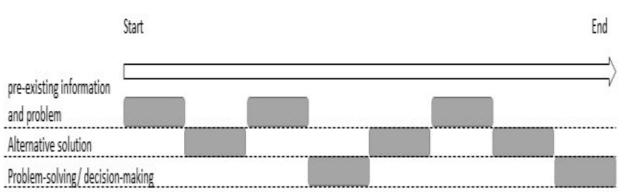

Figure 4. Action in the meeting.

V. Discussion

In Scenarios A and D, the project will be challenged with many technical problems in the schematic design phase if there is no participation of structural and MEP engineers in the concept design phase. Engineers will request the architect to make many changes affecting the conception design that due to wasting time and design costs. Otherwise, with the collaboration of other disciplines, the conceptual design will easily convince the owner to accept, reducing design error, time, and cost. The architect, structural engineer, and MEP engineer participated in the project since the early design phase in Scenarios B and C. As the claim of [41], the actors tend to isolate working, which is the roadblock to BIM collaboration. Thus, the collaborative culture in our scenarios is a good sight of the construction sector in Cambodia to influence BIM collaboration.

The similarity and differences between our workflow scenarios and the workflow we assumed from the FIDIC contracts were figured out. Scenario A and C are comparable to (1). In condition contract for construction, the designer or owner design almost the whole project. At the same time, the designer also brings this action in Scenario A, and the owner completes this task in scenario C. In scenario A and C, the contractor specified the design and completed the works as mentioned in (1).

In Scenario D, the designer designed only the conceptual design. The contractor designed in the schematic design phase. At the same time, the contractor designed almost the whole project in (2). The contractor in Scenario D also handled the work after the design phase, such as giving instructions, specifying design, method, execution, and completing the project, as mentioned in (2). In Scenario B, the owner handles everything by himself. We cannot find a similarity between Scenario B with any case in FIDIC contracts.

Cambodia's construction sector still uses CAD as the main tool to complete projects, as Rezaei and Sistani claimed [40]. Overall, actors are familiar with traditional project delivery methods. They are used to the problem and resistant to change. The participant stated, "normally, we had to re-model, re-check, and re-work. I don't think other tools can reduce it." Nevertheless, the participants who had experience with BIM practice or BIM training strongly believe that the waste from poor cost and schedule performance will be reduced by BIM adoption.

The BIM-based processed in the BID phase (Fig. 6). The contractor modeled BIM models in different disciplines based on the final designs that were provided. The contractor also extended the specific details. He coordinated the BIM-Models collaboration, identified the clashes and co-produced multi-disciplinary model via visualization. Moreover, he estimated the cost and scheduled performance in the further execution works. In our participant's case, the contractor volunteered using BIM by put a lot of effort and had a strong commitment into fighting the barrier of adoption BIM in Cambodia's construction project: "strong industry resistance to change [37]."

A questionnaire survey method was employed for data collection, with participants providing response independently. However, our find revealed significant knowledge gaps among participants and researcher, which is a challenge of research on BIM in Cambodia due to the limited common language, knowledge, and understanding. For example, while eleven out of sixteen respondents had heard of BIM, they were unable to provide an accurate definition. Remarkably, BIM was often equated with Revit, indicating a need for clarification. Furthermore, as mentioned in the results section, respondents associated Building Performance Analysis more with the modelling process than its energy, structural, and environmental aspects. Given these challenges, it became evident that questionnaires alone were insufficient, and interviews would be a more effective means of data collection.

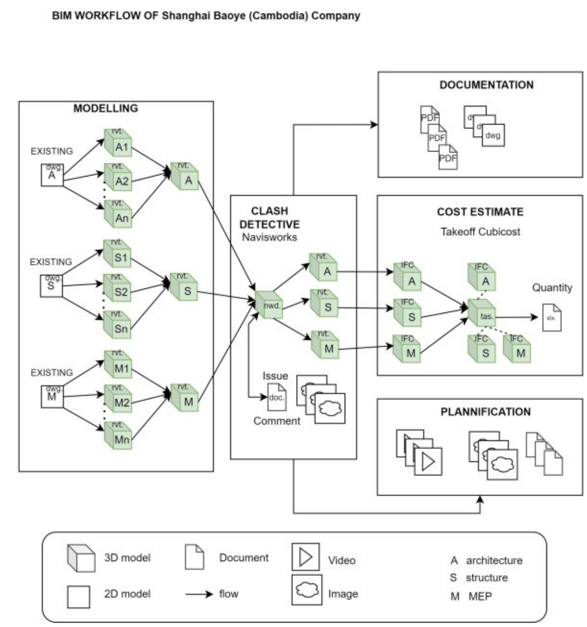

Figure 5. BIM workflow of Shanghai Baoye (Cambodia) Company.

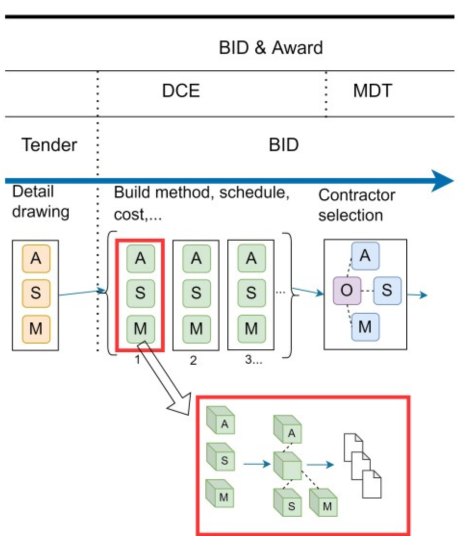

Figure 6. Workflow of BIM modeling in a project in Cambodia [1].

The research of Schöttle et al. [42] has identified trust, communication, commitment, knowledge sharing, and information exchange, are the factors to succeed collaboration. However, these factors are dependent on a shared language, common knowledge, and mutual understanding. Herbert Clark's psycholinguistic research emphasizes the importance of common ground for effective communication [54]. In the context of Cambodia's AEC industry, achieving such a common reference is essential.

To address the challenges faced in Cambodia's AEC sector and enhance BIM adaptation, several recommendations are proposed:

- **Establish common reference and guideline:** Developing a common reference and guidelines specific to the Cambodian context is vital to fostering collaboration and ensuring data centralization for future urbanization projects.
- **Promoting BIM education:** Promoting BIM courses within architecture, engineering, and construction universities is essential to equip future professionals with the necessary skills and knowledge. The companies have a willingness to use BIM by starting from training their staff. Yet, it takes a lot of time and effort. In United States, the companies prefer to employ candidate with BIM skills rather than those who lack BIM knowledge [40].
- **Regulatory framework:** Introducing government or owner requirements for BIM adoption can incentivize AEC companies to transition towards BIM-based practices. Additionally, establishing contractual standards that accommodate multidisciplinary organizational structures is crucial. The architecture company's owner said, "I'll accept to move to a BIM-based model if it is the governments or owners' requirement." Moreover, it also required contractual standards that support multidisciplinary actors' organizational structures [40].

The workflow scenarios describe the relationship of actors depending on the type of each scenario and program of construction. However, the current descriptions lack precision in elucidating the specificities behind these relationships. The limited sample size of 16 interviewees and observations from 2 construction projects prevents generalization to the broader context of Cambodia. It is crucial to explore the complexities and have a more comprehensive understanding.

VI. Conclusion

The empirical findings presented in this study provide valuable into the construction sector, particularly in the context of Cambodia. The research sheds light on factors that can contribute to the successful execution of construction projects in the region.

A. Finding

The research found four workflow scenarios. The main factor differs these scenarios in the Cambodian construction sector is the degree and timing of collaboration built between the owner(s), designers, and contractor(s). The study also underscore that traditional approaches still dominate project delivery in Cambodia, even for large-scale projects.

BIM has not yet gained widespread traction in Cambodia. The experts involved in large projects strongly believe that BIM can influence their project to be more productive. Yet, they still resistance to change. Its adoption requires enhanced motivation, training, and practical implementation, with a particular emphasis on government support by establishing the guidelines and regulations framework. This reference shall identify the accurate tasks, duties, and interactions of actors involved in the project. These guides will serve as a light to aiding the industry stakeholders in the successful implementation of BIM in their projects. Furthermore, the standards should align with the vision for a new project delivery approach, such as BIM, capable of addressing cost and schedule performance challenges and fostering more efficient project outcomes. The adoption of BIM in Cambodia necessitates a focus on human resource development. New roles, including BIM modelers, BIM coordinators, and BIM managers, will play pivotal roles in the BIM process.

B. Further work

Given the small number of samples, this research seeks to deliver valuable insights within its boundaries. Despite the modest sample size, the study aims to provide an understanding by recognizing its limitations and highlight the significance of the findings within the given resource constraints. While the findings are based on a smaller cohort, they contribute meaningfully to the existing knowledge in the field, laying the groupwork for future research with a more extensive participant. Future research should aim to expand the sample size to further validate and build upon the current findings. This broader approach will enable a more comprehensive exploration of the collaboration sector and the intricacies of workflow in the construction industry, facilitating a deeper understanding.

Furthermore, further research should concentrate on evaluating the impact BIM adoption within the Cambodian context. This assessment will provide valuable insights into the effectiveness of BIM in enhancing project outcomes, efficiency, and productivity in this specific regional context.

It is imperative to embark on the development of guidelines aimed at facilitating the integration of BIM practices into Cambodia's construction sector. These guidelines will serve as a critical roadmap for industry stakeholders, paving the way for the adoption of more efficient and technologically advanced methodologies. This objective can be achieved by conducting an extensive review of existing BIM guidelines and standards from a global perspective. Notably, the study should encompass Asian countries such as China, South Korea, and Japan, given their significant role as foreign investors in Cambodia. Additionally, European nations, including Belgium and France, which are pivotal members of the International Federation of Consulting Engineers (FIDIC) contract that finds extensive use in Cambodia, should be considered.

Moreover, the examination of BIM guidelines from leading BIM practitioners such as the United Kingdom and Luxembourg, renowned for their advancements in BIM technology, will provide invaluable insights.

These efforts will play a pivotal role in advancing the industry towards heightened efficiency and technological sophistication, ensuring alignment with global best practices in BIM implementation.

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REFERENCE

[1] K. Keth, S. Ben Rajeb, and V. Han, "Collaborative Works in Construction Projects in Cambodia Toward a Workflow Scenario Identification," in *Proc. 13th In. Conf. on Advanced Collaborative Networks, Systems and Applications (COLLA 2023)*, Mar 2023, pp. 8-16. ISSN: 2308-4227, ISBN: 978-1-68558-063-6. [online]. Available: https://www.thinkmind.org/index.php?view=instance&instance=COLLA+2023

[2] National Bank of Cambodia, NBC: Annual Report 2018. [Online]. Available: https://www.nbc.gov.kh/

[3] S. Bodach, "Partnership Ready Cambodia : The construction sector Current situation," Internationale Zusammenarbeit (GIZ) GmbH, Eschborn, Nov. 2019.

[4] S. Durdyev, M. Omarov, and S. Ismail, "Causes of delay in residential construction projects in Cambodia," *Cogent Eng.*, vol. 4, no. 1, 2017, doi: 10.1080/23311916.2017.1291117.

[5] Y. Kang, Z. Jin, C. Hyun, and H. Park, "Construction Management Functions for Developing Countries: Case of Cambodia," *J. Manag. Eng.*, vol. 34, no. 3, pp. 1-9, 2018, doi: 10.1061/(asce)me.1943-5479.0000609.

[6] *Cambodia Industrial Development Policy 2015-2025: Market Orientation and Enabling Environment for Industrial Development*, Royal Government of Cambodia: Council of Ministers, Phnom Penh, Cambodia, 2015.

[7] G. Wu, X. Zhao, and J. Zuo, "Effects of inter-organizational conflicts on construction project added value in China," *Int. J.*

Confl. Manag., vol. 28, no. 5, pp. 695–723, 2017, doi: 10.1108/IJCMA-03-2017-0025.

[8] S. Hamidah, A. Rahman, I. Rohani, and N. Faisol, "The Importance of Collaboration in Construction Industry from Contractors' Perspectives," *Procedia-Soc. Behav. Sci.*, vol. 129, pp. 414–421, 2014, doi: 10.1016/j.sbspro.2014.03.695.

[9] D. W. Halpin and B. A. Senior, Construction Management, 4th ed. U.S., John Wiley & Sons, Inc., 2010.

[10] V. Peansupap and R. Ly, "Evaluating the Impact Level of Design Errors in Structural and Other Building Components in Building Construction Projects in Cambodia," *Procedia Eng.*, vol. 123, pp. 370–378, 2015, doi: 10.1016/j.proeng.2015.10.049.

[11] S. S. Karkala, "Construction Contracts in Cambodia," Construction-property.com, https://construction-property.com/construction-contracts-in-cambodia/ (accessed Nov. 23, 2022).

[12] *Conditions of Contract for Construction*, 1st ed, FIDIC, ISBN: 2-88432-022-9, 1999.

[13] *Plant and Design-Build*, 1st ed, FIDIC, ISBN: 2-88432-023, 1999.

[14] *Conditions of Contract for EPC / Turnkey Projects*, FIDIC, ISBN: 2-88432-021-0, 1999.

[15] *Short Form of Contract*, 1st ed, FIDIC, ISBN: 2-884320245, 1999.

[16] *The FIDIC Contracts Guide: conditions of contract for construction, conditions of contract for plant and design-build, conditions of contract for EPC/Turnkey projects*, 1st ed. FIDIC, 2000.

[17] C. Fellowes, "Introduction to FIDIC contracts," 2012. [Online]. Available: https://www.mayerbrown.com/en/perspectives-events/publications/2012/12/introduction-to-fidic-contracts (assessed Nov. 24, 2023)

[18] K. Shadan and G. Fleming, "Construction Project Management Handbook," Federal Transit Administration, Washington, No. 0015, Mar. 2012.

[19] *L'architecte et Ses Missions [Architect and his Missions],* Order des Architects, Belgium, 2020.

[20] R. Maskuriy, A. Selamat, K. N. Ali, P. Maresova, and O. Krejcar, "Industry 4 . 0 for the Construction Industry — How Ready Is the Industry ?," *Appl. Sci.*, vol. 9, no. 14, p. 1-26, 2019, [Online]. Available: https://doi.org/10.3390/app9142819

[21] *Rectangular Strategy for Growth, Employment, Equity and Efficiency: Building the Foundation Toward Realizing the Cambodia Vision 2050, Phase IV of the Royal Government of Cambodia of the Sixth Legislature of the National Assembly*, Royal Government of Cambodia, Phnom Penh, Cambodia, 2018, [Online]. Available: https://www.mcs.gov.kh/?p=14985

[22] C. Eastman, P. Teicholz, R. Sacks, and K. Liston, BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Architects, Engineers, Contractors, and Fabricators, vol. 53, no. 9. John Wiley & Sons, Inc., Hoboken, New Jersey, 2008.

[23] B. Succar, "Building Information Modelling Maturity Matrix," in Handbook of Research on Building Information Modeling and Construction Informations: Concepts and Technologies, Hershey, PA, USA: Information Science Reference, IGI Publishing, 2010, pp. 65–103.

[24] "Frequently asked questions about the National HR Standards Project," nationalbimstandard.org. https://www.nationalbimstandard.org/faqs#faq1 (accessed Dec. 06, 2022).

[25] R. Matos, F. Rodrigues, H. Rodrigues, and A. Costa, "Building condition assessment supported by Building Information Modelling," *J. Build. Eng.*, vol. 38, p. 1–12, 2021, doi: 10.1016/j.jobe.2021.102186.

[26] "Modeling, Model, and Management: the three M's of BIM and the right BIM tools," biblus.accasoftware.com. https://biblus.accasoftware.com/en/modeling-model-and-management-the-three-ms-of-bim-and-the-right-bim-tools/ (accessed Nov. 23, 2022).

[27] A. Rezaei and N. S. Sistani, "BIM Implementation in Developing Countries," in proc. *10th Int. Congr. Adv. Civ. Eng.,* Ankara, Turkey, 17-19 Oct., 2012,

[28] M. Oraee et al., "Collaboration barriers in BIM-based construction networks: A conceptual model," *Int. J. Proj. Manag.,* vol. 37, no. 6, pp. 839–854, 2019, doi: 10.1016/j.ijproman.2019.05.004.

[29] S. Durdyev, J. Mbachu, D. Thurnell, L. Zhao, and M. R. Hosseini, "BIM Adoption in the Cambodian Construction Industry: Key Drivers and Barriers," *ISPRS Int. J. Geo-Information*, vol. 10, no. 4, pp. 1–14, 2021, doi: 10.3390/ijgi10040215.

[30] T. Tan, K. Chen, F. Xue, and W. Lu, "Barriers to Building Information Modeling (BIM) implementation in China's prefabricated construction: An interpretive structural modeling (ISM) approach," *J. Clean. Prod.,* vol. 219, pp. 949–959, 2019, doi: 10.1016/j.jclepro.2019.02.141.

[31] Y. Zhou, Y. Yang, and J.-B. Yang, "Barriers to BIM implementation strategies in China," *Eng. Constr. Archit. Manag.*, vol. 26, no. 3, pp. 554–574, 2018, doi: 10.1108/ECAM-04-2018-0158.

[32] L. Ma, R. Lovregilo, W. Yi, T. Yiu, and M. Shan, "Barriers and strategies for building information modelling implementation : a comparative study between New Zealand and China," *Int. J. Constr. Manag.,* vol. 23, no. 12, pp. 2067–2076, 2023, doi: 10.1080/15623599.2022.2040076.

[33] H. Liu, R. Zhang, H. Zhang, H. Jiang, and Q. Ju, "Identification and Analysis of Key Barriers of BIM Application for Small- and Medium-Sized Fire Protection Enterprises," *J. Environ. Public Health*, vol. 2022, no. 9, p. 1–19, 2022, doi: https://doi.org/10.1155/2022/9240224.

[34] Q. To, T. Huong, E. C. W. Lou, and N. Le Hoai, "Enhancing BIM Diffusion through Pilot Projects in," *Eng. J.,* vol. 25, no. 7, pp. 167–176, 2021, doi: 10.4186/ej.2021.25.7.167.

[35] T. Nguyen and D. Nguyen, "Barriers in BIM Adoption and the Legal Considerations in Vietnam," *Int. J. Sustain. Constr. Eng. Technol.*, vol. 12, no. 1, pp. 283–295, 2021, doi: https://doi.org/10.30880/ijscet.2021.12.01.027.

[36] T. Dao and P. Chen, "Critical Success Factors and a Contractual Framework for Construction Projects Adopting Building Information Modeling in Vietnam," *Int. J. Civ. Eng.*, vol. 19, pp. 85–102, 2021, doi: 10.1007/s40999-020-00542-3.

[37] N. Akmal, A. Ismail, M. Nazareth, and M. Yousof, "BIM Adoption in Managing Construction Risks Amongst Malaysian Quantity Surveyors : Current Practice and Challenges," *Int. J. Sustain. Constr. Eng. Technol*., vol. 12, no. 3, pp. 166–175, 2021, doi: https://doi.org/10.30880/ijscet.2021.12.03.017.

[38] M. Harris, A. I. C. Ani, A. . Haron, and A. . Husain, "The way forward for Building Information Modelling (BIM) for contractors in Malaysia," *Malaysian Constr. Res. J.*, vol. 15, no. 2, pp. 1–9, 2014, [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85053321777&partnerID=40&md5=053350fad7faf849dd7cb4efb28179c7

[39] Q. To, T. Huong, P. L. Quang, and N. Le Hoai, "Applying Bim and Related Technologies for Maintenance and Quality Management of Construction Assets in Vietnam," *Int. J. Sustain. Constr. Eng. Technol.,* vol. 12, no. 5, pp. 125–135, 2021, doi: https://doi.org/10.30880/ijscet.2021.12.05.013

[40] W. Syazwani, M. Abdullah, S. Ismail, and R. Takim, "Technology-Organisation-Environment Framework for Building Information Modelling (BIM) Adoption Challenges for Contractor's Organisations in Malaysia Journal," *J. Comput. Theor. Nanosci.,* vol. 16, no. 5, pp. 2282–2288, 2019, doi: 10.1166/jctn.2019.7885.

[41] M. Taib, H. Quanhua, and N. Taib, "Building Information Modelling (BIM) Adoption for Cost Engineering Consultant: Case Study of Southern China," *J. Adv. Res. Appl. Sci. Eng. Technol.*, vol. 29, no. 3, pp. 21–36, 2023, doi: https://doi.org/10.37934/araset.29.3.2136

[42] A. Schöttle, S. Haghsheno, and F. Gehbauer, "Defining cooperation and collaboration in the context of lean construction," in *Proc. 22nd Annu. Conf. Int. Gr. Lean Constr. Underst. Improv. Proj. Based Prod. IGLC 2014*, vol. 49, no. 0, pp. 1269–1280, 2014.

[43] D. J. Wood and B. Gray, "Toward a Comprehensive Theory of Collaboration," *J. Appl. Behav. Sci.,* vol. 27, no. 2, pp. 139–162, 1991, doi: 10.1177/0021886391272001.

[44] M. Ilich, B. Becerik, and B. Aultman, "Online collaboration: why aren't we using our tools? Publication," *Publ. of Architectural Eng. Inst. Constr. Inst. ASCE*, vol. 6, p. 10, 2006, doi: 10.1007/s00766-016-0254-6.

[45] M. Oraee, M. R. Hosseini, E. Papadonikolaki, R. Palliyaguru, and M. Arashpour, "Collaboration in BIM-based construction networks: A bibliometric-qualitative literature review," *Int. J. Proj. Manag.*, vol. 35, no. 7, pp. 1288–1301, 2017, doi: 10.1016/j.ijproman.2017.07.001.

[46] F. Détienne, M. Baker, and J. M. Burkhardt, "Perspectives on quality of collaboration in design," *CoDesign*, vol. 8, no. 4, pp. 197–199, 2012, doi: 10.1080/15710882.2012.742350.

[47] E. A. Poirier, D. Forgues, and S. Staub-French, "Understanding the impact of BIM on collaboration: a Canadian case study," *Build. Res. Inf.*, vol. 45, no. 6, pp. 681–695, 2017, doi: 10.1080/09613218.2017.1324724.

[48] G. DeSanctis and R. B. Gallupe, "Foundation for the Study of Group Decision Support Systems.," *Manage. Sci.*, vol. 33, no. 5, pp. 589–609, 1987, doi: 10.1287/mnsc.33.5.589.

[49] C. Ellis and J. Wainer, "A conceptual model of groupware," *in Proc. 1994 ACM Conf. Comput. Support. Coop. Work. CSCW 1994*, no. January 1999, pp. 79–88, 1994, doi: 10.1145/192844.192878.

[50] X. Calixte, S. Ben Rajeb, and P. Leclercq, "Traçabilité de l'usage des outils de conception dans un processus collaboratif [Traceability of the use of design tools in a collaborative process]," in *Proc. SHS Web Conf.*, vol. 47, pp. 1–12, 2018, doi: 10.1051/shsconf/20184701004.

[51] N. Gasmallah, M. Oussalah, and A. Amirat, "Towards a classification for software architecture evolution studies," in *Proc. Conf. Francoph. sur les Archit. Logicielles, CAL 2016*, no. August, pp. 42–51, 2016, doi: 10.3199/JESA.45.1-n.

[52] X. Calixte, G. Gronier, S. Ben Rajeb, and P. Leclercq, "Impact des outils numériques de communication et d'échanges d'information dans les processus de conception collaborative [Impact of digital communication and information exchange tools in collaborative design processes]," 01 Dessign'11, pp. 1–14, 2018.

[53] P. E. Weiseth, B. E. Munkvold, B. Tvedte, and S. Larsen, "The wheel of collaboration tools: A typology for analysis within a holistic framework," in *Proc. ACM Conf. Comput. Support. Coop. Work. CSCW*, pp. 239–248, 2006, doi: 10.1145/1180875.1180913.

[54] J. Clarkson and C. Eckert, Design process improvement: A review of current practice, 2005.

[55] X. Calixte, "Les outils dans l'activité collective médiatisée en conception : traçabilité des usages au sein du processus de conception architecturale [Tools in mediated collective activity in design: traceability of uses within the architectural design process]," Ph.D. dissertation, School of Poly., Univ. Liège and Univ. Libre de Bruxelles, Belgium, 2021.

[56] J. W. Creswell, Qualitative inquiry and research design: Choosing among five approaches. Sage Publications, Inc., 1998.

Using Mobile Technologies for Situating Bite-Sized Learning at the Workplace

Concepts and Recommendations for Implementation in Small and Medium-Sized Enterprises

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***Abstract*— Learning in the workplace is crucial for updating and upskilling the workforce to both new and existing employees. Given the limited opportunities for informal learning due to solitary work conditions or off-site locations, mobile devices like smartphones and wearables such as smart glasses can play a significant role. The aim of this paper is to investigate the extent to which mobile micro-learning can enhance work-related education, with a focus on lightweight, practical applications in learning-deprived environments. Comparative analyses are presented for mobile micro-learning approaches for smartphones and smart glasses based on recent studies, specifically examining their impact on learning and modes of interaction. Based on good practices of recent MML implementations, we present principles for implementation and offer lightweight proof-of-concept models for both handheld devices and smart glasses. This knowledge might be relevant for researchers, small and medium-sized enterprises, practitioners, and others involved in knowledge transfer.**

Keywords-work-based learning; informal learning; mobile micro-learning; smartphone; smart glasses; QR code; peer collaboration.

I. Introduction

Learning within the workplace plays a vital role in keeping today's workforce updated and improving their skills. However, in numerous occupations, chances for informal learning are limited. One example is remote working at the customer site or solitary tasks such as goods delivery. Mobile Micro-Learning (MML), which refers to bite-sized lessons accessed via mobile devices, can serve as a potent tool to boost informal learning in fields where learning opportunities are scarce [1]. While this previous research set the focus on classical MML based on handheld devices such as smartphones and tablets, we now extend our research and compare it against the potential that wearables, in particular smart glasses, offer for informal learning at the workplace.

The power of work-based learning for continuously updating workers' qualifications on the job [2] is a well-known fact, with the lion's share of learning being informal [3]. Informal learning takes place outside a prescribed learning framework (no organized event or package) and without a professional trainer [4]–[6]. It may be conceived as learning *in* work [7]: Embedded ("situated") in daily work routines [1][5], informal learning is initiated in a self-directed manner by workers and triggered by "an internal or external jolt" [5], i.e., on-demand when a specific work task is requiring it. Typical examples are observing, seeking help or feedback from others, discussing, trial and error, reflecting, or searching the intra- or Internet for information [2][5]. Informal learning can hence rely on the interaction with others ("social learning"), or on self-initiated study, practice, and experimentation ("learning by doing") [5].

However, in many occupational fields, the conditions for informal learning at work may be limited: In decentralized work settings (e.g., trains, trucks or delivery drivers, mobile care workers there is little direct interaction between workers). The same is true in highly mechanized settings with large physical distances between workers as well as in settings contexts where a product, such as a fire sprinkler system [8], must be maintained by a specialist working alone at the customer site, and in work environments with a lot of noise or high language diversity among workers – all of which is rather typical for blue-collar work [9], [10]. This hampers learning by observing, asking questions, and receiving feedback [11].

Due to tight schedules or high degrees of automation, many jobs offer little autonomy, which is seen as a crucial condition for experimentation on the job or other self-directed learning activities [10], [12]. Finally, access to codified organizational or external knowledge from the Internet [13] is difficult for those who have no permanent access to a stationary desktop computer. "Learning-deprived" jobs [11] typically suffer from reduced speed and intensity of informal learning at the workplace and jeopardize workforce upskilling.

This paper shows to what extent MML, i.e., learning based on bite-sized learning nuggets delivered by mobile devices [14], can help to improve work-related learning in learning-deprived environments. Learning based on bite-sized learning nuggets has been termed micro-learning or MML as it is typically delivered by mobile devices [14].

We propose a lightweight MML approach that integrates learning units into daily work tasks across both handheld and wearable devices, utilizing self-directed and peer-based learning methods. In this context, we also discuss the role of asynchronous and synchronous forms of MML. This paper surpasses the scope of previous work in [1], with respect to the devices and learning methods used, providing valuable additional insight into the capabilities of mobile-micro-learning at work. First, wearables allow a more seamless experience as learners do not necessarily have to interrupt their workflow while learning. Second, incorporating synchronous forms of learning facilitates direct interactions within the workplace or with experts, which is considered one of the main pillars of informal learning at work. The remainder of the paper is structured as follows: Section II illustrates existing concepts and good practices of micro-learning at the workplace, develops a typology of MML at the workplace, and explores the potential of different types of MML for informal learning. We then sketch design principles for lightweight approaches to anchor informal MML at the workplace and illustrate it with proofs-of-concept for both handheld devices and wearables such as smart glasses (Sections III and IV). In Section V, we discuss our findings, critically reflect on our approach and conclude with an outlook.

II. Related Work and Good Practices

A. Mobile Micro-Learning

Micro-learning typically consists of short learning nuggets (1-5 minutes) that are focused on one narrow topic and that are provided in rich, interactive media formats [14]–[16], e.g., (animated) videos, podcasts, job aids, cheat sheets, flashcards, quizzes or even gamified elements [17] and virtual reality nuggets [18]. Micro-learning is undertaken just-in-time when needed ("on demand") [14]. In this context, mobile technologies are found to naturally match the concept of micro-learning and play an important role in its delivery [19], [20]. The use of mobile devices (e.g., smartphones, tablets, wearables) for learning anytime without being tied to a tightly-delimited physical location [21] is termed mobile learning [20][21]. In what follows, we subsume the above-mentioned learning practices under MML [16], [17]. Note that in the context of informal learning at the workplace, the concepts of micro-learning and micro-training are often used interchangeably, as both refer to short, often digital training or learning activities that can be easily integrated into daily work routines [24], [25]. In this paper, we stick to the term (mobile) micro-learning because it favors somewhat more the notions of self-directed learning that go beyond the mere acquisition of knowledge and skills.

MML has been found to increase learners' motivation and improve knowledge retention thanks to reduced cognitive load and repetition [16], [20], [26]. At the same time, it is an efficient strategy to integrate learning into busy schedules, as well as for employees working in distributed settings [26], [27].

MML seems appropriate for and is widely used in informal learning settings [17], also if implemented at the workplace [16]. It stimulates self-directed learning, allowing learners to consume learning nuggets on-demand when they become aware of a problem or question in a specific situation [28], [29]. MML can be easily embedded in daily work routines and allows for informal work-related learning, also in deprived work settings as described in Section I (decentralized work, limited opportunities for interaction, lack of access to desktop computers). If properly designed, MML is not limited to the acquisition of narrow knowledge or skills, but may also enable higher-order learning such as analysis of a certain topic [28], which is particularly relevant for the experimental and reflective dimensions of informal work-related learning [30].

B. Typology of Mobile Microlearning at the workplace

Classical e-learning theory differentiates between synchronous and asynchronous forms of learning [31], [32]: Synchronous learning happens in real time, with learners and instructors participating simultaneously in activities such as live webinars, virtual classrooms, video conferences, and instructor-led training sessions. It fosters immediate interaction, feedback, and collaboration among participants. On the other hand, asynchronous learning is self-paced and doesn't require real-time involvement of others. Learners access pre-recorded lectures, online courses, reading materials, and assignments at their convenience, offering flexibility in managing their time and progress [ibid.].

In previous research and applications of MML, asynchronous settings dominate [22]. In many settings, it is even the expressed desire to partly or fully replace synchronous forms of learning with MML units [14, p. 792].

In this paper, we suggest the MML Matrix to broaden our perspective and differentiate between different modes of MML, depending on delivery mode and delivery device. Delivery mode depicts whether learning contents are delivered synchronously or asynchronously. Delivery device refers to either handhelds or wearables such as smart glasses which allow one to learn without having to interrupt manual work activities (hands-free). Figure 1 shows the MML matrix.

We do obtain a typology with four variants on how to implement MML. Please note that as this paper deals with the opportunities and challenges of MML for workplace learning, we strictly stick to the concept that MML units should not be longer than 5 minutes and that they should be situated in actual work routines.

As described above, *(1) handheld-MML* refers to MML based on handhelds such as smartphones or tablets. This is the most common type of MML. Synchronous *(2) mobile micro training (MMT)* where learners and trainers directly interact via handheld mobile devices is less frequent. Two potential explanations for this phenomenon are as follows: On the one hand, it may be simply too complex to organize a synchronous micro-training session that ultimately lasts less than 5 minutes – in particular, on-demand when employees need a certain learning bite. On the other hand, handhelds offer much less comfort and functionality for the users when interacting virtually as compared to a classical stationary desktop computer.

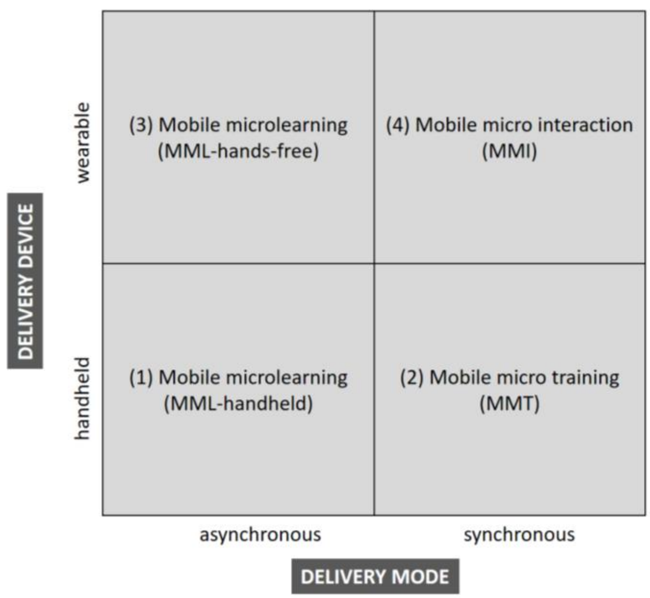

Figure 1. MML Matrix

As compared to handhelds, wearables, especially smart glasses, allow seamless integration of digital information and learning content into the user's working environment. A great benefit is that they enable on-demand access based on allowing hands-free interaction with digital devices so that learners can simultaneously continue with manual operations in their actual work task [33]–[35]. Smart glasses are frequently used for synchronous *(3) mobile micro-interactions (MMI)* between experts and employees with training on-the-job needs [36]. A prominent and widely used example hereby is the remote assistance of technicians maintaining machines and equipment at the customer’s site [37]. As interactions are on-demand and normally consist of short instructions for the technicians, the definition of MML holds in these cases [36].

The last type, *(4) hands-free MML* refers to learning snippets that are delivered through a wearable such as a smart glass without synchronous interaction with a trainer. Many applications of Augmented Reality (AR) are based on this approach and can be found in diverse fields such as industrial assembly [38], healthcare or logistics, and supply chain management [39]. Note that it depends on the length and instructional design of learning snippets whether these applications fall under hands-free MML or not.

In what follows, we first study the most common type of MML, which is handheld MML, and evaluate its potential for informal learning in learning-deprived work settings (Subsection C). In the next step (Subsection D), we then study the chances of hands-free asynchronous MML as well as synchronous micro-interactions (MMI) for informal MML at the workplace based on smart glasses and discuss whether they also can be implemented in learning-deprived work settings.

Four aspects are central to our analysis:

- To what extent can learners self-direct their learning activities?
- Are forms of higher-order learning such as practice, experimentation, feedback, and reflection sufficiently triggered?
- How are learning activities “situated” in actual work routines?
- Do media formats and instructional strategies enable learning among workers who are not used to consuming longer verbal explanations or engaging in self-directed learning?

C. Examples of handheld-MML at the Workplace

Researchers and practitioners highlight the potential of MML for onboarding, ongoing professional qualification, and just-in-time learning [40]–[43]. Typical applications of MML at the workplace are compliance training in occupational safety [44] or information system security [34][35], building knowledge on new and existing products [47]–[49], or improving customer service [43]. Other, albeit less frequent are providing procedural work instructions, e.g., for installing or technical equipment [48] or in medical care [50], and machine use [51]–[53], as well as improving soft skills such as team management or goal setting [44][45]. Prominent examples from the industry are micro-learning initiatives for occupational safety at Walmart or Bloomingdale’s that came with high participation rates and considerable savings [26] or the case of InterContinental Hotels Group to improve the management of complex customer service requests based on micro-learning which helped to reduce onboarding time for new employees from five to two weeks [56].

Recent scientific cases and evaluation studies on MML in real-life work settings cover a great variety of topics, e.g., how to keep costs in large building projects [57], dementia-friendly approaches for staff in neighborhood convenience stores [48][49], methods and approaches in pharmacovigilance [60] as well as a great number of examples from health and medical care [40][51]. Further attempts have been made in the hospitality sector [43], in logistics [62], in ICT [53][54], for public administration and NATO staff [30][55], for librarians [66], for school and university teachers [57][58] as well as for childcare workers [69], and even for employees of dairy farms [70]. Unfortunately, these examples are either not validated in a real-world setting, contain little information about the actual approach, rely on relatively lengthy learning units, or were published before 2020. Recent topical reviews provide even more examples of MML [17][21][24][29][57][61]–[63]. Still, the great majority of these studies were tested in an educational setting, only. In particular, empirical evidence on industrial applications of MML remains rare in this context [73].

Six studies were analyzed in-depth (S1 – S6, see Table 1) to investigate how companies and public organizations implement MML. All were conducted in real-work settings, underwent scientific evaluation with at least 20 participants, and contained sufficient details about implementation.

TABLE I. SELECTED MML STUDIES IN REAL WORKPLACE SETTING

Study	*Country no. of learners*	*Topic and learners*
S1 [60]	>100 countries (N>2000)	Pharmacovigilance (pharmacists, medical doctors, others)
S2 [57]	Norway (N=334)	Cost-efficiency in construction projects (project managers, engineers, architects and other)
S3 [47][48]	Japan (N=62)	Dementia-friendly customer care" (employees in neighborhood convenience stores)
S4 [50]	Australia (N>2000)	Clinical care and no-clinical topics (nurses, medical staff, non-clinical staff)
S5 [67]	USA (N/A)	Teaching skills and learning science (faculty at academic health centers)
S6 [61]	USA (N=26)	Point-of-care training for high-risk, low volume therapies (nurses)

The examples chosen rely on short learning nuggets (< 5 min) and primarily draw on rich, interactive media. Looking at studies published not later than 2020 allows us to get an overview of the state-of-the-art.

Three of the six examples analyzed come with a prescribed learning curriculum to improve specific competencies. S1 to S3 fall in this category. S1 consists of four modules, each comprising 6 to 8 short (2-3 min) videos and a final quiz at the end of every module [60]. Here, learning nuggets are not self-contained as content, practice, and quizzes are separated from each other [48][50]. In such a setting, learners are less expected to engage in self-directed learning but directed toward the predefined learning objectives in small steps, just as in classical e-learning courses [60, p. 1171].

The three other studies, both from the medical and health care field, allow for more self-directed learning: In S4 [50], a group of Australian hospitals provides the micro-learning format "Take 5 – learning for busy people" to their care, medical and non-clinical staff. Learners go through slide decks with condensed information about clinical and non-clinical topics. A learning nugget could explain the procedure in case of a "code blue" (a patient having a medical emergency such as cardiac arrest). Delivery happens browser-based by the internal website so that staff can search for learning nuggets whenever a problem or question arises during the work process. S5 applies an almost identical approach ("Take 5" on teaching skills and learning science for faculty members in academic health centers [67]): A website contains 41 Take-5 videos, jointly with other resources for learning and development. The videos were professionally recorded, prepared in conversational language, and not longer than 800 words. A blueprint suited for just-in-time learning was suggested and used: A teaser catching attention followed by expert advice. Animations were used to improve the retention of central issues.

However, searching indexes of available learning nuggets using a mobile phone as in S4 and S5 is unlikely to be effective in settings where workers tend to be less savvy in the self-directed use of large amounts of digital information.

In S6 [61], nurses can access point-of-care training for high-risk, low-volume therapies based on Quick Response (QR) codes affixed to work equipment. Scanned with a smartphone, they link to short training videos (2-3 minutes).

The preferred format used in the five examples of MML is slide desks, short video clips (sometimes animated), and quizzes. Only one study additionally uses animated videos and mini-simulation games [58]. Text-based information still plays an important role, as in some work situations, learners cannot play the audio, and videos have to come with transcripts, then [60].

The focus of the analyzed MML seems to be more on information and learning and less on practice, experimentation, and reflection. In study 1 [60], learners explicitly point out that they see included quizzes as a valuable instrument for self-assessment, feedback, and reflection, but would like to get more opportunities to practice. In S4 to S6, MML primarily relies on static microsites and video clips and does not offer quizzes or other activities related to reflection or practical exploration.

To sum up, up to now, the potential of MML for informal, work-related learning depicted in Subsection II is realized only very selectively. Instead of offering self-directed learning, MML is often implemented according to the same principles as classical e-learning courses that follow a prescribed path. Repositories of learning nuggets without QR tags in the working environment do offer a higher degree of self-direction in learning but still lack the anchor to actual working routines. Apart from using quizzes to self-assess learning progress, the examples analyzed do not offer strategies to enhance practice, experimentation, and reflection beyond the mere acquisition of knowledge and skills. Finally, as written or spoken text still is the main pillar of micro-learning units, learners with difficulties comprehending written texts and spoken language may be left behind.

D. Examples of wearable MML at the Workplace

The discussed research on MML above appears to predominantly focus on the handheld mobile devices of choice, and asynchronous learning without a trainer. However, in the context of small and medium-sized enterprises (SMEs), there are practical scenarios where employees need to maintain hands-free operations. This is particularly relevant in physically demanding environments, such as cramped technical spaces that necessitate specific postures, or in settings with hygiene constraints where workers handle substances like oil, which may not be compatible with handheld devices.

Smart glasses are emerging products in the field of wearable computing and have the potential to revolutionize jobs [74]. The features of smart glasses that are particularly useful for professionals include overlaying digital information on the physical environment and providing hands-free operation, which can offer task guidance, real-time information, and real-time collaboration. The use of smart glasses for workplace learning has been observed across multiple sectors, for instance in the food industry [75], healthcare [76], and dentistry [77].

Similarly to handheld-MML (see previous Section) publications specifically focused on on-demand MML in a practical setting are still limited, there are nevertheless results to be gleaned from the intersection of workplace learning and smart glasses. Databases were searched for in the title and abstract with the search string "workplace learning AND smart glasses." The databases included Web of Science (7 hits), ERIC–Ebsco (3 hits), IEEE Xplore (4 hits), and PubMed (0 hits) A narrower search string yielded no or fewer results. Most of the studies located using this search string were either conceptual or lab experiments. Other publications that were found focused on requirements and conceptual design, as well as a few publications that have also conducted practice-oriented research.

Hands-free MML. The learning outcomes from recent research involving smart glasses and MML are varied. Learning systems for training have been developed for example for procedural knowledge [78], [79]. Similar to MML with handheld devices, there is the possibility for self-directed learning, allowing personalized learning through scanning QR codes [79]. In a comparative study between handheld mobile devices and smart glasses in museum learning activities, wearable mixed-reality learning activities generally yielded better results than mobile handheld activities in terms of situational interest [80]. This result is promising due to the short-term engagement of situational interest, but the context of the workplace is often more constrained than a museum visit, warranting further research. Another example from the food industry showed that the use of smart glasses led to worse results than traditional video instruction [75]. However, this also seems to depend on the type of task and the form of training.

More practical examples are found in healthcare. In nursing, a pilot study was conducted using speech commands related to tasks such as: “Please select wound treatment”, and all tasks were achieved and experienced as supportive and helpful [8]. Smart glasses were also used as a tool to record real-life situations and used for remote education by synchronous live streaming or watching the recorded material at a later stage. Although the image and audio quality were sufficient, participants in the medical sector felt uneasy diagnosing clinical situations. Also, the connectivity of smart glasses and other devices remains a challenge [78], [80].

These studies indicate that both research and practical application are in the early stages. At the same time, it is clear that promising methods like scanning QR codes in handheld mobile learning can also be applied with smart glasses. However, learning outcomes via smart glasses need to be further examined in a specific context with clear task descriptions to compare results across different contexts and tasks. User perspectives also merit further investigation. While we see positive results in the medical field, remote observation was experienced as uncomfortable by students. This could be due to the specific patient situation concerning privacy, or the students' position having less experience compared to more experienced practitioners.

In summary, in the area of workplace learning with smart glasses as a form of MML, there is a need for more knowledge due to: 1) a lack of studies conducted in practice, 2) sectors in which it is being used, 3) the type of learning tasks, 4) functionalities of smart glasses being used, such as the screen, camera, or a combination thereof, 5) demands on the user, and 6) the objective and subjective learning experience.

Mobile micro interaction (MMI). While voice and video calling via smartphones or other handheld devices are no longer considered exceptional, smart glasses offer these functionalities in a hands-free manner. Smart glasses also allow camera use so that the receiver can view a first-person perspective or the user of smart glasses can receive screen-based instruction. Remote experts can assist smart glasses users via voice or video calling, offering task guidance and real-time information displayed on the screen. This paves the way for remote collaboration between experts and field workers. Remote guidance and collaboration have been developed for both augmented reality and virtual reality [81], such as assistance through visualization and 3D environmental reconstruction [82], or through remote observation and telepresence or teleconferencing as applied in healthcare [83].

The majority of examples in the literature on the application of smart glasses for remote collaboration are found in healthcare. The applications of smart glasses usually involve remote learning or collaboration via a video call [83] or screen-based instruction [84]. In a feasibility study involving teleconferencing, where an intervention team makes a video call with a remote expert paramedic, no differences were found compared to conventional on-site triage by paramedics [83]. This indicates in this specific use case that smart glasses yield results comparable to traditional methods of assessing clinical situations. Beyond teleconferencing, the use of the screen for instructions during the call has been also explored. By using WebRTC, a real-time communications framework for internet browsers and mobile devices, both video calls and custom data, such as drawings, can be facilitated [84] and WebRTC is open-source and available on GitHub [85].

Although proposals for applications have been made and several technical papers are available, there still exists a gap in knowledge focusing on 1) practical application with smart glasses 2) learning focus, 3) the use of smart glasses, and 4) lightweight requirements for implementation, which is particularly important for SMEs.

III. Implementation Approach For Hand-Held MML

Based on our findings in Section II and general design principles for MML [17], [28], [29], we provide recommendations on instructional strategy and technical implementation for a lightweight approach for MML that fosters informal work-related learning in learning-deprived occupational contexts. In this Section, we focus on classical forms of handheld MML. Additional recommendations for designing MML based on wearable devices will be elaborated on in Section IV.

A. Suggestions for Design and Implementation

A good point of departure for designing and implementing MML is the four principles for MML design summarized from earlier research by [28] and validated in a pilot test by [29].

- MML content should fit on the small screens of mobile devices.
- MML should address learners at the moment they feel the need to learn something. Connected to this, MML content should be short (no longer than 5 minutes).
- MML learning nuggets should be designed following an instructional flow that starts with an information snippet to provide an aha moment about the relevance (step 1), followed by instructional snippets with short exercises (quizzes, microgames, ideas for practice and experimentation at the workplace) and instant feedback (step 2). This instructional flow is based on an earlier model of Gagne [86], as cited in [29].
- MML content should be designed in a way that triggers interaction between the learner and the content (e.g., using practical and/or gamified activities).

These principles are an excellent starting point for designing MML for informal work-related learning. To make them even more suited to support and trigger informal workplace-related MML in learning-deprived occupational contexts, the following clarifications and additions are put forth:

- We favor short learning nuggets covering a single topic (1-2 minutes) to fit tight schedules, meet a single, specific question arising from the work context, and reduce cognitive load for learners. This is particularly important in the workplaces we focus on as they are often characterized by high time pressure (e.g., in health and care services) or a noisy work environment [53].
- To trigger learning from within work processes, several approaches [51], [87], [88] have found QR codes affixed to work equipment and locations to be a good practice to link to learning nuggets that might be useful in the respective work context (mobile tagging system).
- The instructional flow suggested helps to design learning nuggets that go beyond the mere acquisition of knowledge and that are still self-contained. However and as pointed out already by [28], besides opportunities for experimentation and practice, learning nuggets for effective workplace learning should also contain practices for reflection, which further enhances higher-order learning.
- Animated videos or visual, interactive work aids should be preferred over text-based and verbal information to enable learners who are less used to consuming large amounts of text or speaking another language.

Revising and complementing the original principles for designing MML content by [28] makes MML more lightweight: First of all, short videos preferably with visualizations and animations lower the barrier for learning for those with less favorable prerequisites for effective informal workplace learning. Second, self-contained learning nuggets that also comprise reflective activities help to enhance higher-order learning processes that are vital for successful workplace learning. Third and last, mobile tagging based on QR codes is a strong trigger to engage in informal learning activities when encountering questions and challenges in the work process.

However, we want to point out that due to its anytime-anyplace nature, asynchronous MML offers by nature only limited potential for learning through experimentation and practice at the workplace (“learning-by-doing”) and even fewer opportunities for “social learning” through direct interaction in terms of observation, feedback, or help-seeking. Some authors point out that it is still an open question of how this can be best achieved [28], and our lightweight approach does not solve this problem, either.

Similarly, implementing MML for informal workplace learning should be also lightweight from a company perspective. This is captured in two additional recommendations:

Recommendation 1 refers to an easy-to-use authoring tool: Learning managers should be able to generate learning nuggets without too much effort, as studies show that time constraints, a lack of technical skills, and inadequate infrastructure are major barriers to the implementation of digitally-supported learning activities [89]. Content types should support the instructional scheme suggested above and support mobile display. H5P allows the user to create HTML5 interactive content and publish it in learning or content management systems such as Moodle, Canvas, WordPress, or Drupal [90]. It is free and open source, appears easier to use than most commercial e-learning authoring tools, and offers many predefined interactive formats that support active learning [91]. Moreover, H5P content can be shared and reused, and open licensing is encouraged [90]. An example of MML that uses H5P to implement interactive content is [63], whereas others use authoring tools such as Articulate Storyline 360 [51] or iSpring Suite [49], or simple video recording and editing software [40][51][57].

Recommendation 2 refers to a secured platform to manage, store, and distribute learning nuggets: In most cases, developing a custom micro-learning platform will not be viable. Instead, many companies use a Learning Management Tool (LMS) with support for eLearning [92]. Most LMS support the authoring and distribution of H5P content. However, introducing and operating a fully-fledged LMS exclusively for MML might be perceived as too high an investment. This will often be the case for SMEs. As an alternative, a more lightweight Content Management System (CMS) such as WordPress seems to be sufficient: It supports H5P content generation and storage, comes with user authentication, and offers an appropriate structure to manage modular learning nuggets [68][69].

To conclude, the proposed principles and recommendations are considered effective in supporting our learners: They need short learning nuggets anchored in the work process that foster engagement in knowledge acquisition, practice, experimentation, and reflection. The low-threshold approach benefits learners in learning-deprived work contexts who may be less adept at self-directed learning. Similarly, creating and distributing learning nuggets is kept simple so that barriers to adoption are low, even for SMEs or companies with little experience with digital learning.

B. *Proof-of-Concept*

As a proof-of-concept, we use a simple website based on WordPress with an H5P plugin as a micro-learning platform. It comes with role-based authentication to protect learning nuggets against unauthorized viewing or editing. With the proof of concept, we demonstrate that implementing MML for informal workplace learning based on a lightweight approach is viable. The proof-of-concept can kick-start further refinements based on stakeholder feedback and lowers adoption barriers for institutions with limited resources to introduce MML at the workplace.

Figure 2 shows how learning managers would generate a learning nugget and attach the automatically generated QR code to a physical object in the work environment, where learners "Scan to learn" with their smartphone camera.

An exemplary learning nugget has been developed and automatically equipped with a QR code. Hereby, an H5P content type "interactive video" is wrapped into an H5P element "KewAR Code" which auto-generates a QR code linking to the readily designed learning nugget when saved. Note that to reference H5P content instead of a URL or other text content, the content type "KewAR Code" has to be extended as suggested by [71]. The H5P plugin in WordPress offers this combination of content types by default and provides comfortable authoring for such learning nuggets.

The learning nugget has been structured as suggested above, following a blueprint that allows triggering higher-order learning (see Figure 3). The example refers to using a car polishing machine in a garage. The starting point is a short video where learners see an employee operating the machine and explaining the most important do's and don'ts, which comes close to "learning by observing". Visual overlays to the video present key aspects, so that verbal or written text is not a main mode of presentation. The video integrates quiz questions with immediate feedback to allow learners to assess their progress. The example you see in Figure 3 is a visual true and false activity the angle at which the machine must be placed on the coating surface. Learners provide their answers by dragging the correct and the wrong options to their respective places.

A sidebar with four activity buttons was added to the video. The first refers back to the relevance of the topic. In our example, an infographic provides an aha moment, showing how expensive it can be if workers apply the polishing machine to the car at the wrong angle and cause scratches to the paint.

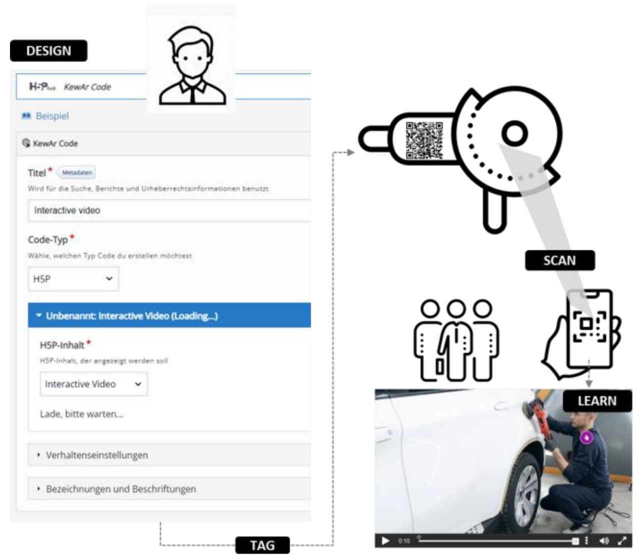

Figure 2. Scan-to-learn system

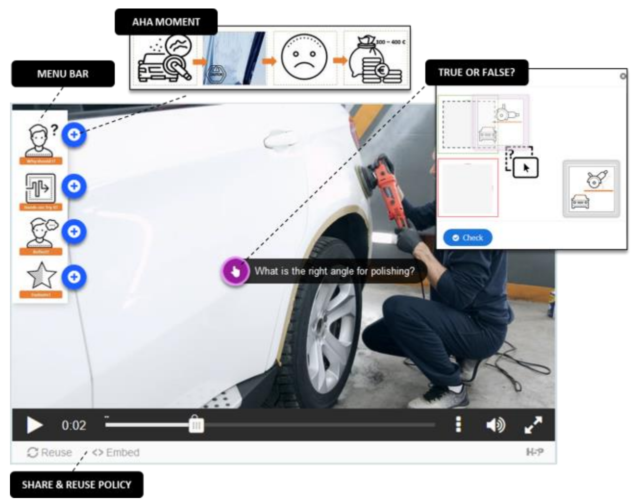

Figure 3. Example of micro-learning nugget

The second button contains ideas for practice and experimentation at the workplace. The third button offers starting points to reflect on the topic of the learning content. Workers can hit the last button to provide feedback on the learning nugget (optional). The activity buttons remain displayed throughout the video, and learners can freely decide whether and when to use them.

The exemplary learning nugget has been produced in less than one hour (excluding video recording) thanks to the existing blueprint and the user-friendly authoring tool in the H5P plugin. We are aware of the fact that commercial micro-learning platforms like EdApp [94] offer all needed functionality for our lightweight approach for handheld MML even in its cost-free version (authoring tool for interactive micro-content, automated generation of QR codes). However, as shown in [1], they come with several drawbacks (limited video upload, mandatory registration, and more click-work for learners). To conclude, our H5P-based approach for handheld MML meets the design recommendations for effective MML at the workplace at a higher level than most existing implementations described in Subsection II.C and offers improved opportunities for digitally-supported activities of informal workplace learning.

IV. Implementation Approach For Synchronous MML Based on Smart Glasses

While the suggestions discussed above in Section III are also applicable to MML with wearable devices, there are additional, specific considerations for smart glasses that warrant attention. In light of the insights gathered from Section II, we offer guidelines for both implementation approaches and technical execution aimed at promoting informal learning in the workplace through a streamlined wearable MML system.

A. *Additional Suggestions for the Design and Implementation based on Smart Glasses*

In practice, the following aspects are important to consider in advance:

- The use of smart glasses for MML must be either necessary or beneficial, such as for hands-free use, first-person perspective camera use, and/or digital overlay through the screen. Refer to the literature on smart glasses adoption for more details [76], [95].
- Reliable connectivity with other devices and the internet is essential. Consider interference from other devices, the space where the user is located, or remote areas [78], [80].
- The task should be compatible with the capabilities and limitations of the specific type of smart glasses being used. Factors to consider include battery life, open or closed screen, video/audio quality, and ease of use [83], [83].
- The cognitive demands of the task must be mapped out and weighed against the cognitive load imposed by using smart glasses [75], [77].

This means that a thorough exploration is essential between the work task, the most suitable wearable devices or type of smart glasses, as well as the anticipated acceptance by future users, to increase the likelihood of successful implementation.

B. *Proof-of-Concept*

Based on an authentic case study, we aim to demonstrate that smart glasses can be effectively utilized for the purpose of remote collaboration in a lightweight manner. There are three ways to implement this namely 1) purchasing a solution from a software developer that is tailored to the needs of the company, 2) using widely available software, and 3) building an Android-based app using open source. Two use cases in healthcare and education will be discussed below.

Figure 4. Illustrative example of smart glasses usage in wound care (shared with permission)

Use case: A patient with a complex wound requires regular visits to a hospital specialist and receives at-home nursing care for wound management. By integrating smart glasses into the home-care regimen, a connection can be established with a remote medical expert located at the hospital.

This allows the expert to evaluate the wound remotely, instruct the community nurse on specific treatments, and ultimately save both the patient (and their caregiver) a trip to the hospital. Additionally, it saves time for the hospital-based expert and provides a direct learning experience for the community nurse [36]. See Figure 4 for an illustrative example using Google Glass. As a proof-of-concept, the Vuzix M400 smart glasses were used in practice instead of Google Glass due to EU regulations. Furthermore, in the use case in wound care, additional software from an external provider was used because of the ease of use. In another use case involving remote assessments of students, Microsoft Teams was utilized.

Another example of this use case also involves Android-supported smart glasses like the Vuzix M400. On this platform, applications can be manually installed as discussed in Section II. With that software, in addition to video broadcasting, it is also possible to selectively share data: for example, drawings on a captured photo or forms. Software for remote expert viewing can be acquired from partners selling smart glasses or through platforms like Microsoft Teams. The rapid and increasing implementation of Microsoft Teams since the COVID-19 pandemic has demonstrated its capability for hosting virtual meetings or broadcasting live video streams [96].

V. Discussion And Conclusions

In the future, we need even more informal learning to support a tremendous level of workforce upskilling as we face major transformation processes related to climate change, population aging, as well as ongoing digitization and automation. However, many jobs offer limited opportunities for informal learning, in particular, if human-human interaction is scarce, access to stationary desktop computers is difficult, and workers are less experienced in self-directed learning.

In Section II, we have shown that the concept of MML closely overlaps with the characteristics of informal learning. Variations of MML (hand-held vs. hands-free and synchronous vs. asynchronous) have been described suggesting the MML matrix as a novel classification approach.

To conclude, Table II evaluates how much informal workplace learning can be enhanced by two common types of MML that we studied in detail: classical handheld MML and mobile micro-interactions (MMI) using smart glasses as an example of wearable devices. For handheld MML, we additionally differentiate between current implementations (column 1), and our novel lightweight approach based on open-source technologies and an H5P instructional blueprint following the design recommendations for MML (column 2).

Best practices analyzed (Section II.C) have shown that MML based on handheld devices and following an asynchronous approach without a trainer is the most broadly used approach to offer mobile micro-learning nuggets at the workplace.

The proof-of-concept for handheld MML in Subsection III shows that based on a lightweight approach using a website with a simple CMS system, H5P interactive technology, and QR codes, the design and distribution of short but engaging MML nuggets are achievable even for novices in the field of micro-learning and SMEs with limited resources for workforce training. Our novel approach reduces the effort needed for content creation – often perceived as time-consuming and cumbersome – to a minimum (see also [1]).

Good practices to overcome the pitfalls of existing implementations of handheld MML (see Subsection II.C) are: Using short videos as a basis, placing visuals and animations over "verbals", designing stand-alone learning nuggets for self-directed learning with integrated quizzes and other activities that foster experimentation and reflection.

TABLE II. MML TYPES AND POTENTIAL FOR INFORMAL LEARNING

Criteria	*handheld MML*	*handheld-MML (H5P)*	*MMI (hands-free)*
	(1)	*(2)*	*(3)*
Self-directing learning activities	●	●●	●●
Forms of higher-order learning	●	●●	●●●
Learning units situated in work process	●	●●	●●●
Media formats and instructional strategies suited for learning-deprieved settings	●	●●	●●
Lightweight implementation (suited for SMEs)	●●	●●●	●
Overall potential for informal workplace learning	6	11	11

Legend: ● some potential ●● medium potential ●●● high potential for informal workplace learning with respect to the criteria evaluated

To sum up, the improved approach to handheld MML based on an H5P-based instructional blueprint fosters the effectiveness of MML for informal workplace learning concerning all the criteria evaluated in Table II. Still, keep in mind that the anytime-anyplace nature restricts the opportunities for the social part of learning at the workplace (see also Section III.a).

The use case presented in Subsection IV depicts how smart glasses as an example of assisted reality wearables allow to smoothly offer hands-free synchronous learning based on micro-interactions (MMI) with experts, without interrupting learners' manual work. Using wearables to bring learning content to the learner tremendously improves the degree learning units are situated in actual work routines as compared to classical handheld.

MML. Moreover, higher-order learning based on practice and experimentation may be fostered when a remote expert guides the learner step-by-step through the respective work routine and provides real-time feedback. Albeit at a distance, MMI even provides some opportunities for social learning. As the main communication modes are verbal and visual when implementing MMI based on smart glasses, access for learners with restricted reading comprehension is somewhat improved as compared to current implementations of handheld MML where understanding written text is often more important. Still, synchronous MMI highly relies on verbal communication which imposes learning barriers for those with limited linguistic abilities.

A major drawback so far for using wearables such as smart glasses for MML at the workplace is however, that it is a rather complex technology, which often pushes back small companies with a high share of blue-collar workers or other occupations outside classical office spaces. Moreover, smart glasses are still in an early phase of diffusion and are currently mainly used for synchronous MMI. This necessitates the involvement of a remote expert. If the expert is from within the company, this can be managed through remote work. However, consulting an external expert is often too costly for small businesses. Asynchronous, hands-free MML where learners can access learning snippets on-demand without interrupting their manual work processes are still rare in publications to date. The reader may object that smart glasses are broadly used for augmenting real work settings with additional information based on AR and VR technologies. We consciously have abstained from including this approach in our paper as authoring AR and VR content demands high investment in terms of time, competency, and money that in most cases, small companies are not able to cover.

In conclusion, both methods discussed in this paper - the enhanced handheld MML approach and the hands-free MMI approach - perform similarly well in promoting informal workplace learning. Table II overview shows that these two methods have complementary strengths and weaknesses. An encouraging avenue for future research could be to combine them: Creating an evidence-based, reusable digital blueprint using interactive, open-source technologies like H5P and adapting them for smart glasses as a hands-free delivery method.

In a broader sense, each of these two feasible methods, when considered individually, still requires further in-depth research, especially in terms of learning outcomes and applying the training to real-world settings with non-academic learners, instead of relying solely on evidence from academic educational environments. Therefore, we recommend generating and implementing more use cases for the improved handheld MML approach and MMI with smart glasses in a real-world context, with a focus on making the implementation easier and reducing barriers to learning in environments that may not yet have ideal informal learning conditions. Knowledge and practical experience in this area are crucial for taking the next steps and are relevant for researchers, small and medium-sized enterprises, practitioners, and other stakeholders in knowledge transfer.

References

[1] K. Frosch, “Scan to Learn: A Lightweight Approach for Informal Mobile Micro-Learning at the Workplace,” The Fifteenth International Conference on Mobile, Hybrid, and On-line Learning (eLmL 2023) IARIA, Apr. 2023, pp. 53–61, ISBN: 978-1-68558-081-0.

[2] K. Smet, I. Grosemans, N. D. Cuyper, and E. Kyndt, “Outcomes of Informal Work Related Learning Behaviours: A Systematic Literature Review,” Scandinavian Journal of Work and Organizational Psychology, vol. 7, pp. 1–18, 2022, doi: 10.16993/sjwop.151.

[3] A. Clardy, “70-20-10 and the Dominance of Informal Learning: A Fact in Search of Evidence,” Human Resource Development Review, vol. 17, pp. 153–178, 2018, doi: 10.1177/1534484318759399.

[4] M. Eraut, “Informal learning in the workplace,” Studies in Continuing Education, vol. 26, pp. 247–273, 2004, doi: 10.1080/158037042000225245.

[5] A. Manuti, S. Pastore, A. F. Scardigno, M. L. Giancaspro, and D. Morciano, “Formal and informal learning in the workplace: a research review,” International Journal of Training and Development, vol. 19, pp. 1–17, 2015, doi: 10.1111/ijtd.12044.

[6] M. Le Clus, “Informal learning in the workplace: A review of the literature,” Australian Journal of Adult Learning, vol. 51, pp. 355–373, 2011.

[7] S. Sambrook, “Factors Influencing the Context and Process of Work-Related Learning: Synthesizing Findings from Two Research Projects,” Human Resource Development International, vol. 8, pp. 101–119, 2005, doi: 10.1080/1367886052000342591.

[8] Sobral, J. and Ferreira, L., “Maintenance of fire sprinkler systems based on the dynamic assessment of its condition,” Process Safety Progress, pp. 84–91, 2016, doi: 10.1002/prs.11740.

[9] D. Hovens, “Workplace Learning through Human-Machine Interaction in a Transient Multilingual Blue-Collar Work Environment,” Journal of Linguistic Anthropology, vol. 30, pp. 369–388, 2020, doi: 10.1111/jola.12279.

[10] J. Decius, N. Schaper, and A. Seifert, “Work Characteristics or Workers’ Characteristics? An Input-Process-Output Perspective on Informal Workplace Learning of Blue-Collar Workers,” Vocations and Learning, vol. 14, pp. 285–326, 2021, doi: 10.1007/s12186-021-09265-5.

[11] S. Skule, “Learning conditions at work: a framework to understand and assess informal learning in the workplace,” International Journal of Training and Development, vol. 8, pp. 8–20, 2004, doi: 10.1111/j.1360-3736.2004.00192.x.

[12] C. P. Cerasoli et al., “Antecedents and outcomes of informal learning behaviors: A meta-analysis,” Journal of Business and Psychology, vol. 33, pp. 203–230, 2018.

[13] D. Song and C. J. Bonk, “Motivational factors in self-directed informal learning from online learning resources,” Cogent Education, vol. 3, publication no. 1205838, 2016, doi: 10.1080/2331186X.2016.1205838.

[14] J. Thillainadesan, D. G. Le Couteur, I. Haq, and T. J. Wilkinson, “When I say … microlearning,” Med Educ, vol. 56, pp. 791–792, 2022, doi: 10.1111/medu.14848.

[15] T. Hug, “Mobile Learning as ’Microlearning’: Conceptual Considerations towards Enhancements of Didactic Thinking,” International Journal of Mobile and Blended Learning, vol. 2, pp. 47–57, 2010, doi: 10.4018/jmbl.2010100104.

[16] Y.-M. Lee, “Mobile microlearning: a systematic literature review and its implications,” Interactive Learning Environments, pp. 4636-4651, 2021, doi: 10.1080/10494820.2021.1977964.

[17] A. Taylor and W. Hung, “The Effects of Microlearning: A Scoping Review,” Education Tech Research Dev, vol. 70, pp. 363–395, 2022, doi: 10.1007/s11423-022-10084-1.

[18] R. Horst, R. Naraghi-Taghi-Off, L. Rau, and R. Dorner, “Bite-Sized Virtual Reality Learning Applications: A Pattern-Based Immersive Authoring Environment,” JUCS, vol. 26, pp. 947–971, 2020, doi: 10.3897/jucs.2020.051.

[19] K. Leong, A. Sung, D. Au, and C. Blanchard, “A review of the trend of microlearning,” Journal of Work-Applied Management, vol. 13, pp. 88–102, 2020, doi: 10.1108/JWAM-10-2020-0044.

[20] M. S. Shail, “Using Micro-learning on Mobile Applications to Increase Knowledge Retention and Work Performance: A Review of Literature,” Cureus Journal of Medical Science, vol. 11, publication no. e5307, 2019, doi: 10.7759/cureus.5307.

[21] C. Pimmer and N. Pachler, “Mobile learning in the workplace: Unlocking the value of mobile technology for work-based education,” in M. Ally and Tsinakos, A., Mobile Learning Development for Flexible Learning: Athabasca: AU Press, pp. 193–203, 2014.

[22] M. M. Grant, “Difficulties in defining mobile learning: analysis, design characteristics, and implications,” Education Tech Research Dev, vol. 67, pp. 361–388, 2019, doi: 10.1007/s11423-018-09641-4.

[23] D. Yu, Z. Yan, and X. He, “Capturing knowledge trajectories of mobile learning research: A main path

analysis," Educ Inf Technol, vol. 27, pp. 7257–7280, 2022, doi: 10.1007/s10639-021-10869-6.

[24] R. C. Peebles, I. K. Nicholson, J. Schlieff, A. Peat, and D. J. Brewster, "Nurses' just-in-time training for clinical deterioration: Development, implementation and evaluation," Nurse Education Today, vol. 84, publication no. 104265, 2020, doi: 10.1016/j.nedt.2019.104265.

[25] H. Lukosch and P. de Vries, "Supporting Informal Learning at the Workplace," International Journal of Advanced Corporate Learning (iJAC), vol. 2, pp. 39–44, 2009.

[26] R. Sankaranarayanan, J. Leung, V. Abramenka-Lachheb, G. Seo, and A. Lachheb, "Microlearning in Diverse Contexts: A Bibliometric Analysis," TechTrends, vol. 67, pp. 260-276 2022, doi: 10.1007/s11528-022-00794-x.

[27] Y. Y. Ho et al., "Turning Coffee Time into Teaching Moments Through Bite-Sized Learning for Adult Learners," The Journal of Continuing Higher Education, pp. 1–16, 2022, doi: 10.1080/07377363.2021.2024000.

[28] I. Jahnke, Y.-M. Lee, M. Pham, H. He, and L. Austin, "Unpacking the Inherent Design Principles of Mobile Microlearning," Tech Know Learn, vol. 25, pp. 585–619, 2020, doi: 10.1007/s10758-019-09413-w.

[29] Y.-M. Lee, I. Jahnke, and L. Austin, "Mobile microlearning design and effects on learning efficacy and learner experience," Education Tech Research Dev, vol. 69, pp. 885–915, 2021, doi: 10.1007/s11423-020-09931-w.

[30] R. Helyer, "Learning through reflection: the critical role of reflection in work-based learning (WBL)," Journal of Work-Applied Management, vol. 7, pp. 15–27, 2015, doi: 10.1108/JWAM-10-2015-003.

[31] H. Alzahrani et al., "Students' Perception of Asynchronous versus Synchronous Distance Learning during COVID-19 Pandemic in a Medical College, Southwestern Region of Saudi Arabia," BMC Medical Education, vol. 23, 2023. doi: 10.1186/s12909-023-04034-5.

[32] S. Z. M. Osman, "Combining Synchronous and Asynchronous Learning: Student Satisfaction with Online Learning using Learning Management Systems," Journal of Education and e-Learning Research, vol. 9, pp. 147–154, 2022, doi: 10.20448/jeelr.v9i3.4103.

[33] B. Kress, "See through optical architectures for wearable displays," Imaging and Applied Optics, publication no. JTu1A.1, 2014, ISBN: 978-1-55752-308-2.

[34] G. O. Klein, K. Singh, and J. von Heideken, "Smart Glasses–A New Tool in Medicine," Studies in health technology and informatics, vol. 216, pp. 901–901, 2015.

[35] M. Tsubosaka et al., "Additional visualization via smart glasses improves accuracy of wire insertion in fracture surgery," Surgical Innovation, vol. 24, pp. 611–615, 2017.

[36] N. Zuidhof, O. Peters, P.P. Verbeek, and B. Allouch, "Appropriation of smart glasses: a qualitative study from multiple perspectives on long-term use of smart glasses in healthcare", 2023 (submitted, under review).

[37] A. Hariharan, M. Risling, A. Felic, and T. Ostertag, "Integration of Smart Glasses for Knowledge Transfer in Industrial Remote Maintenance: Learnings from Practice," in Extended Reality and Metaverse, T. Jung, M. C. tom Dieck, and S. M. Correia Loureiro, Eds. Cham: Springer International Publishing, pp. 297–308, 2023, doi: 10.1007/978-3-031-25390-4_26.

[38] O. Danielsson, M. Holm, and A. Syberfeldt, "Augmented reality smart glasses in industrial assembly: Current status and future challenges," Journal of Industrial Information Integration, vol. 20, publication no. 100175, 2020, doi: 10.1016/j.jii.2020.100175.

[39] A. Rejeb, J. G. Keogh, G. K. Leong, and H. Treiblmaier, "Potentials and challenges of augmented reality smart glasses in logistics and supply chain management: a systematic literature review," International Journal of Production Research, vol. 59, pp. 3747–3776, 2021, doi: 10.1080/00207543.2021.1876942.

[40] Y.-M. Lee, "Mobile microlearning: a systematic literature review and its implications," Interactive Learning Environments, vol. 31, pp. 1–16, Sep. 2021, doi: 10.1080/10494820.2021.1977964.

[41] A. Dolowitz, J. Collier, A. Hayes, and C. Kumsal, "Iterative Design and Integration of a Microlearning Mobile App for Performance Improvement and Support for NATO Employees," TechTrends, vol. 67, pp. 143–149, 2023, doi: 10.1007/s11528-022-00781-2.

[42] P. S. Hogle, "Microlearning in Corporate Settings," in Microlearning in the Digital Age, J. R. Corbeil, B. H. Khan and M. E. Corbeil, Eds. New York: Routledge, pp. 139–154, 2021.

[43] M. J. Dolasinski and J. Reynolds, "Microlearning: A New Learning Model," Journal of Hospitality & Tourism Research, vol. 44, pp. 551–561, 2020, doi: 10.1177/1096348020901579.

[44] A. M. Selko, "Is Micro Learning a Better Way to Train Our Workforce?" Jul. 2019. [Online]. Available from: https://www.industryweek.com/talent/article/22027877/is-micro-learning-a-better-way-to-train-our-workforce (last accessed: Dec 1, 2023).

[45] J. Kävrestad and M. Nohlberg, "Context-Based Micro Training: A Framework for Information Security Training," in Human Aspects of Information Security and Assurance, N. Clarke and S. Furnell, Eds. Cham: Springer International Publishing, pp. 71–81, 2020.

[46] J. Kävrestad, "Context-Based Micro-Training: Enhancing cybersecurity training for end-users," University of Skövde, School of Informatics, Skövde, 2022. [Online]. Available from: http://urn.kb.se/resolve?urn=urn:nbn:se:his:diva-21819 (last accessed: Dec 1, 2023).

[47] K. Govender and M. Madden, "The effectiveness of micro-learning in retail banking," South African Journal of Higher Education, vol. 34, pp. 74–94, 2020.

[48] A. Hoberg, C. Piele, and J. Veit, "Mobile Learning for Smart Home/Smart Grid" ["Mobiles Lernen für Smart Home/Smart Grid,"] HMD Praxis der Wirtschaftsinformatik, vol. 50, pp. 80–94, 2013.

[49] G. Dutton, "Game To Train." 2018. [Online]. Available from: https://pubs.royle.com/article/Game+To+Train/3177437/523001/article.html (last accessed: Dec 1, 2023).

[50] N. May, J. Young, and L. Gillman, "Take 5: Designing and evaluating 5-minute eLearning for busy hospital staff," Focus on Health Professional Education, vol. 22, pp. 60–71, 2021, doi: 10.3316/INFORMIT.120475124591839.

[51] S. Jaschke, "Mobile learning applications for technical vocational and engineering education: The use of competence snippets in laboratory courses and industry 4.0," in 2014 International Conference on Interactive Collaborative Learning (ICL), Dec. 2014, pp. 605–608. doi: 10.1109/ICL.2014.7017840.

[41] M. S. Billert et al., "Vocational Training With Microlearning—How Low-Immersive 360-Degree Learning Environments Support Work-Process-Integrated Learning," IEEE Transactions on Learning Technologies, vol. 15, pp. 540–553, 2022, doi: 10.1109/TLT.2022.3176777.

[53] T. Weinert, M. Billert, M. T. de Gafenco, A. Janson, and J. M. Leimeister, "Designing a Co-creation System for the Development of Work-process-related Learning Material in Manufacturing," Comput Supported Coop Work, vol. 32, pp. 5–53, 2023, doi: 10.1007/s10606-021-09420-5.

[54] I. Goller, C. Kobe, R. Tscharner, S. Jud, and C. Hertach, "Using Micro Interventions to Develop Team Competencies," Conference of the International Society for Professional Innovation Management (ISPIM), Jun. 2021, pp. 1–9.

[55] Zavvy, "Creating a training routine for leaders at Freeletics." [Online]. Available from: https://www.zavvy.io/case-studies/freeletics (last accessed: Dec 1, 2023).

[56] RapL, Streamlining Employee Onboarding with Microlearning. [Online]. Available from: https://getrapl.com/blog/streamlining-employee-onboarding-with-microlearning/ (last accessed: Dec 1, 2023).

[57] T. Beste, "Knowledge Transfer in a Project-Based Organization Through Microlearning on Cost-Efficiency," The Journal of Applied Behavioral Science, 2021, doi: 10.1177/00218863211033096.

[58] H. Matsumoto, Y. Hagiwara, N. Yamamoto-Mitani, and A. Igarashi, "A randomized control trial for ReDeSign: A dementia-friendly mobile microlearning training for store workers in Japan," The Gerontologist, vol. 20, pp. 1–11, 2023, doi: 10.1093/geront/gnac182.

[59] H. Matsumoto, A. Igarashi, Y. Hagiwara, and N. Yamamoto-Mitani, "Relational Design for Dementia and Job Significance (ReDeSign): Study protocol for a randomized controlled trial of an online dementia training for retail workers," Contemporary Clinical Trials Communications, vol. 26, publication no. 100896, 2022, doi: 10.1016/j.conctc.2022.100896.

[60] A. Hegerius, P. Caduff-Janosa, R. Savage, and J. Ellenius, "E-Learning in Pharmacovigilance: An Evaluation of Microlearning-Based Modules Developed by Uppsala Monitoring Centre," Drug Saf, vol. 43, pp. 1171–1180, 2020, doi: 10.1007/s40264-020-00981-w.

[61] M. Robalino, "Intervention Development: Quick Response Code Implementation for Point-of-Care Training Needs in the Emergency Department," Journal of Emergency Nursing, vol. 47, pp. 938–943, 2021, doi: 10.1016/j.jen.2021.08.003.

[62] H. Lukosch, S. Kurapati, D. Groen, and A. Verbraeck, "Microgames for Situated Learning: A Case Study in Interdependent Planning," Simulation & Gaming, vol. 47, pp. 346–367, 2016.

[63] U. Zandbergs, J. Judrups, E. Plane, and R. Uscins, "Improvement of microlearning with help of learning analytics in enterprises," presented at the 20th International Scientific Conference Engineering for Rural Development, pp. 1584–1589, 2021 doi: 10.22616/ERDev.2021.20.TF338.

[64] L. Butgereit, "Gamifying mobile micro-learning for continuing education in a corporate IT environment," in 2016 IST-Africa Week Conference, May 2016, pp. 1–7. doi: 10.1109/ISTAFRICA.2016.7530597.

[65] J. I. Criado, C. Herranz, and J. Villodre, "Informal Virtual Learning in the Public Sector: Educating Public Servants in Digital Social Innovation Environments," in The Palgrave Handbook of the Public Servant, H. Sullivan, H. Dickinson, and H. Henderson, Eds. Cham: Springer International Publishing, pp. 1–18, 2020. doi: 10.1007/978-3-030-03008-7_46-1.

[66] I. Isibika and C. Zhu, "Microlearning training intervention for librarians: design and development," 16th annual International Technology, Education and Development Conference (INTED2022), pp. 7432–7440, 2022.

[67] L. N. Dyrbye, A. L. Bergene, A. N. L. Hunderfund, and H. A. Billings, "Reimagining Faculty Development Deployment: A Multipronged, Pragmatic Approach to Improve Engagement," Acad. Med., vol. 97, pp. 1322–1330, 2022, doi: 10.1097/ACM.0000000000004688.

[68] T. Shamir-Inbal and I. Blau, "Micro-learning in designing professional development for ICT teacher leaders: The role of self-regulation and perceived learning," Professional Development in Education, vol. 48, pp. 734–750, Oct. 2022, doi: 10.1080/19415257.2020.1763434.

[69] E. Pölzl-Stefanec and C. Geißler, "'Micro-steps' on the route to successful online professional development for Austrian Early Childhood Educators," International Journal of Educational Research, vol. 115, publication no. 102042, 2022, doi: 10.1016/j.ijer.2022.102042.

[59] A. Hesse et al., "Short communication: Microlearning courses are effective at increasing the feelings of confidence and accuracy in the work of dairy personnel," Journal of Dairy Science, vol. 102, pp. 9505–9511, 2019, doi: 10.3168/jds.2018-15927.

[71] S. Nanjappa, V. Ghosh, S. Acharya, H. S. Mukerjee, and V. Stl, "Microlearning in Corporate Settings: Practitioner Perspectives," Human Resource Development International, pp. 1–8, 2022, doi: 10.1080/13678868.2022.2160688.

[72] C.-L. Lai, "Trends and research issues of technology-enhanced self-regulated learning in the mobile era: a review of SSCI journal articles," International Journal of Mobile Learning and Organisation, vol. 16, pp. 150–172, 2022, doi: 10.1504/IJMLO.2022.121879.

[73] E. Roth, M. Moencks, G. Beitinger, A. Freigang, and T. Bohné, "Microlearning in Human-centric Production Systems," 2022 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), 2022, pp. 0037–0041, doi: 10.1109/IEEM55944.2022.9989589.

[74] L. Kolodzey, P. D. Grantcharov, H. Rivas, M. P. Schijven, and T. P. Grantcharov, "Wearable technology in the operating room: a systematic review," BMJ Innovations, vol. 3, pp. 55–63, 2017, doi: 10.1136/bmjinnov-2016-000133.

[75] J. Clark, P. Crandall, R. Pellegrino, and J. Shabatura, "Assessing Smart Glasses-Based Foodservice Training: An Embodied Learning Theory Approach," Canadian Journal of Learning & Technology, vol. 45, pp. 1-19, 2019, doi: 10.21432/cjlt27838.

[76] N. Zuidhof, S. Ben Allouch, O. Peters, and P.-P. Verbeek, "Perspectives on the Acceptance and Social Implications of Smart Glasses: A Qualitative Focus Group Study in Healthcare," International Journal of Human–Computer Interaction, pp. 1–11, 2022, doi: 10.1080/10447318.2022.2111046.

[77] J. Kuhn, P. Lukowicz, M. Hirth, A. Poxrucker, J. Weppner, and J. Younas, "GPhysics-Using Smart Glasses for Head-Centered, Context-Aware Learning in Physics Experiments," IEEE Transactions on Learning Technologies, vol. 9, pp. 304–317, 2016, doi: 10.1109/TLT.2016.2554115.

[78] S. Hobert and M. Schumann, "LearningGlasses App-A smart-glasses-based learning system for training procedural knowledge," 16th European Conference on e-Learning, 2017, pp. 185-194.

[79] Y.-B. Lin, D.-J. Deng, I. You, and C.-C. Lin (Eds.), "IoT as a Service", Proceedings of the Third International Conference IoTaaS, Cham: Springer, 2017.

[80] A. Sridhar, J. Burrows, C. Nameth, and Y. M. Huang, "Real Time, Remote, and Recorded: Medical Student Experiences with Smart Glasses in Obstetrical Simulation," Southern Medical Journal, vol. 116, pp. 686–689, 2023, doi: 10.14423/SMJ.0000000000001585.

[81] J. Venerella, T. Franklin, L. Sherpa, H. Tang, and Z. Zhu, "Integrating AR and VR for mobile remote collaboration," Adjunct Proceedings of the 2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR-Adjunct, 2019, pp. 104–108. doi: 10.1109/ISMAR-Adjunct.2019.00041.

[82] M. Tait and M. Billinghurst, "The Effect of View Independence in a Collaborative AR System," Computer Supported Cooperative Work: CSCW: An International Journal, vol. 24, pp. 563–589, 2015, doi: 10.1007/s10606-015-9231-8.

[83] M. X. Cicero et al., "Do You See What I See? Insights from Using Google Glass for Disaster Telemedicine Triage," Prehospital and Disaster Medicine, vol. 30, pp. 4–8, 2015, doi: 10.1017/S1049023X1400140X.

[84] M. Spitzer, I. Nanic, and M. Ebner, "Distance learning and assistance using smart glasses," Education Sciences, vol. 8, 2018, doi: 10.3390/educsci8010021.

[85] Muaz-khan, "RTCMultiConnection - WebRTC JavaScript Library", [Online]. Available from: https://github.com/muaz-khan/RTCMultiConnection (last accessed: Dec 1, 2023).

[86] R. M. Gagne, L. Briggs, and W. W. Wager, *Principles of Instructional Design Fort Worth*, San Djego: HBJ College Publishers, 1992.

[87] S. M. Hirsch, E. Bueno, and K. C. Tenure, "Quick Response Codes: An Innovative Approach to Just-in-Time Education," Journal of Neuroscience Nursing, vol. 52, pp. 308–310, 2020, doi: 10.1097/JNN.0000000000000550.

[88] C. T. Karia, A. Hughes, and S. Carr, "Uses of quick response codes in healthcare education: a scoping review," BMC Med Educ, vol. 19, 2019, doi: 10.1186/s12909-019-1876-4.

[89] D. O'Doherty, M. Dromey, J. Lougheed, A. Hannigan, J. Last, and D. McGrath, "Barriers and solutions to online learning in medical education – an integrative review," BMC Medical Education, vol. 18, 2018, doi: 10.1186/s12909-018-1240-0.

[90] M. Fischer, M. Rohweder, and P. Dewan, "H5P (product review)," vol. 42, pp. 178–180, 2021.

[91] G. Kiryakova, "Engaging Learning Content for Digital Learners," TEM J., vol. 11, pp. 1958–1964, 2022, doi: 10.18421/TEM114-65.

[92] R. P. Díaz Redondo, M. Caeiro Rodríguez, J. J. López Escobar, and A. Fernández Vilas, "Integrating micro-learning content in traditional e-learning platforms," Multimed Tools Appl, vol. 80, pp. 3121–3151, 2021, doi: 10.1007/s11042-020-09523-z.

[93] T. Javorcik, "Content Management System for Creating Microlearning Courses," in 2021 International Symposium on Educational Technology (ISET), 2021, pp. 223–227. doi: 10.1109/ISET52350.2021.00053.

[94] S. Bratt, "Essential strategies for developing mobile-based micro-learning," presented at the EdMedia+ Innovate Learning, Association for the Advancement of Computing in Education (AACE), 2020, pp. 17–25.

[95] M. John-Otumu and S. Amadi, "Issues on Smart Glasses Technology Adoption," International Journal of Advanced Trends in Computer Applications (IJATCA), vol. 7, pp. 6–11, 2020.

[96] J. Mehta, T. Yates, P. Smith, D. Henderson, G. Winteringham, and A. Burns, "Rapid implementation of Microsoft Teams in response to COVID-19: One acute healthcare organisation's experience," BMJ Health and Care Informatics, vol. 27, e100209, 2020, doi: 10.1136/bmjhci-2020-100209.

Affordable Sensors for Agricultural Applications

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***Abstract*— Agricultural sensors are crucial in improving crop yields and reducing resource waste. It has led researchers to develop affordable sensors that can be easily integrated into existing farming systems. The developing of low-cost sensors involves adequate materials and simple manufacturing methods, ensuring reliable and accurate measurements. Embrapa Instrumentation's has been putting efforts for the low-cost agricultural sensor's development. This article discusses a sensor for soil moisture measurement using the microwave technique; a sensor for measuring the apparent electrical conductivity of soils; a sensor for measuring water and plant relationships; and a sensor for evaluating spray solution concentration to weeds control to improve crop yield and reduce the use of water. Such affordable sensors in agriculture can provide an effective and sustainable solution to enhance productivity into small and medium farms, as well as increasing in food security and supporting sustainable agriculture.**

Keywords - affordable sensors; soil moisture; soil electrical conductivity; water-plant measuring; spray quality; pest control.

I. Introduction

This paper presents an extended version of a previous study presented at the Eighth International Conference on Advances in Sensors, Actuators, Metering and Sensing (ALLSENSORS 2023), organized by the International Academy, Research and Industry Association (IARIA), and held in Venice in April 2023 [1].

The applications of sensors in general, and more specifically, affordable sensors, are the basis for developing devices for instrumentation, automation, precision agriculture, and digital agriculture.

The global agricultural sensors market size was valued at USD 4.74 billion in 2021. It is expected to reach USD 16.83 billion by 2030, growing at a Compound Annual Growth Tate (CAGR) of 15.12% during the forecast period (2022–2030) [2].

The low-cost sensor is a technology initially developed for consumer and research applications. Competitive and low-cost due to economies of scale, these sensor technologies allow new applications or more economical use of sensors in production and environments [3][4].

Despite being used in research, most field sensors are still in their infancy in their commercial relationship. Soil moisture sensors can be mentioned, sensors that can correlate fertility, scales that could indicate performance, sensors, and indicators of pests and diseases, among others, and if they were present in the field, they could be connected to IoT (Internet of things) [5].

The review by Kayad and their colleagues highlights the numerous advantages of using sensor applications to enhance the quality of life for humans. The comprehensive paper covers various topics, such as soil and plant sensing, farm management, and post-harvest applications. The examples illustrate how sensors can measure soil moisture content, keep tabs on drain pipes, monitor topsoil displacement during harrowing, prevent spray drift in vineyards, evaluate winter wheat and tree health with thermography, and remotely oversee the various agricultural processes. Furthermore, the review delves into the digitalization of food systems and the utilization of archived data from plowing operations. Lastly, the paper explores the potential of post-harvest sensor applications for sunflower seeds [6].

Below, one may find a brief discussion of affordable sensors for agriculture that were developed at Embrapa Instrumentation. In the next sections there are the descriptions of the recent development of affordable sensors, which are: a sensor for measuring soil moisture using microwaves with two techniques (waveguide and free space); a system for measuring the apparent electrical conductivity of ECa soils; a sensor for measuring the water and plant relationship; and a sensor to evaluate spray solution concentration to control weeds to improve crop yield and reduce water.

The sensors listed have something in common: they are affordable and designed to be used in agricultural environments. They are capable of measuring different aspects of the environment, such as soil, water, plants, and to provide support for weed control. Additionally, they can also be integrated into IoT technologies.

II. SENSOR FOR SOIL MOISTURE MEASUREMENT, USING MICROWAVE TECHNIQUES

The content and availability of water in the soil are parameters of fundamental importance in the various fields of basic and applied science, as well as in technologies for agriculture, geology, meteorology, hydrology, and various areas of engineering.

The most used techniques for measuring soil water are gravimetric, neutron moderation and gamma-ray attenuation, Time Domain Reflectometry (TDR), and remote sensing.

The choice of microwave frequency, 10 GHz, was based on two main reasons: first, because this is an intermediate frequency, between maximum absorption by water and maximum penetration of the electromagnetic wave in the water-soil system; second, because oscillators are commercially found. tuned to that frequency. Under normal temperature conditions, in the frequency range of 1.0 GHz to 30 GHz, the water power constant is in the range of 40 to 80 and the loss tangent varies from 0.15 to 1.20. Most dry matter, in particular dry soil, has a dielectric constant of the order of 1 to 5 and losses. Between 0.001 and 0.050, i.e., differences in this order of magnitude.

Through the interaction of electromagnetic waves, at microwave frequency, with the water-soil system, greater or lesser attenuation of the signal is obtained depending on the volumetric moisture content present.

Figure 1 presents a system for measuring soil moisture content that uses microwave signal transmission and reception through the waveguide technique, in the X band, with an operating frequency of 10 GHz and a power of 25 mW. In tests carried out at the laboratory level, we proved the correlation of the attenuation in dB with the volumetric humidity in clayey, sandy, and glass microsphere soils [7].

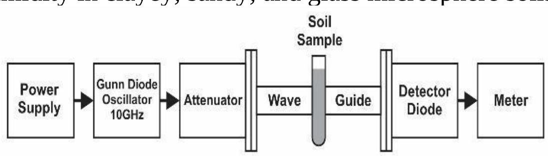

Figure 1. A system for measuring soil moisture content that uses microwave signal transmission and reception through the waveguide technique.

The electrical specifications, provided by the manufacturer, of the gunn system used are listed in Table I.

Figure 2 presents the results that show the influence of water in the water-soil system, in the attenuation of microwaves, through the relation of the attenuation of the signal in dB by the volumetric soil moisture in sandy soil (1.20 < soil density (g/cm3) < 1.26), clayey (0.83 < soil density (g/cm^3) < 0.92)) and glass microsphere (1.13 < soil density (g/cm^3) < 1.19)). The error in sample preparation was 4.7%. All measurements were conducted under laboratory conditions (room temperature ~23.0 ± 0.5 °C and Relative Humidity (RH%) equal to 36%).

The combination of sand, lime, and clay mixed with water can affect the microwave signal and the detection of soil through microwaves. A study conducted by Schmugge [8] delved into the influence of soil texture on soil detection through microwaves. By analyzing the behavior of water molecules when introduced to soil, researchers could understand the effect of soil removal better.

When water molecules align with an applied field, they exhibit a high dielectric constant. However, factors such as freezing, high frequencies, or a solid connection to soil particles can restrict water's free molecular rotation, decreasing its dielectric constant. When first added to dry soil, the initial water molecules attach to the particle surface due to physical-chemical interactions, leading to a slight increase in the dielectric constant. As more water is added and surpasses a transitional level, these molecules move away from the particle surface and contribute to a more significant increase in the power constant. The water retention of soil depends on particle size or texture distribution, with clay soils possessing a larger water surface and retaining more water. Consequently, they bind more firmly to water compared to sandy soil. The transition point occurs in clay soil at higher moisture levels than in sandy soil.

TABLE I. OPERATING CHARACTERISTICS OF THE GUNN SYSTEM

RF central frequency	10,250MHz-4V varactor bias
RF output power	25 mW
Tuning: mechanical **Electronics**	±100MHz 60 MHz Minimum
Stability in frequency	350 kHz/°C
RF power vs temperature and tuning voltage	6 dB max
Noise figure	12 dB max
Entry requirements: **Gunn Voltage** **Gunn Current** **Tuning Voltage**	 + 10 Vdc 500 mA maximum +1 a+20 volts
Temperature of operation	30 °C to +70 °C

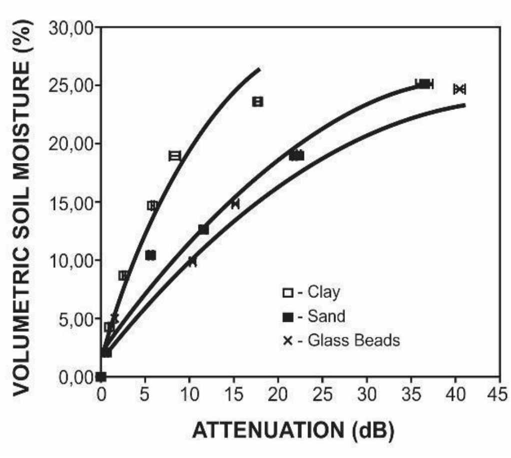

Figure 2. The attenuation calibration curve in dB, as a function of the volumetric soil moisture of the samples.

A network analyzer, model 8510 from Hewlett-Packard, was used, evaluating the parameter insertion loss S_{21} (dB) to compare with the results obtained in the attenuation system in dB. Figure 3 presents the results for all samples with a linear regression where their r^2 was 0.976.

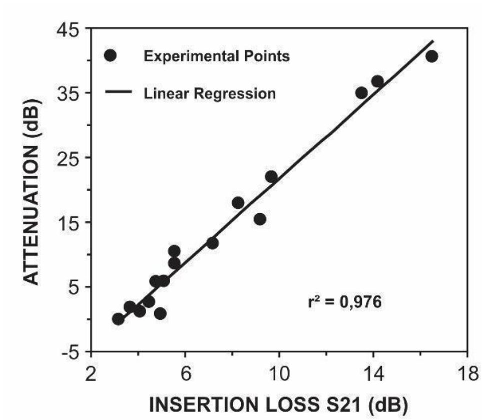

Figure 3. Comparison between the results obtained with the proposed system and those obtained the insertion loss S_{21} (dB), using the 8510 HP network analyzer.

Investigating the behavior of plant root system growth as a function of soil water is essential for studying root physiology. Figure 4 shows a non-invasive tool based on the transmittance of electromagnetic waves in the microwave frequency range, operating close to 4.8 GHz, which was developed using microstrip patch antennas to determine volumetric soil moisture in rhizoboxes. Antennas were placed on both sides of the rhizobox, and the S parameters were measured using a vector network analyzer.

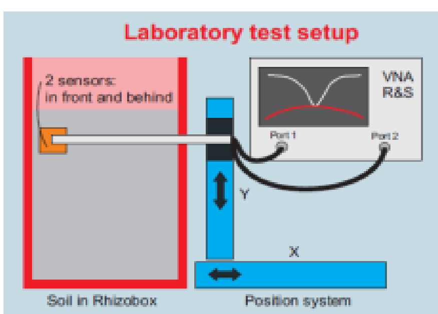

Figure 4. Block diagram of the system developed to measure S21 (dB) of soil moisture in the rhizobox, using the Vector Network Analyzer, in the microwave frequency range (4.6–5.0 GHz).

The dispersion parameter S21 (dB) was also used to show the effect of different soil types and temperatures on the measurement. In addition, the sensitivity, reproducibility, and repeatability of the system were evaluated (Fig. 5). The measurement was carried out three times to each dot (n = 3). The red dots represent the reproducibility (98.9%) averages, and the black dots represent the repeatability (93.0%) averages. The quantitative results of soil moisture, measured in rhizoboxes, presented in this work, demonstrate that the microwave technique using microstrip patch antennas is a reliable non-invasive and accurate system, and has shown potentially promising applications for measurement of roots based on rhizobox phenotyping [9].

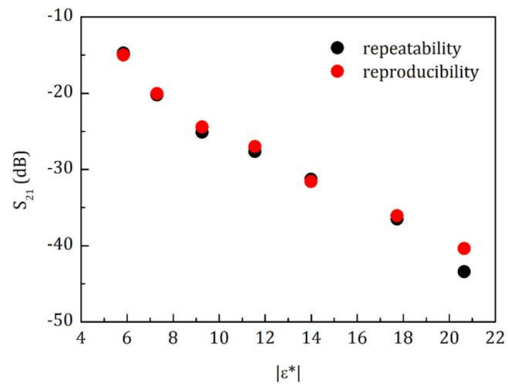

Figure 5. Relation between $|\varepsilon^*|$ versus the average of S_{21} (dB) shows the repeatability and reproducibility of the system developed were calculated.

Figure 6 shows the relationship between the S_{21} measured with the developed system and the volumetric soil moisture θ_V (%) determined and calculated by the second and third-order polynomial equation. The calibration was obtained using four (04) samples, which are: Cerrado Soil (squares), Kaktus Soil (open circles), and Glass Beads (triangles). The experiment was carried out at the standard laboratory ambient conditions (Temperature (T(°C)) = 25.0 ± 0.5 °C, and RH (%) equal to 30%.

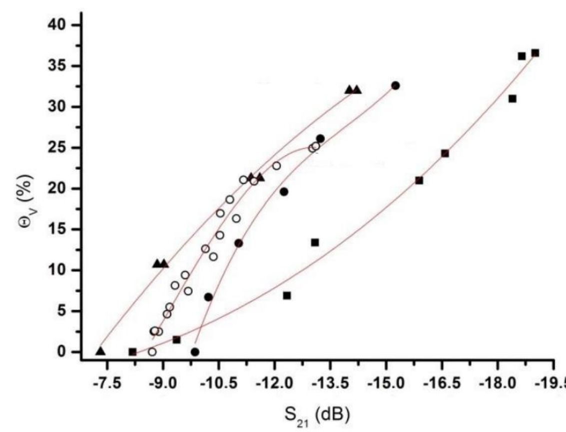

Figure 6. Relationship between the S_{21} measured with the developed system and the volumetric soil moisture θ_V (%). The four (04) samples used are Cerrado Soil (squares), Kaktus Soil (open circles) and Glass Beads (triangles).

Besides, by using the microwave techniques, since the temperature affects the error of volumetric soil moisture measurements, a calibration curve requires information on soil temperature and soil water content. The distinct effect of porous media on the calibration curve (S_{21} (dB) vs θ_V (%)) has also been observed, giving the opportunity to use such an approach to investigate plant root growth in different soil types and moisture.

Techniques that allow deepening the study of water relations in plants are impacting areas of Agronomic Engineering in addition to cutting-edge areas such as Plant Phenotyping.

III. SYSTEM FOR MEASURING THE APPARENT ELECTRICAL CONDUCTIVITY OF SOILS

Soil apparent electrical conductivity (ECa) originated from measuring soil salinity, a pertinent problem in arid zones associated with irrigated crops and areas with shallow water tables. Soil ECa is greatly influenced by a vast combination of physical and chemical properties of the soil, such as soluble salts; mineralogy and clay content; the amount of water present in the soil; volumetric density; organic matter, and soil temperature.

The most effective application of apparent soil electrical conductivity is at field scale in mapping the spatial variability of many edaphic properties, e.g., organic matter, moisture, and in the determination of a wide variety of anthropogenic properties, such as leaching fraction; irrigation and drainage patterns; compaction patterns due to machinery [10].

Soil ECa is a quick, more reliable, and easy tool than other techniques, but it only sometimes correlates with crop yield. Therefore, the ECa measurement is among the most frequently used tools in precision agriculture research for the space-time characterization of edaphic and anthropogenic properties that influence crop productivity.

The measurement of electrical conductivity (σ) originates from the measurement of electrical resistivity (ρ), which consists of using a sample of known shapes and dimensions (square, cylindrical, and others).

The following equation then calculates the electrical resistance:

$$R = \rho\left(\frac{L}{A}\right) \tag{1}$$

where R is the electrical resistance [Ohms, Ω], ρ is the electrical resistivity [Ohms x centimeters, Ω.cm], and L is the sample length [centimeters, cm].

For samples of undefined shapes and dimensions, the method known as the four-point system [11] is used (Figure7), which consists of using four metal electrodes sequentially, aligned, i.e., taking into account the predefined distances S_1, S_2, and S_3.

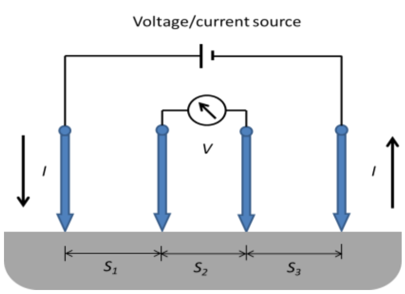

Figure 7. Four-point system.

Applying electrical current, I (Ampere) to the outer electrodes and with a voltage V (Volts) reading from the two center electrodes. The resistivity is then calculated with the following equation:

$$\rho = \frac{2.\pi\left(\frac{V}{I}\right)}{\frac{1}{S_1}+\frac{1}{S_2}-\frac{1}{S_1+S_2}-\frac{1}{S_2+S_3}} \tag{2}$$

Electrical conductivity, σ, is defined as the inverse of electrical resistivity, so we have:

$$\sigma = \frac{1}{\rho} \tag{3}$$

Figure 8 illustrates the block diagram of the developed system, which uses the PIC18F258 manufactured by Microchip Technology [12] as its central processor. The system was designed for reading two four-point measurement systems, consisting of two voltmeters, one of unitary gain and the other of gain three for deeper measurements, an alternating voltage source of 159 Hz for measuring electric current, three signal filters for reading channels, three alternating to continuous signal converters, 1024 bits; 1 bit resolution; 4.88×10^{-3} Volts dc; 32-character Liquid Crystal Display (LCD) for viewing electrical conductivity measurements and control information, four-function keyboard for user-machine communication; standard RS232 serial port for communication and transfer of stored data and the National Marine Electronics Association (NMEA) sentences for Global Navigation Satellite System (GNSS) system and flash memory for storage of collected data, as well as memory capacity equal to 64 Kbytes (Figure 9).

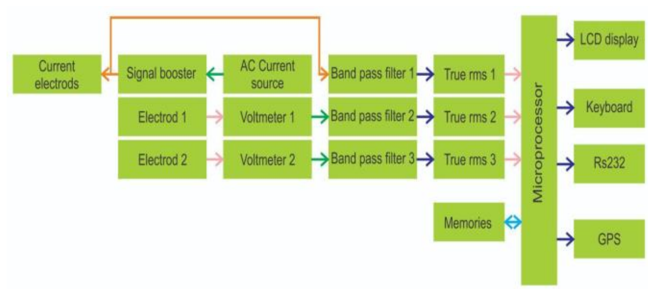

Figure 8. Apparent electrical conductivity system block diagram.

Figure 9. Electrical soil conductivity measurements system.

A. Applications of soil apparent electrical conductivity.

Scudiero et al. [13] developed a mobile platform and data post-processing algorithm to facilitate geospatial measurements of CEa along or near driplines. Gamma-ray (γ-ray) spectrometry is commonly used for clay content and type mapping. The development of this platform allows for better characterization of soil properties in micro-irrigated orchard systems using motion detection technology.

Luchiari Junior et al. worked to define management zones using electrical conductivity through electromagnetic induction to define management zones according to other parameters used in the work [14] where it specifies that the electrical conductivity map revealed similar patterns to the reflectance and management zone maps (Figure 10).

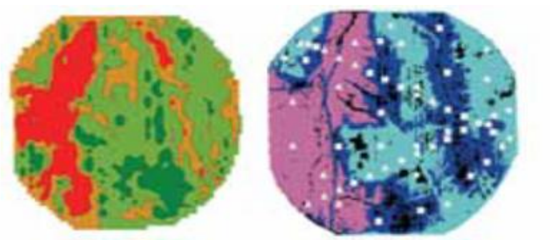

Figure 10. a) Map of apparent electrical conductivity of the soil; and b) Map of homogeneous management zones.

Vilela et al. [15] and Resende and Vilela [16] conducted a thorough assessment of the application of precision agriculture in annual crops. They particularly focused on the tools utilized to characterize the variability of the areas under study, such as soil electrical conductivity sensors, digital terrain elevation models, and aerial images. These tools facilitated the identification of factors that affect productivity variations in the study plots.

Moreover, Oliveira, Franchini, and Debiasi [17] conducted a study on the spatial variability of soybean, corn-soybean productivity, and soil electrical conductivity in a specific type of soil, namely, a Latossolo Bruno. According to the authors, ECa and soybean productivity are determined by the space where they were mapped. Soybean productivity was significantly and inversely correlated with ECa, which makes ECa a valuable parameter in defining different management zones within a crop. (For more information, please refer to Figure 11).

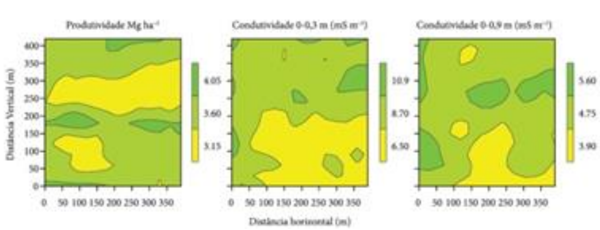

Figure 11. Apparent electrical conductivity and soybean productivity maps.

Brandão et al. [18] conducted a study in the Cerrado region of Goiás, Brazil, to investigate the correlation between soil electrical conductivity (ECa) and pH. The study generated ECa maps to evaluate spatial variability and found a substantial similarity between ECa and pH values. The authors concluded that ECa can be used to characterize variability and estimate soil acidity in the Cerrado Biome.

Oliveira and Benites [19] conducted a study on soil variability to indicate the opportunity for precision agriculture in a direct planting system. The study used quantitative techniques to evaluate the potential of information in supporting a decision-making process for the production system. The authors emphasized soil electrical conductivity's importance in interpreting spatial variation and supporting optimized soil sampling schemes.

Greco et al. [20] conducted a geostatistical study of the electrical conductivity and altitude of soil cultivated with sugar cane. The study aimed to verify the spatial variability of the soil's electrical conductivity and the soil's slope under a direct planting system. The authors concluded that the spatial variability in the electrical conductivity results correspond to differences in altitude, which can help diagnose soil and plant characteristics that vary according to the terrain's topography (Figure 12).

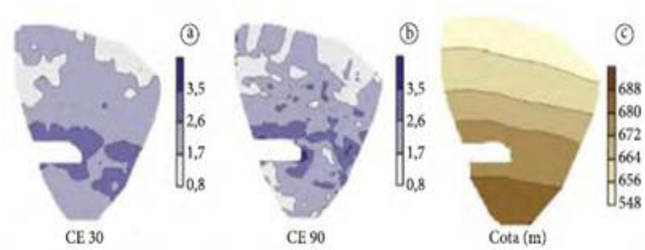

Figure 12. Isoline maps a) apparent electrical conductivity 0-30 cm; b) conductivity 0-90 cm and c) altitude elevation.

Perez et al. carried out a study on spatial variability in crop-livestock integration systems [21], where it has been correlating a given pest with electrical conductivity. Such authors concluded that a pattern of reinfestation is associated with areas of greater electrical conductivity.

Salton et al. studied electrical conductivity to correlate with some physical and chemical attributes of an oxisol with a 15-year management history [22], where they found that electrical conductivity can help delimit management zones and homogeneous areas when subjected to the same management system.

Tutmez [23], in this study were used advanced regression algorithms for the interpretation capacity of functional precision models against the lower-level mechanistic models. To explore the relationships between electrical conductivity (EC), which is the most critical indicator for salinity and irrigation, and soil parameters (texture, chemical concentrations), a comparative assessment based on supervised learning algorithms was conducted and the results were interpreted. by statistical learning. A comparative evaluation of the results revealed that unlike conventional mechanistic models, machine learning interpretation provides additional interpretations, meta-data and transparency for sustainable soil and environmental management.

To improve management techniques in grape cultivation, Miele, Flores, and Filippini Alba study the use of various precision agriculture techniques [24], including soil electrical conductivity, to assist in making the best decisions ways of management. Also, Nascimento et al. conducted a study in the grapevine to determine homogeneous areas with electrical soil conductivity in semi-arid soil [25]. Figure 13 illustrates measurements taken using the system in the study's area where vines are planted and the definition of homogeneous areas for this crop.

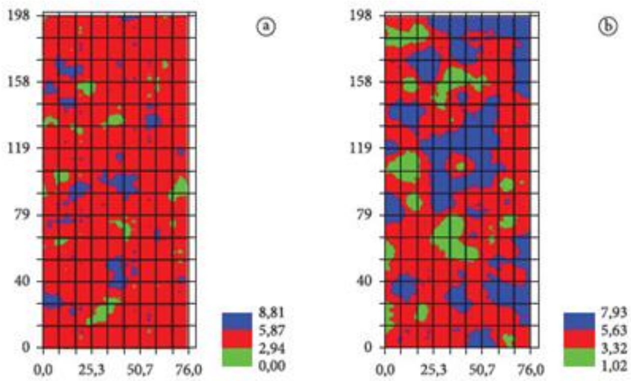

Figure 13. Maps of homogeneous zones of apparent electrical conductivity of the soil, grapevine culture, semiarid region, in Brazil.

Rabello and their team have comprehensively explained their research on electrical conductivity methods, equipment development, and adaptations of imported systems for use in agricultural implements such as subsoilers and seeders [26]. Furthermore, they have detailed the creation of a tropical system suitable for general electrical conductivity measurements [27] [28].

The developed system, as described above, is based on the 4-point electrical conductivity measurement methodology that consists of 4 metallic rods, where 2 rods are injected with a known electric current and two are used to measure the potential difference. Similar equipment uses the same methodology, but with rods with already defined distances between them. Unlike the equipment developed, the rod distances are adjustable (within their limitations), thus enabling the measurement of electrical conductivity at different depths and measurements at different agricultural crops

The authors are currently continuing their research on conductivity measurement systems. They have produced reports assessing the feasibility of directly reading soil electrical conductivity data and making it available on the cloud for analysis using artificial intelligence. This will enable interested parties to access the data, integrate it with productivity maps, soil attributes, and soil fertility, and make real-time decisions regarding crop management. The system can also be configured for variable rate application systems, updated with modern technologies, expanded for use with the IoT, and programmed for use on cell phones.

IV. SENSOR FOR MEASURING WATER AND PLANT RELATIONSHIPS

Studies in water relations of higher plants often present many ongoing debates about the mechanisms responsible for the ascent of water in plants. In the 70's, one of the most useful techniques to aid in direct measurements of plant cells, called the pressure probe [29], was developed. It consisted of a glass capillary connected to a chamber filled with oil that punctured the cell wall, thus establishing a hydraulic connection between the cell sap and oil content.

Using an optical microscope, it was possible to measure the movement of the oil/cell sap boundary, the meniscus, and then by raising or lowering the oil pressure inside the chamber mechanically until the meniscus returned to its original position, one could measure the pressure with a sensor in the oil chamber. Through this technique, as well as a series of improvements (such as system automation), it was possible to more accurately determine how plant cell pressure varies under different physical conditions, thus enabling an understanding of the hydraulic conductivity of cell membranes and the volumetric modulus of the cell's elasticity [30].

So far, in that time, there had not been a detailed physical model describing how to calculate measurement errors, time constants, dynamical behavior, and temperature correlation. Bertucci Neto developed a physical model of the pressure probe and proposed an automated pressure probe based on thermal, instead of mechanical, compensation [31].

Figure 14. Video image of the meniscus in the capillary.

The meniscus movement could be parameterized and correlated with the pressure applied to the capillary tip. One of the detection techniques developed was based on video image digitization. A single video line related to the meniscus position was striped and digitized. In this manner, the meniscus position is correlated to the time base. In

Figure 14 the whole video image is shown, while Figure 15 shows the information of a video frame and a striped video line related to the meniscus position.

The information obtained on the single video line is shown in Figure 16 as well as the digitized signal. The other technique was based on image treatment (through LabView). The meniscus positional datum was used to control the system and return the meniscus to its original position through a feedback loop. Through the camera signal, it was, therefore, possible to select a region in the image in which a single video line carried the entirety of the data on the meniscus' position.

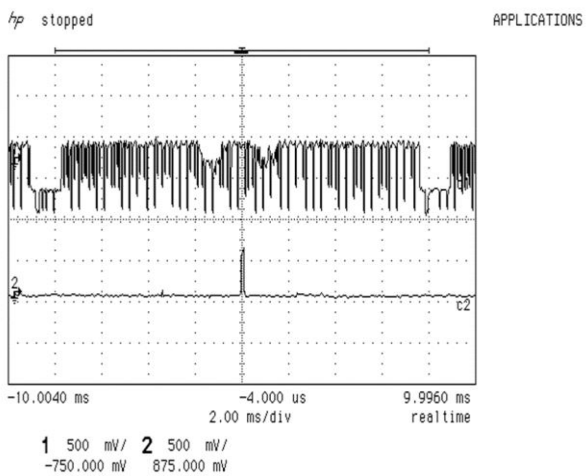

Figure 15. Oscilloscope signal. Above: Video signal of 262.5 lines of a frame. Below: Single video line stripped from the frame in the region of the meniscus image.

As predicted in the modeling study, the relationship between electric heating voltage and the meniscus position in pixels is quadratic. The quadratic approximation presents a standard deviation of less than 10 pixels. After applying an external pressure, the meniscus' position returns to its origin with the help of a Proportional -Integral – Derivative (PID) controller action. The Control System Principle (CSP) was based on a regulation method in which the electrical power signal, generated as a counterbalance, is correlated with the measure, in order to maintain the output signal (in this case the meniscus' position) constant despite pressure variations applied on the capillary's tip'. Figure 17 shows the quadratic behavior between the voltage signal applied to the heater versus the meniscus displacement in pixel. Using this data, a linear expression relating electric power supply in watt and displacement in pixel can be obtained. This calculation is useful to the linearization of the mathematical model set up. Based on experimental data, it is possible to calculate the dynamical response of the power generated by the heater to keep the meniscus on its original position. This is shown in Figure 18 where the experimental signal in watt (in black) represents the effort made by the electric heater to keep the meniscus on its original position. In the same figure, for comparison purposes, a theoretical simulated outcome based on actual parameters is shown in red.

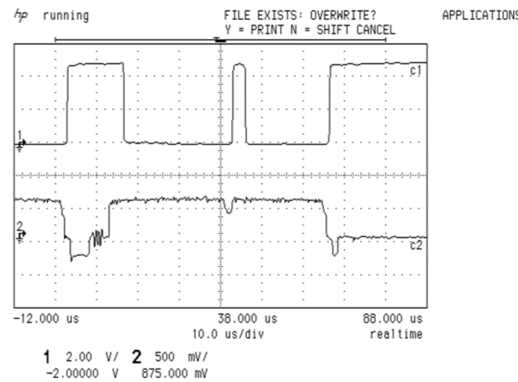

Figure 16. Oscilloscope signal. Above: digitized signal after the voltage comparator. Down: voltage information of the single video line.

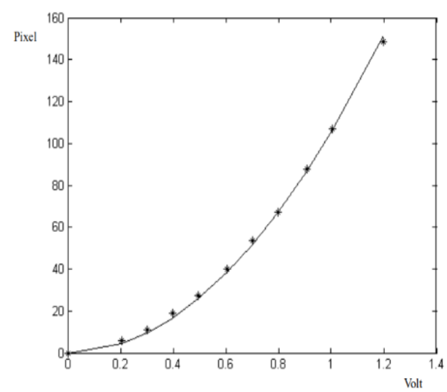

Figure 17. Quadratic behavior between electric power in volt and meniscus' displacement.

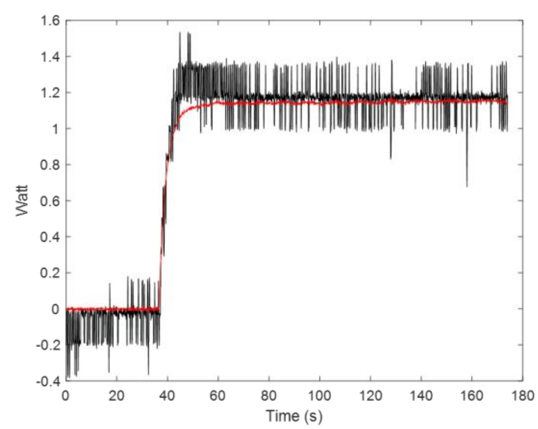

Figure 18. Power supply effort in watts to counterbalance the pressure step on the tip of the capillary: experimental response (black), and theoretical response (red).

V. SENSOR FOR THE PH REAL TIME MEASUREMENTS IN AGRICULTURAL SPRAY SOLUTION

The pH is a scale from 0 to 14 used to determine the degree of acidity of a solution, being possible to classify it as acidic (pH < 7), basic (pH > 7), or neutral (pH = 7). It is based on the degree of acidity of an aqueous solution based on the concentration of hydronium ions (H3O+).

Acidic solutions have excess hydronium ions and a pH lower than 7. On the other hand, basic solutions have an excess of hydroxyl ions (OH-) and pH values greater than 7. In addition, solutions considered neutral have the same concentration of H_3O+ ions and OH- ions, and their pH measurement is 7.

The negative logarithm of the molar concentration of H3O+ ions in the form can obtain the pH measurement:

$$\mathrm{pH} = -\log[H_3O^+] \tag{4}$$

Naturally when one is considering water the process of auto-ionization has the same amount of H_3O+ and OH- ions. Therefore, aqueous solutions of any substance have these two types of ions, and the condition of acidity or basicity of the medium is defined by the ratio between the amounts of H_3O+ and OH-, so as follows (Table II).

TABLE II. MEDIUM AND STATUS FOR THE PH OCCURRENCE.

	Status
Acid	excess H_3O^+ ions
Basic	excess OH^- ions
Neutral	equal amounts of H_3O^+ and OH^- ions

Hydronium ions are formally represented as H_3O+. However, it is common to find the notation H+ for hydronium ions or to refer to the acidity of a medium.

Pesticides, insecticides, and herbicides have their effectiveness modified by the pH of the solution resulting from the preparation of syrup that involves the active agent of these products and water.

Generally, for weed control, herbicides are used, which work better in slightly acidic pH, around pH 4 to 6, and in some exceptions may act better in slightly alkaline. Glyphosate, for example, acts preferentially between pH 3.5 to 5.0, being a weak acid [32][33].

At this pH of the spray solution, the ions are dissociated, favoring the foliar absorption of glyphosate due to the greater ease of crossing cell membranes, increasing the effectiveness of the product [34]. Besides, the effectiveness of glyphosate is affected both by the pH of the medium and by the presence of cations in the spray water [35].

The above or below ideal range can initiate degradation of the molecule, or hydrolysis. For example, when a weak acidic herbicide is mixed in a solution with an acidic pH, it tends to remain intact, however if it is mixed in a solution with an alkaline pH, it can result in the breakdown of molecules. In fact, despite many pesticides having a buffering effect in their formulations, special attention should be considered in pH value monitoring. Therefore, regardless of the pH of the pre-existing spray solution, one may adjust to the pH close to the ideal of each formulation.

This is a fact that the producer must be aware of, especially in mixtures with fungicides and insecticides, which may have negative effects on the effectiveness of other pesticides.

A portable optical instrument for pH measurements was presented in 2011, and it makes it possible to determine pH with a colorimetric sensor array [36]. In fact, the use of four membranes containing acid-base indicators makes it possible to cover the full range of pH using the hue (H) coordinate measurements of the HSV color space. The resulting microcontroller-based system has shown to be immune to optical and electrical interferences. Besides, the authors showed that the pH response of the selected four sensing elements was modeled, and calibration curves were applied to a validation set and real samples obtaining positive correlations between the real and predicted data.

In 2013, a seawater pH data with good spatial and temporal coverage to apprehend ocean acidification phenomena studies was presented [37]. In such a way, it performed an accurate and precise autonomous in situ pH sensor for long term deployment on remote platforms. The widely used spectrophotometric pH technique was capable of the required high-quality measurements. In fact, it has been reported a key step towards the miniaturization of a colorimetric pH sensor with the successful implementation of a simple microfluidic design with low reagent consumption. The system featured a short-term precision of 0.001 pH and accuracy within the range of certified values. Likewise, the optical set up was robust and relatively small due to the use of an USB mini-spectrometer, a custom-made polymeric flow cell and an LED light source.

In addition, a portable electronic instrumentation for pH in-situ reading based on the use of a conductive polymer was also presented in literature [38]. Authors have used polyaniline, which proved to be useful to be used as a sensor for pH measurements. In such instrumentation the spectroscopy in the UV - Vis was successfully used.

Furthermore, for education purposes, in 2018 it has been presented as an open-source potentiometric instrument for pH determination experiments with Bluetooth wireless connectivity [39]. The hardware was built on a solderless breadboard and mainly composed of an Arduino Nano microcontroller, a 16-bit analog-to-digital converter, two electronic buffer amplifiers, a temperature sensor, and a Bluetooth module, i.e., a low-cost instrument. Also, the software was written in Arduino Sketch and the cross-platform Python language, both of which the students were allowed to access and modify freely. The instrument was demonstrated with a traditional glass electrode and a custom palladium/palladium oxide pH sensing electrode, and compared with a commercial pH meter. Results showed that both the accuracy and precision of the developed instrument were adequate for teaching purposes.

Recently, at Embrapa Instrumentation, a pH sensor has been developed to operate in real time directly embedded into a spray nozzle, which is located on the spray boom (Figure 19).

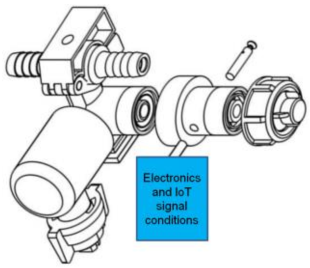

Figure 19. Technical draw of the intelligent pH sensor assembled on the nozzle for direct injection sprayer.

It has been used as a Raspberry Pi (RPi) due to its powerful processor, rich I/O interface, and Internet of Things (IoT) capability, which allowed the remote control across existing spray boom infrastructure and reduced human intervention [40]. Besides, the developed IoT pH system can gather measurements data for intelligent evaluation by resident software.

The RPi is a mini-embedded computer developed in the United Kingdom by the Raspberry Pi Foundation in association with Broadcom. The model used was the RPi 3 B+, where its specifications can be seen in Table III.

TABLE III. RASPBERRY PI 3 MODEL B+ CHARACTERISTICS

Processor	BCM2837B0 Cortex-A53 (ARMv8) 64-bit		
Clock	1.4 GHz	GPIO	40 pins
Memory	1 GB SDRAM	Gigabit Ethernet	1 connector
USB Port	4 USB 2.0	HDMI	1 connector
Camera serial interface (CSI)		Display serial interface (DSI)	
Wireless (dual band)		Bluetooth 4.2/BLE	
3,5mm 4 Jack output		Micro SD card slot	
Support Power-over-Ethernet		Input DC 5V/2.5A	

The internal memory is defined using a micro SD card, where the kernel of the operating system is also present, being recommended the use of at least 8 Gbytes of memory. In addition, the RPi 3 B+, unlike previous family models, enables BCM43438 wireless LAN and Bluetooth Low Energy (BLE) communication, allowing wireless data exchange.

When it is being applied to a direct injection sprayer it has a typical control loop as shown in Figure 20. In this figure, the upper blocks indicate the direct injection components and corresponding variables q_{href}, V_h, and q_h, which represent the set point for the chemical flow, controlled, and measured variables, respectively. In the lower blocks, at the same figure, is possible to observe the sprayer components, which are described as q_{fref}, V_f, and q_m, which represent the set point for the mixture flow, controlled, and measured variables respectively.

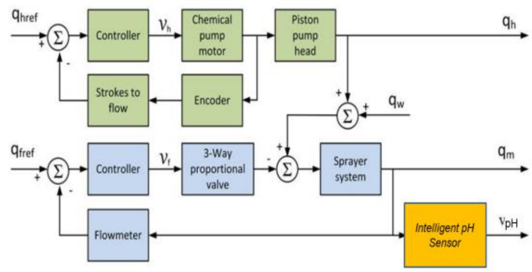

Figure 20. Block diagram for the fungicides, herbicides or insecticides, mixture control, and the intelligent pH sensor.

In this type of direct injection sprayer, the injection point is located upstream from the sprayer pump as presented in [41][42]. The water flow q_w is dependent on both the flow mixture q_m and the injection flow q_h. The intelligent sensor is assembled to measure the pH of the spray solution, which is proportional to its output denoted V_{pH}.

Figure 21 shows the flow-diagram of the algorithm for real time self-diagnostics.

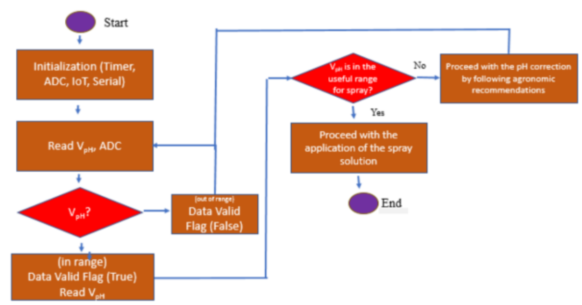

Figure 21. Computational Flow diagram for the real time measurements and flag related to the spray solution pH evaluation.

The calibration curve for the intelligent sensor for pH measurements is presented in Figure 22.

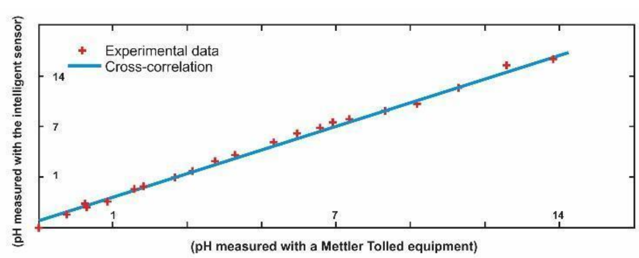

Figure 22. Calibration Curve and comparison with values obtained with prepared solutions with well-known pH values.

The information provided by the intelligent pH sensor could be in the form of a flag, which shows a confidence level of the spray solution quality during its applications. Furthermore, the results show additional information than traditional sensors and meet prospects in practical applications, bringing potential benefits for sustainability, precision agriculture processes, and the potential to be used in IoT systems. Its configurations will depend on demand and large-scale applications.

VI. CONCLUSIONS

By using the sensor developed with microwave technique in the GHz frequency, it was possible to see that the main benefits with the instrument proposed here were not only the use of a non-destructive methodology, but also easy measurement of soil water, portability, use of non-ionizing radiation, speed in the measurement, and low cost. Besides, the use of the apparent electrical conductivity of the soil has demonstrated usefulness as an important tool for precision agricultural work, since one may find its simplicity, as well as time and cost savings in carrying out decision-making in the areas of agricultural management having spatial variability. However, it is important to observe that ECa alone does not allow to answer all questions needed after the data mosaic be provided. Likewise, by supplying the physical model for the pressure probe and its improvement it has become possible an automated pressure gauge. Such a gauge is quite useful to investigate the displacement of a meniscus in the observation of the water-plant ratio, i.e., the water potential direct in agricultural crops. Furthermore, the possibility to have an intelligent sensor to measure the pH of a mixture (pesticide plus water) in spray systems contributes to decrease environmental impacts as well as in cost-reduction associated with the pest control efficiency. Finally, such affordable sensors proved to be innovative to improve production and resilience in agriculture. Future works will be focused on improvements in interoperability and real time operations to support agricultural databases and decision making based on the use of artificial intelligence.

ACKNOWLEDGMENT

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REFERENCES

[1] P. S. P. Herrmann Junior, L. M. Rabello, V. Bertucci Neto, P. E. Cruvinel, "Developing Affordable Sensors in Agriculture Based on Results Obtained at Embrapa Instrumentation", The Eighth International Conference on Advances in Sensors, Actuators, Metering and Sensing (ALLSENSORS 2023), IARIA, Apr. 2023, pp. 8-15, ISSN: 2519-836X, ISBN: 978-1-68558-083-4.

[2] *Agricultural Sensors Market Growth, Share, Forecast to 2030*. [Online]. Availablefrom: https://straitsresearch.com/reports#:~:text=Market%20Snapshot&text=The%20global%20agricultural%20sensors%20market,period%20(2022%E2%80%932030).%202021%2015/02/ 2023.02.15.

[3] T. M. Banhazi, et al., "Precision livestock farming: An international review of scientific and commercial aspects", International Journal of Agricultural and Biological Engineering, vol. 5, Iss. 3, pp. 1-9, 2012.

[4] P. E. Cruvinel and L. Martin Neto, "Subsidies for the development of Brazilian agribusiness: the agricultural automation program, vision and strategies". (Original in Portuguese Language: Subsídios para o desenvolvimento do agronegócio brasileiro: o programa automação agropecuária, visão e estratégias), Technical Document, Embrapa Instrumentation, no. 32, pp. 1-4, Sep. 1999.

[5] G. S. Hundal et al, "Exploring Barriers to the Adoption of Internet of Things-Based Precision Agriculture Practices" Agriculture 2023, vol. 13, 163: htps://doi.org/10.3390/agriculture13010163

[6] A. Kayad, D.S. Paraforos, F. Marinello, S. Fountas, "Latest Advances in Sensor Applications in Agriculture", Agriculture 2020, vol. 10, pp. 362, https://doi.org/10.3390/agriculture10080362.

[7] P. S. P. Herrmann, "Characterization of an equipment for measuring soil moisture using the microwave technique" (Original inn Portuguese Language: Caracterização de um equipamento para medida de umidade do solo através de técnica de micro-ondas), M.Sc Dissertation, São Carlos School of Engineering, Department of Electrical Engineering, University of São Paulo (USP), pp. 1-124, 1993.

[8] T. J. Schmugge, "Remote sensing of soil moisture: recent advances", IEEE Transactions on Geoscience and Remote Sensing, vol. 21, pp. 336-344, 1983.

[9] P. S. P. Herrmann, V. Sydoruk, and F. N. Marques Porto, "Microwave Transmittance Technique Using Microstrip Patch Antennas, as a Non-Invasive Tool to Determine Soil Moisture in Rhizoboxes", Sensors, vol. 20, pp. 1166, 2020, https://doi.org/10.3390/s20041166.

[10] D. R. Nielsen, J. W. Biggar, and K. T. Erh, "Spatial variability of field-measurement soil-water properties", Hilgardia, Berkeley, vol. 42, no. 7, pp. 215-259, 1973.

[11] F. M. Smits, "Measurement of sheet resistivities with the four-point probe", Bell System Technical Journal, New York, pp. 711-718, 1958.

[12] *Microchip Technology*. [Online]. Available from: htttp://www.microchip.com/ 2023.03.15.

[13] E. Scudiero, D.L. Corwin, P.T. Markley, T. Rounsaville, T. Bughici, T.H. Skages, "A system for concurrent on-the-go soil apparent electrical conductivity and gamma-ray sensing in micro-irrigated orchards", Soil and Tillage Research, vol. 235, 105899, Jan. 2024.

[14] A. Luchiari Junior et al, "Management Zones: Theory and Pratice", (Original in Portuguese Language: Zonas de manejo: teoria e pratica, In: Precision agriculture: a new look. (R. Y. Inamassu et al, (Ed.)), São Carlos: Embrapa Instrumentation, Brazil, pp. 60-64, 2011.

[15] M. F. Vilela et al, "Preliminary Mapping of Management Zones in a Corn-soybean Production System in the Cerrado", (Original in Portuguese Language: Mapeamento preliminar de zonas de manejo em sistema de produção de milho-soja no Cerrado) In: Precision agriculture: a new look. (R. Y. Inamassu et al, (Ed.)), São Carlos: Embrapa Instrumentation, Brazil, pp. 189-193, 2011.

[16] A. V. Resende and M. F. Vilela, "General Evaluation, Results and Perspectives of the Use of Precision Agriculture in anual crops", (Original in Portuguese Language: Avaliação geral, resultados e perspectivas do uso de agricultura de precisão em culturas anuais), In: Precision agriculture: a new look. (R. Y. Inamassu et al, (Ed.)), São Carlos: Embrapa Instrumentation, Brazil, pp. 135-137, 2011.

[17] F. A. Oliveira, J. C. Franchini, H. Debiasi, "Spatial variability of soybean productivity and electrical conductivity of a Bruno Oxisol", (Original in Portuguese Language: Variabilidade espacial da produtividade da soja e da condutividade elétrica do Latossolo Bruno). In: Precision agriculture: a new look. (R. Y. Inamassu et al, (Ed.)), São Carlos: Embrapa Instrumentation, Brazil, pp. 153-156, 2011.

[18] Z. N. Brandão et al, "Apparent electrical conductivity and its correlation with pH in soils in the cerrado of Goiás" (Original in Portuguese Language: Condutividade elétrica aparente e sua correlação com o pH em solos no cerrado de Goiás), In: Precision agriculture: a new look. (R. Y. Inamassu et al, (Ed.)), São Carlos: Embrapa Instrumentation, Brazil, pp. 162-167, 2011.

[19] R. P. Oliveira, V. M. Benites, "Soil variability as an indicator of the opportunity for precision agriculture in a direct planting system", (Original in Portuguese Language: Variabilidade do solo como indicador da oportunidade da agricultura de precisão em sistema de plantio direto). In: Precision agriculture: a new look. (R. Y. Inamassu et al,

(Ed.)), São Carlos: Embrapa Instrumentation, Brazil, pp. 194-200, 2011.

[20] C. R. Greco et al, “Geostatistics applied to soil electrical conductivity and altitude of soil cultivated with sugar cane”, (Original in Portuguese: Geoestatística aplicada à condutividade elétrica do solo e altitude do solo cultivado com cana-de-açúcar. In: Precision agriculture: a new look. (R. Y. Inamassu et al, (Ed.)), São Carlos: Embrapa Instrumentation, Brazil, pp. 245-248, 2011.

[21] N. B. Perez et al, “Spatio-temporal Variability in Crop-livestock Integration in the Sothern Region of Brazil: Perspectives for Intervention with Precision Agriculture”, (Original in Portuguese Language: Variabilidade espaço-temporal em sistemas de integração lavoura-pecuária na Região Sul do Brasil: perspectivas de intervenção com agricultura de precisão). In: Precision agriculture: a new look. (R. Y. Inamassu et al, (Ed.)), São Carlos: Embrapa Instrumentation, Brazil, pp. 249-253, 2011.

[22] J. C. Salton et al, “Electrical conductivity and physical and chemical attributes of an Oxisol after 15 years under management systems in Mato Grosso do Sul” (Original in Portuguese Language: Condutividade elétrica e atributos físicos e químicos de um Latossolo apos 15 anos sob sistemas de manejo em Mato Grosso do Sul), In: Precision agriculture: a new look. (R. Y. Inamassu et al, (Ed.)), São Carlos: Embrapa Instrumentation, Brazil, pp. 254-260, 2011.

[23] Tutmez, B. Identifying electrical conductivity in topsoil by interpertable machine learning, Model Earth Syst. Environ, 2023, https://doi.org/10.1007/s440

[24] A. Miele, C. A. Flores, and J. M. Filippini Alba, “Current Status of Precision Viticulture Research in Rio Grande do Sul: First Results from Production Unit (PU) Grape for Wine” (Original in Portuguese Language: Status atual da pesquisa de viticultura de precisao no Rio Grande do Sul: primeiros resultados da UP Uva para Vinho), In: Precision agriculture: a new look. (R. Y. Inamassu et al, (Ed.)), São Carlos: Embrapa Instrumentation, Brazil, pp. 267-272, 2011.

[25] P. S. Nascimento et al, “Homogeneous zones of apparent electrical conductivity in Quartzanic Neossolo in the Semiarid”, (Original in Portuguese Language: Zonas homogêneas de condutividade elétrica aparente em Neossolo Quartzarenico no Semiárido), In: Precision agriculture: a new look. (R. Y. Inamassu et al, (Ed.)), São Carlos: Embrapa Instrumentation, Brazil, pp. 290-293, 2011.

[26] L. M. Rabello, “Soil electrical conductivity, topics and equipaments” (Original in Portuguese Language: Condutividade elétrica do solo, tópicos e equipamentos). Technical Document, São Carlos: Embrapa Instrumentation, pp. 1-19, 2009.

[27] L. M. Rabello, R.Y. Inamassu, and A. C. C. Bernardi, “Soil eletrical conductivity measurement system”, (Original in Portuguese Language: Sistema de medida de condutividade elétrica do solo), Sao Carlos: Embrapa Instrumentation, Technical Document, no. 54, pp. 1-8, 2010.

[28] L. M. Rabello et al, “Soil electrical conductivity measurement adapted to a planter” (Original in Portuguese Language: Medida de condutividade elétrica do solo adaptada a uma plantadeira), Sao Carlos: Embrapa Instrumentation, Technical Document, no. 46, pp. 1-4, 2008.

[29] D. Hüsken, E. Steudle, and U. Zimmermann, “Pressure probe technique for measuring water relations of cells in higher plants.” Plant Physiology. vol. 61, pp. 158-163, 1978.

[30] D. J. Cosgrove and D. M. Durachko, “Automated pressure probe for measurement of water transport properties of higher plant cells”, Review of Scientific Instrument, vol. 57. no. 10, pp. 2614-2619, 1986.

[31] V. Bertucci Neto, "Modeling and automation in a new measurement technique for water and plant relationships”, (Original in Portuguese Language: Modelagem e automação em nova técnica de medida para relações de água e planta), Ph.D Thesis. São Carlos School of Engineering, Department of Electrical Engineering, University of São Paulo (USP), pp. 1-181, 2005.

[32] P. Christofolleti, “Classroom material”, AgroAdvance, pp. 1-35, 2021.

[33] T. L. C. Andrade, "Acaricidal action of hexythiazox, dicofol and fenbutatin oxide, at three pH levels of the syrup, in the control of the mite *Brevipalpus phoenicis Geijskes*, under laboratory conditions” (Original in Portuguese Language: Ação acaricida do hexythiazox, dicofol e óxido de fenbutatin, em três níveis de pH da calda, no controle do ácaro *Brevipalpus phoenicis Geijskes*, em condições de laboratório), MSc. Dissertation in Agronomy, Area of Concentration in Agricultural Entomology, Faculty of Agricultural and Veterinary Sciences, State University of São Paulo (UNESP), pp. 1-70, 1997.

[34] D. M. Sanchotene et al, (“Influence of salts and water pH on the efficiency of imazethapyr + imazapic in controlling red rice”, Planta Daninha, vol. 25, pp. 415-419, 2007.

[35] S. J. P. Carvalho et al, “Efficacy and pH of glyphosate mixtures after the addition of nitrogen fertilizers and the use of a sprayer pressurized by CO_2”, Brazilian Journal of Agricultural Research, vol. 44, no. 6, pp. 569-575, 2009.

[36] A. Martinez-Olmos et al, “Sensor Array-Based Optical Portable ´ Instrument for Determination of pH”, Sensors and Actuators B: Chemical, pp. 840-848, 2011. DOI:10.1016/j.snb.2011.02.052.

[37] V. M. C. Rérolle et al, “Development of a colorimetric microfluidic pH sensor for autonomous seawater measurements”, Analytica Chimica Acta, vol. 786, pp. 124-131, 2013.

[38] G. Vendramini, Development of portable electronic instrumentation for pH measuring in the field using an optical sensor based on polyaniline film base, MSc Dissertation, Federal University of São Carlos (UFSCar), SãoCarlos, pp. 1-81, 2015.

[39] H. Jin et al, Open-source low-cost wireless potentiometric instrument for pH determination experiments, Journal of Chemical Education, vol. 95, pp. 326−330, 2018. DOI: 10.1021/acs.jchemed.7b00479.

[40] *Raspberry Pi 3, Model B+*. [Online]. Available from: https://datasheets.raspberrypi.com/rpi3/raspberry-pi-3-b-plus-product-brief.pdf. 2023.08.15.

[41] U. R. Antuniassi, P. Miller, and M. Paice, Performance evaluation of injection metering systems, Brazilian Journal of Agricultural and Environmental Engineering, vol. 6, Issue 1, pp. 159-165, 2002.

[42] K. P. Gillis et al, Injection mixing system for boomles, target-activated herbicide spraying, Transaction of the ASAE, vol. 46, Issue 4, pp. 997-1008, 2003.

Access to Escape: Didactic Conception and Accessible Game Design of a VR-Escape Room for Accessibility Education

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***Abstract*—*Access to Escape* is a Virtual Reality (VR) Escape Room, aimed at sensitizing computer science students to the importance of digital accessibility. Since these students will develop digital content in the future, this target group is an important starting point to create awareness towards the topic. This article outlines the development of a VR game based on the viewpoints of Accessibility Education, Game Accessibility, and accessible VR to offer access to a wide range of people. The primary objective is to address the research question of what steps are necessary to create an accessible VR game and what the design process should entail to achieve this goal. The first step involves developing a didactic conception to create an educationally valuable learning offer. A guide by didactic expert Kerres is presented, which supports the development process of a didactic design including the application to the VR-Escape Room. The development process of *Access to Escape* also showed that the Game Accessibility Guidelines (GAG) workflow offered a low-threshold starting point, for example, by making the vast amount of accessibility guidelines more tangible. Here, it should be emphasized that the prioritization, as suggested by the workflow, must not lead to the exclusion of any applicable guidelines, since every guideline is needed to guarantee an accessible game experience. However, during the implementation process of our VR-Escape Room, it became apparent that many resources and a well-defined time schedule are needed to achieve a fully accessible game. To counteract this issue, more information material and open-source solutions are needed to meet all accessibility requirements. An evaluation of the first development phase of *Access to Escape* showed that the VR-Escape Room is a suitable format for educating about accessibility and, based on these results, further steps regarding the development are discussed such as the use of Artificial Intelligence, a multiplayer mode or the transfer to other topics.**

***Index Terms*—Accessibility Education; Virtual Reality; Game Accessibility; Escape Room; Didactic Design.**

I. Introduction

With the increasingly digital nature of everyday life, the importance of digital accessibility moves further into focus. This makes it necessary to bring the topic closer to developers of digital content. As a possible solution, we developed *Access to Escape* providing a low-threshold starting point for dealing with digital accessibility [1]. As computer science students represent the future developers of digital products, it is necessary to educate these stakeholders on the importance of digital accessibility and teach them methods for implementing inclusive software. Using an immersive learning format such as a VR game, it was aimed to sensitize the players by making barriers more tangible and thus relatable. Although gamification and VR technology offer benefits such as the mentioned immersion, they also introduce new challenges, including the need for accessible VR gaming experiences. To design an accessible VR-Escape Room, we formulate the following research question:

"What does the design process for creating an accessible VR game entail, and what implementation steps are necessary to achieve this goal?"

To address the presented research question, we will first give an overview of the related topics in Section II, which includes Accessibility Education, Game Accessibility, and Accessible VR. Then, in Section III, we outline the considerations made regarding the didactic design of the learning offer. Section IV will offer an overview of the implementation of *Access to Escape*. We will explain the game story and the corresponding learning goals, how we implemented the GAG workflow, and demonstrate the outcome of the implemented accessibility features. The evaluation of the developed VR-Escape Room is presented in Section V. The lessons learned and limitations of the VR-Escape Room will then be discussed in Section VI. Finally, in Section VII, we summarize our findings and formulate tasks for future work.

II. Disciplines of Accessibility

For a successful implementation of our research objectives, it is necessary to consider different disciplines of digital accessibility. *Access to Escape*, for one, represents a tool for learners to grasp the content related to digital accessibility. For another, the VR game needs to be accessible so it can be played by every learner. The following subsections address the topics necessary to achieve the objectives. The teaching of accessibility and connected specifications will be discussed. Further, the requirements for accessible game design and inclusive VR applications will be examined.

A. Accessibility Education

Accessibility Education is a broad field in which learners are supposed to acquire various competences: Initially, they need to develop theoretical understanding and procedural knowledge regarding accessibility [2]. Only with the aid of this foundational knowledge, learners can develop technical skills in this discipline.

To teach these skills, educators need resources that can teach accessibility while considering the current knowledge and skill set of students [3]. As digital accessibility is still not a widespread mandatory subject at every university, it is necessary to create such learning materials that provide a low-threshold introduction to the subject, so even students who do not have any prior educational knowledge about digital accessibility can have easy access to the content.

In order to provide that simple introduction to the topic, it is beneficial to make barriers tangible and thus provide learners with a realistic experience [4]. For example, Kletenik and Adler [5] developed three games in which the players are confronted with simulated disabilities to raise awareness of accessibility. It became apparent that the students who played these games increased their empathy for people with impairments or disabilities and also their motivation to design more accessible content.

These results provide a constructive basis for the development of additional learning materials. However, in future conceptualizations, the following insight could be considered, which could further enhance the awareness-raising effect: To make simulated barriers even more immersive, VR technology has the potential to create experiences that make them as tangible as possible [6].

B. Game Accessibility

Game Accessibility describes the subarea of game development that addresses the removal of barriers for people with impairments or disabilities [7]. It should be emphasized that removing the barriers, and by that, creating an accessible game, is limited by the game rules. Games often include intended barriers, which represent the challenges of the game story. If those challenges were removed, the intention and / or the entertaining character of the game could be compromised.

For the development of accessible games that comply with the corresponding game rules, the Game Accessibility Guidelines (GAG) [8] by the International Game Developers Association (IGDA) have been established in different elaborations [7], [9], [10], [11]. The GAG [8] are guidelines, which are based on an online survey that gathered methods to make games more accessible to different user groups. The current version (May 2021) includes 122 guidelines that can be classified according to motor, cognitive, visual, auditory, linguistic, and general barriers. Each of these six groups is classified again into three subgroups (basic, intermediate, and advanced). The classification into these subgroups depends on the following three factors:

Reach: People benefiting from meeting the requirements.

Impact: Qualitative difference for players.

Value: The cost incurred for implementation.

The *basic guidelines* [8] describe accessibility features that make playing easier for a large number of players and are also easy to implement. The *intermediate guidelines* [8] include features that require additional planning and resources, but are still easy to implement and reach many players. Finally, the *advanced guidelines* [8] involve complex modifications and high costs. Although only a few specific players benefit quantitatively from these modifications, they have a very high qualitative value for those players.

The need for each guideline of the GAG is emphasized by a realistic use case, making the traceability of a barrier easier for developers [8]. Further support provided by the guidelines are the listed best-practice games that have particularly well implemented the respective guideline.

Regarding the implementation of accessible games, the following workflow is recommended by the IGDA [8]:

1) *Familiarize:* Before the implementation phase begins, the guidelines must be considered, since a variety of requirements can already be met through simple design decisions in the conception phase.
2) *Evaluate & plan:* In the second phase, it must be investigated which guidelines will be relevant and applicable in the context of the planned game to create a reduced subset of requirements to be implemented.
3) *Prioritize & schedule:* The selected requirements from the second phase are prioritized according to the available resources and scheduled in the development plan.
4) *Implement:* To achieve the best results, experts and players with a disability or impairment should also test the game during the implementation phase.
5) *Inform:* Players should be made aware of the implemented guidelines in tutorials and loading screens, as there is a risk that they will go unnoticed in various menu settings.
6) *Review & learn:* Information on how often players have used accessibility features helps future projects when conducting the third phase, especially when prioritizing requirements.

C. Accessible VR

The use of VR is steadily increasing and is becoming a more prevalent tool in education. This makes access to VR technology even more important. The developer manual of the company Oculus emphasizes that accessible VR applications can reach a wider range of users [12]. VR applications are considered accessible when people with different types of visual, auditory, mobility, perceptual, and cognitive impairments can interact with the given content. The manual presents procedures for seven application areas of a VR application, which partly overlap with the GAG and the Web Content Accessibility Guidelines (WCAG) [7]. The sections of the manual are presented in the following:

User Experience (UX) and User Interaction (UI) [12]: To achieve an inclusive UX, game developers must first become aware of exclusive UX design. As an example of such an exclusive design, the chosen size of the play area is mentioned: Players with a limited movement area could experience a below-average or even unplayable user experience. Only when the game can be completed without blockages or external help, an inclusive UX design is achieved. It must be constantly tested to see if this is the case. For example, it is useful to play the game with disabled sound or color filters. Also, the use of auditory, visual, and haptic interaction possibilities makes the UX more inclusive.

Controls and Interactions [12]: The predefined controls of a game can hinder players, for example those with motor impairments, from interacting with the game. To improve this situation, selection options and alternative types of interaction should be presented. Modifications help not only people with disabilities but also all players. For example, the ability to re-assign control keys not only helps players who cannot fulfill the default input requirements due to motor impairments but also benefits habitual players who prefer personalized interaction.

Movement and Locomotion [12]: In order for the movement of players in the virtual world to be feasible for everyone, among other things, developers must consider how a person who cannot move in the real world could still move around in the virtual world. For example, navigation via joysticks eliminates the barrier for players who cannot move freely in the real world.

Display [12]: Personalizing screen displays, such as variable brightness settings, is now standard on many devices. In VR applications, this personalization is even more important because the complete occupancy of the visual space and the proximity to the human eye pose a risk of sensory overload. A personalized display prevents this danger for all players, with and without impairments. For example, the ability to enlarge text elements or objects in the virtual world can support people with visual impairments.

App Design [12]: Elements of app design can support the accessibility of VR applications. For example, a clear and mandatory tutorial at the beginning of the game provides the opportunity to become familiar with the game mechanics. Clearly defined rules and objectives help players stay focused on the game. Through such methods, the basic understanding of the game can be simplified for all players. Additionally, the game can be made more accessible by adding a Guiding Character. For players who were unable to process auditory, visual, or haptic signals, these characters can, for example, provide additional hints.

Audio [12]: In addition to the possibilities of visual and haptic interaction, audio offers another form of communication. Short and simple audio tracks can signal actions and processes. However, despite the advantages of sound, the option should be kept open to deactivate it without loss: People who, for example, have difficulty concentrating and therefore choose to turn off the sound, must not experience any loss of information.

Captions and Subtitling [12]: Captions refer to the textual reproduction of spoken dialogues. Whereas, subtitling refers to the translated textual reproduction of spoken foreign-language dialogues. These forms of information transfer help a variety of people: players with hearing or cognitive impairments, players who do not understand the game language, and players who prefer to read dialogues instead of hearing them.

III. Didactic design

We created the didactic design of *Access to Escape* using Kerres' guide [13]. To support the development process of learning offers the guide uses various analysis and decision steps. In the following, the individual steps will be briefly introduced and applied to the VR-Escape Room.

A. Contexts

According to Kerres, the educational context of the learning offer has to be defined first [13]. Here, a distinction is made between three types of contexts into which a learning offer can be classified: Formal education describes intended institutional education with the aim of a degree such as school or university education. Non-formal education does not aim at a degree but it is still intended and organised. In contrast, informal learning is unintentional and takes place in everyday life, for example, through conversations.

Access to Escape is a virtual learning environment that enables knowledge acquisition through independent interaction with the game assisted by educators. Currently, the game is not embedded in a university lecture and thus constitutes a learning offer in a non-formal education context. However, if the game will be offered in connection to a course it can be considered as part of formal education.

B. Stakeholder

The learners' characteristics need to be identified and thus the target group will be defined. To enable this identification, Kerres introduces several attributes including *number of participants*, *level of education* and *motivation* [13]. Special focus is on the prior knowledge of the learners. In addition, other actors such as teachers, as well as the constellation between the participants are important.

The VR-Escape Room is primarily intended to enable computer science students to identify and ideally remove barriers. This target group should be made aware of barriers as early as possible in their studies, so that these barriers can be taken into account in the further course of their education.

C. Educational Concern

Based on the used guide, a learning offer aims to solve an educational problem [13]. For this, it is necessary to first identify the problem and then formulate an educational concern in concrete terms. In this context, the understanding of education must be determined: Kerres distinguishes between *Education as Disposition*, where the goal is the development of competences, *Education as Transaction* with the goal of developing qualifications, and *Education as Transformation*, where the aim is personality development.

The educational problem that we try to solve with our learning offer is the insufficient presence of digital accessibility in the study field of computer science even though those students will create digital content in the future. With this in mind, the educational concern can be formulated as follows: *Digital accessibility must be considered and implemented by developers of digital content. However, there is a lack of awareness of digital barriers and the opportunity to get familiar with the topic easily.* The understanding of education regarding the learning offer can be split up into all three categories. The learners should be empowered to identify and preferably eliminate barriers (*education as disposition*). The obtained knowledge can support the learners career opportunities as digital accessibility gains importance due to the digitisation of everyday life (*education as transaction*). Further, *Access to Escape* gives learners the opportunity to be sensitized to barriers and thus expand their view of the environment (*education as transformation*).

D. Teaching Objectives

Teaching objectives are structured within the context of the *competence domain* and *competence dimensions* and categorized by *performance levels* [13]:

Competence domains include the *subject competence* (understanding and knowledge about the world), *self competence* (regulation of one's actions) and *social competence* (interaction with others).

The *competence dimensions* describe *knowledge*, *motor or cognitive skills*, and *attitudes, values, and norms* each regarding objects, individuals, and oneself.

Within the context of competence domains and dimensions, various *performance levels* can be achieved. Learners may *recall* knowledge about subject competences, *comprehend* them in greater depth, or achieve even higher levels of performance.

The VR-Escape Room intends to teach subject competence related to accessibility, which is why the performance levels are applied to said competence domain. Regarding the dimension "knowledge", learners are supposed to achieve the following performance levels:

Remembering: Learners can recognize and reproduce barriers they have encountered during the game; *Understanding*: Learners can find examples of similar barriers and explain why such a barrier is a hindrance; *Apply*: Learners can apply the acquired knowledge by identifying and removing barriers.

Further, the learners should develop *skills* in the *cognitive phase*, which means the barriers are known and can be described verbally and also in the *associative phase* meaning the possibilities to remove a barrier are known and can be applied.

Lastly, the VR-Escape Room is supposed to affect the *attitudes* of the learners in the following aspects:

Attentive: Learners are willing to engage with new norms and values; *Reacting*: Learners voluntarily pay attention to digital barriers as they continue to study and integrate their knowledge into further developmental tasks; *Values*: The learners recognize the importance of digital accessibility and take it into account in their further work; *Adopting Values*: Learners adopt the learned values into their value system.

E. Selection of the Teaching Content

Based on the teaching objectives (see Subsection III-D), the teaching content for the competence dimensions "knowledge", "skills", and "attitudes" must now be defined. Using different *positions* offered by Kerres [13], the teaching content for the VR-Escape Room was identified:

Position A: "Teaching content can be justified by future requirements and qualification needs." [13] - Increasingly, employers are obliged to provide a barrier-free presence [14], which requires qualified employees. They should know and be able to apply the basic concepts of digital accessibility. *Position B: "Teaching content should enable an educational experience that changes the person. (transformation)"* [13] - By confronting learners with real-life challenges, a formative experience should be made possible. Thereby the learners are sensitized to barriers and their consequences. *Position C: "Teaching content can be defined based on an analysis of tasks to be performed."* [13] - Since the range of topics in digital accessibility is very broad, the teaching content must be made concrete. Tasks can look like so:

For example, if the task is to develop a low-barrier website, the WCAG must be considered (*Step 1: Finding the Guidelines*). Understanding the specific barriers (*Step 2: Understanding the success criterion*) and the corresponding solutions (*Step 3: Understanding the Solutions*) are a necessity for creating barrier-free access to a website. The modular structure of the guidelines allows the definition of clearly delimited tasks from which teaching content can be derived. Each success criterion deals with one barrier and thus corresponds to one potential task. Further, the validity of the WCAG is not exclusively limited to web content. For example, correct language markup of texts must also be available in a game or other applications. Selected WCAG success criteria that are universally applicable are therefore suitable teaching content.

Considering these positions, the following teaching contents could be identified: speech markup, alternative text, representation of color, heading hierarchies, and appropriate button size.

F. Didactic Principles

Learning offers can be structured as more expository or exploratory [13]. The former describes a step-by-step introduction and practice of the teaching content. The latter conveys teaching content through the direct confrontation with complex problems.

The VR-Escape Room consists of elements of both principles. Explorative elements are the *flatly structured teaching material*, which do not build upon each other, the *non-formal learning situation* since the teaching contents do not belong to a formal course, the very *diverse target group* consisting of students of different levels of knowledge and learning motivations and the *self-study learning habit* of the target group. Further, the playful VR learning offer can trigger intrinsic motivation among students (explorative). If instructors choose to use the game alongside a lecture and reward it, for example, with bonus points, it can also stimulate extrinsic motivation in students (expository). Another expository element is the limited prior knowledge of the target group. According to the module handbook, students have little exposure to digital accessibility [15].

G. Learning Times

The learning process is characterized by three components, which are stimulated to different degrees by the learning offer [13].

Learning by *reception* includes learning by taking in and processing presented information. The component *communication* refers to the learning theory behaviorism, which states that learning is influenced by external factors: Feedback or reinforcement from the environment informs about the correctness and incorrectness of an issue and leads to learning. The third component *construction* describes that simple processes in the environment can be learned by trial and error. Through experiences, pushing boundaries, and reflecting on processes, not only are predefined contents learned, but rather new horizons are discovered.

Essentially, the three components presented can be attributed to the three competence dimensions (see Subsection III-D). Reception is mainly concerned with the transfer of knowledge, communication is related to attitudes, and construction contributes to the acquisition of skills.

The largest part of the planned learning activity is devoted to learning through construction. This is due to the game mechanics of *Access to Escape*, which involves solving puzzles through independent interaction within the given space. The remaining components of the learning process involve learning through reception and learning through communication. Prior to the game, players receive information that is relevant to their understanding of the game; in a concluding debriefing, a series of information is presented for learners to absorb and process (learning through reception). Through hints and encouragement before and during the game, as well as feedback on insights during the debriefing, information is conveyed in an interpersonal manner (learning through communication).

H. Learning Processes

The introduced components of reception, communication and construction (see Subsection III-G) will be used to break down how learning processes can be initiated by the learning offer, according to Kerres [13].

Reception: Asking the question of how learning processes can be supported by the presentation of information, Kerres focuses on the so-called *didactisation of the presentation*. Here, various approaches are introduced, which support the learning process through a curtain presentation of information. One approach being the *use of questions* to initiate independent thinking processes. Instead of just naming facts and results, the learners develop a solution to given questions. The VR-Escape Room goes one step further: Learners figure out the questions on their own as they are confronted with barriers. Only by eliminating the barriers, they can go on within the game. This inevitably raises the question of how accessibility can be implemented in the respective area. If the learners cannot define the questions on their own or cannot find an answer, hints can be received at any time. Further, Kerres mentions the *use of examples* to vividly present complex content and by that, support the learning process. All puzzles are examples of a barrier. One of the puzzles shows that conveying information only through color is a barrier. The learners have to figure out another way to convey information and can thus remove the barrier.

Communication: Kerres claims that communication always includes a *content level* and a *relationship level*. On the content level, knowledge regarding accessibility is conveyed through the learning offer. On the relationship level, power and appropriate behavior on the side of the teachers are essential aspects to consider. The aim is to create an environment conducive to learning. In the case of the VR-Escape Room, a power imbalance can almost completely be ruled out. Knowledge is conveyed in a playfully without an evaluation of performance. Throughout the game, the learners can ask for hints and are supported by teachers.

Construction: Here, the question arises as to which learning activity can best initiate cognitive activation. Kerres describes that especially the active engagement with the learning content leads to learning success. Learning activities, like summarizing or drawing, are said to promote learning. The VR-Escape Room is no suitable learning offer to apply these learning activities. However, another type of activity can be reached in the game: Through the practical examination of the content in a virtual environment, cognitive activation is stimulated to subsequently build up competences. This is intended to enable learners to apply the learning content in future situations.

I. Learning Spaces and Learning Media

The learning spaces and learning media play an important role concerning the learning process and finally the learning success. According to Kerres, learning spaces have the potential to influence the learning experience [13]. The learning offer can convey information through different learning media, also influencing the learning experience. Every learning room features a didactic design and therefore has the potential to influence the learning experience. The resources available, but also the furniture in the room, are factors that influence learning and teaching. In addition, learning spaces have a so-called affordance, which means they suggest certain behaviors: While some rooms may encourage focused individual work, others encourage creative group work. There are also differences in the digital world: Some digital learning spaces may be particularly helpful for flexible, self-determined learning, while others have a positive effect on group dynamics and thus promote collaborative learning. Here, it should be noted that the extent of the influence that a learning space has on learning behavior is a subjective perception varying from person to person.

Access to Escape is a learning offer, which uses playful elements and tension to achieve learning success. Since the aim is to make barriers tangible, the use of VR as a learning medium is ideal as it can recreate a realistic experience. In addition, the immersion associated with VR can encourage learners to stick with it. The individual rooms in *Access to Escape* should not appear cramped, but should not be too spacious either so that the learner does not lose their orientation. By using appropriate light sources and unobtrusive sounds, the focus should be entirely on learning and not be wasted on disruptive factors.

J. Learning Organization

Based on Kerres' definition, learning organization describes how the learning offer is organized in terms of time, whether and when synchronous or asynchronous elements are planned, and which social forms should be used [13]. However, due to its current short-term and isolated use, the VR-Escape Room does not fit the concept of learning organization. For now, there is no plan for recurring use of the learning offer; rather, the Escape Room only needs to be completed once. Since the learners will use the learning offer alone, the social form can clearly be defined as individual work (with supervision).

K. Evaluation

Evaluating a learning offer provides insights into the positive as well as negative aspects of an implemented concept. Based on the identified characteristics, future teaching can be made more efficient and effective. Four key evaluation areas include:

- Acceptance: Learner perspectives and invested resources (time).
- Engagement: Cognitive, emotional, and behavioral involvement.
- Learning Outcomes: Competences acquired.
- Consequences: Effects on individuals, organizations, and society.

The VR-Escape Room is evaluated using the method of observation, open-ended feedback as well as two questionnaires: the User Experience Questionnaire (UEQ) and the Goethe University Frankfurt's Course Evaluation Questionnaire (CEQ). The UEQ provides insights into the acceptance and learning engagement parameters of the learning offer. The CEQ also assesses learning engagement in the learning process, evaluates the scope of learning outcomes, and hints at the prospects of learning consequences. Further details on the questionnaires, their application, and results can be found in Section V.

L. Examination

Examinations play a crucial role in assessing developed competences in both formal and non-formal educational offers. It is the responsibility of educators to design an examination format that aligns with the instructional methods employed. For instance, if the primary focus for achieving teaching and learning objectives was on pure knowledge transfer, the examination format should not include complex application tasks to avoid a discrepancy between the learning and testing situations.

Competence assessment through an examination is not planned in the first phase of this project. Several reasons underlie this decision: Firstly, the VR-Escape Room constitutes a learning activity that is conducted only once. Consequently, the amount of content that can be covered through the learning offering is limited. The plan is to introduce learners to five barriers in a playful manner, which does not allow for the creation of a comprehensive examination. It is only during the debriefing, following the completion of the game that participants are explicitly informed about the learning content. Assessing the learning content immediately in a subsequent examination would only reflect whether learners have temporarily memorized the information from the debriefing. However, assessing competence acquisition in the case of *Access to Escape* is more about whether learners are sensitized to the barriers in the long term and can recognize them and provide solutions even after a significant amount of time has passed. Furthermore, the developed learning offer was evaluated during a pandemic. The presence of an examination and the associated effort could have had a discouraging effect on the already reduced number of participants. Due to these reasons, competence assessment was not initially planned. To still be able to make a statement about the added value of the learning offer and its consequences, the focus shifts to evaluation (see Section V).

IV. Implementation

The implementation is divided into different sections: First, we introduce the VR-Escape Room *Access to Escape* and its learning objectives. They specify what skills and knowledge the learners are supposed to gain. Next, the application of the GAG workflow is presented, which exemplifies how the workflow can be integrated into the development process. Finally, the implemented accessibility features are presented and categories for clustering them are proposed.

A. Access to Escape

At the beginning of the game, the player is in a university building and has to find a certain auditorium. Initially, the person playing is on the first floor where a training room is located. As soon as the player is ready, they can use an elevator to go to the desired location but because of a defect, the elevator crashes shortly after. Finally, the player lands on the basement floor where five puzzles, each representing a barrier, need to be solved to get the elevator running again.

- Puzzle 1: Once the elevator crashes onto the basement floor, a security box opens. In it, a numerical code - the so-called security code - can be seen. There are also three symbols: the London Eye, the Eiffel Tower and the Brandenburg Gate. Under each of the landmarks is a slot. Initially, the card is in the Eiffel Tower slot. To open the elevator doors, the security code must be figured out. Just as in real life, they are supposed to press the emergency button, recognizable by the yellow bell (see

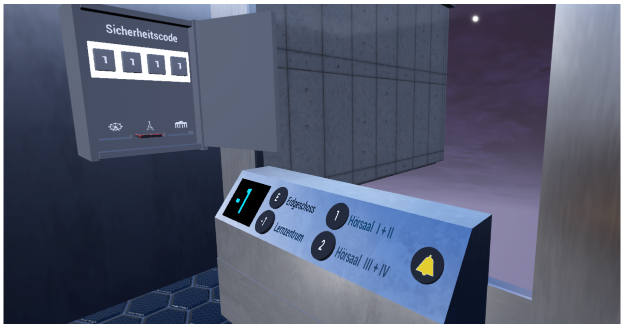

Fig. 1. Puzzle 1: Interior view of the elevator after the crash.

Fig. 2. Access card and scanner to enter a room.

Figure 1). However, the following announcement is not understandable, as it sounds like the French sound image but does not contain any French text. Only when the mentioned card is inserted into the Brandenburg Gate slot the originally German text can be understood. After entering the correct code, which was hinted at by the announcement, the elevator doors open.

The incomprehensible speaker announcement is caused by an incorrect language setting, which introduces the learning objective of the first puzzle: *WCAG success criterion 3.1.1 Language of Page (Level A)*. This success criterion requires the ability to programmatically determine the language of the content at hand. People who use a screen reader will encounter this barrier, for example, when a web page has no or an incorrect language tag. If the screen reader pronounces text in a different sound than the language in which the text is written, the read-out text is very difficult or even impossible to understand.

Fig. 3. Puzzle 2: Overview of the room.

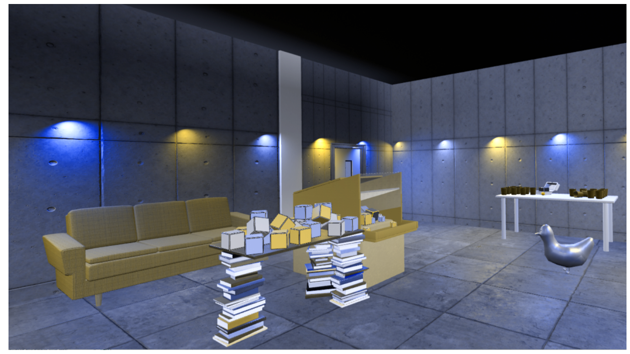

Fig. 4. Puzzle 3: Using a color filter, the player experiences the perception of a person with a color vision deficiency (deuteranopia).

As soon as the player leaves the elevator, they find themselves in the foyer of the former computer science learning center. Various objects can be seen there, some of which resemble the atmosphere of an abandoned building. One object, however, is relevant for the further game: On a shelf is an access card on which the outline of Goethe's head is depicted in reference to the Goethe University Frankfurt (see Figure 2). The scanners on the doors leading from the foyer to other rooms also show a Goethe head. The players should recognize that the access card must be placed on the scanner to open a door. Only one of the doors can be opened with the first access card. Once the correct door is opened, the player can start puzzle 2 (see Figure 3).

- Puzzle 2: Within the entered room, a multitude of blocks are distributed, which are labeled with different letters. An important code, which is needed to move on within the game is projected onto a wall as an extremely blurry image. On another wall, there is a hint: "bei uns können Alle Leute Teilnehmen" (engl. "with us all people can participate", see Figure 3). The incorrect capitalization indicates the solution word: "A", "L", "T". By placing the correct cubes in the designated trays, an alternative text appears on the monitor. In addition, the image on the projector screen becomes sharp. Both provide information about the code that is needed to open the door lock in the room, which hides another access card. In case the player does not find the solution through the clue on the wall alone, there is a Guiding Character, which appears here for the first time and accompanies the player with clues throughout the game. This Guiding Character is a robot chicken that is supposed to represent a project from a university module and claims to have been left behind in this place.

  Puzzle 2 introduces the player to the difficulties caused by inaccessible graphics, which are mentioned in the *WCAG success criterion 1.1.1 Non-text Content (Level A)*. Here, it is described that non-text content needs an alternative textual access point.
- Puzzle 3: After solving the previous puzzle, the player receives another card that allows them to enter a room

Fig. 5. Puzzle 4: Three button options next to the magic carpet, each representing a different heading level.

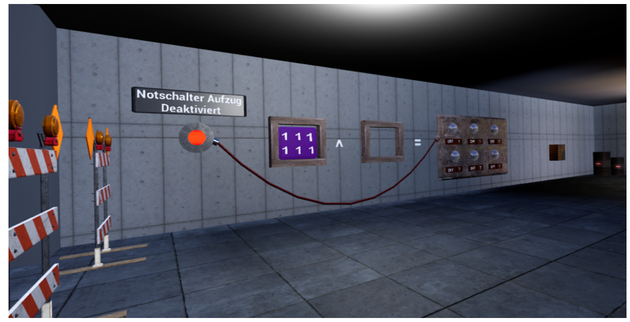

Fig. 6. Puzzle 5: Overview of the room.

containing a color-dependent puzzle. However, just a few seconds after entering the room, they can only see a limited amount of colors due to a color filter, which imitates the color vision deficiency deuteranopia (see Figure 4). As they cannot perceive all colors, the player must consider other ways to convey information, in this case through patterns: To solve the puzzle, the player needs to arrange some blocks on the shelf. But currently, the colors of these blocks look quite similar, making it impossible to get the correct order. The player needs to find a so-called color-scanner, which can add patterns to the blocks. After that, the puzzle can easily be solved.
Here, the player is introduced to the content of *WCAG success criterion 1.4.1 Use of Color (Level A)*, which states that color should not be the only way to convey information. If content is conveyed through color alone, people with limited color perception may not be able to assimilate this information.

- Puzzle 4: In the next room, a cliff has to be crossed by choosing the correct order of labeled buttons, which represent heading levels (see Figure 5) and by that, the player becomes familiar with the content of *WCAG success criterion 1.3.1 Info and Relationships (Level A)*. This success criterion requires that the structure of (web) content must be programmatically determinable. If the correctness of the heading order is not given, the comprehensibility of the digital content is limited.
With a hint from the Guiding Character, the player can cross the cliff, using a so-called magic carpet. The challenge is to understand that the correct heading order is given whenever the current heading level is followed by a level that is either lower, equivalent, or only one level above the existing level. The player can choose between three different buttons each representing a heading level. If the player selects the wrong button they will travel down to that level but immediately get back to the previous position. Only by selecting the correct level, they will advance to a position further ahead and can then choose the next button. Due to simulator sickness, which can occur within a virtual environment [16], we implemented another game mode to solve this puzzle: The player is standing in front of a panel divided into three pieces each representing a heading level equivalent to the buttons of the first game mode. Through teleportation to the piece representing the correct heading level, a new panel appears and the player can again try to select the correct level. Using one of these game modes, the player can finally reach the other side of the room where they find a board with six bits on it that is necessary to solve the last puzzle.
- Puzzle 5: The board discovered in the previous puzzle can now be combined with the existing board in the foyer (see Figure 6). This allows the solution of the resulting propositional logic equation. To operate the lights, three buttons below them can be used: the "OFF" button, which deactivates the respective light; the "ON" button, which activates it; and a "?" button, randomly toggling each of the six lights. The challenge arises from the "ON" button's small size (see Figure 7), often leading to inadvertent contact with surrounding buttons. After several wrong attempts, the puzzle gets blocked by a wall sliding over the light panel. Simultaneously, an audible signal sounds, and a fuse box opens. Among those is the "Lamp Function" fuse, enabling interaction with the light panel. There is also a lever related to button size, initially set to "small". Switching it enlarges the "ON" button to match the others. Consequently, the puzzle can be effortlessly solved following the logical equation and by that, the elevator can be reactivated.
This puzzle is based on *WCAG success criterion 2.5.5 Target Size (Level AAA)*, which states the necessity to maintain a minimum size for buttons (and other interactive elements) in order to guarantee their operability for all users.

B. Implementation of GAG Workflow

The development process of the VR-Escape Room follows the phases of the IGDA workflow for an accessible implementation:

Phase 1 - Familiarization: The structure and content of the GAG and the presented Oculus manual were considered.

Phase 2 - Evaluate & Plan: The GAG are provided in the form of an Excel spreadsheet in which each row represents a success criterion whereas the Oculus manual contains var-

Fig. 7. Puzzle 5: Inaccessible target size of the "ON" Button making it impossible to select the element.

Guideline	Importance	Ease
Hearing		
Basic		
Provide subtitles for all important speech	1	1,5
Provide separate volume controls or mutes for effects, speech and background / music	1	2
Ensure no essential information is conveyed by sounds alone	1	1

Fig. 8. Excel spreadsheet with a rating of guidelines.

ious texts, which are spread over several pages. To allow a structured evaluation, we converted the content of the Oculus manual into an organized Excel spreadsheet. The further evaluation of the now prepared guidelines was approached together with the following phase.

Phase 3 - Prioritizing & Scheduling: The prioritization of the guidelines has been carried out in several steps. First, it was decided that, in addition to the Oculus manual, only the basic GAG guidelines would be considered. These do not require a complex implementation and yet help a large number of gamers, making them a suitable basis for the first prototypical implementation. In the next step, the Excel spreadsheet from phase 2 was extended by two additional columns, "Importance" and "Ease", which take a value between 1 (important resp. easy) and 3 (rather unimportant resp. difficult) for each guideline (see Figure 8). "Importance" is used to indicate how necessary a guideline is for the concrete game experience of *Access to Escape*. Thus, the guideline to use a readable text size is associated with the importance of "1", whereas the guideline to inform about accessibility features during the game is rated with the importance of "2". The latter policy aims to improve the game experience by providing information; the former policy aims to provide a basic perceptible game experience, which is why it is considered more important. "Ease" describes how complex and time-consuming a potential implementation of the policy is estimated. After determining whether a policy applies to the game (see Phase 2), the values of "Importance" and "Ease" were discussed and recorded. By looking at the final scores, a prioritization of the guidelines or features could be performed.

Phase 4 - Implementation: Throughout the development process, the game was evaluated by usability and accessibility experts. Because of these evaluations, an implemented puzzle could be identified as a trigger for simulator sickness and thus as non-accessible. Therefore, an alternative path to the game was developed, which avoids the sickness-indicating factors.

Phase 5 - Informing: Game-internal informing was not considered in the context of the prototypical VR-Escape Room. *Access to Escape* does not have any settings that can be accessed by the players but the implemented policies represent features that are inevitably encountered in the game anyways.

Phase 6 - Assessing & Learning: The testing phase of *Access to Escape* included 11 participants with connections to the study field of computer science [17]. We were present throughout the testing, which made it easy to observe how the participants reacted to the accessibility features. Here, it became apparent that the implemented features were also able to provide a better gaming experience for players without impairments or disabilities. They showed positive reactions to multiple access possibilities. Examples are the textual content conveyance through subtitles, the auditory signaling of events via sound effects, and the haptic feedback in the form of different vibration patterns of the controllers.

C. Implementation of Accessibility Features

This section sketches the implemented and discarded guidelines and presents different categories in which these guidelines can be clustered. The respective categories are not to be considered disjunctively; thus, a guideline that is assigned to one category may also be part of another. In the following, the categories and exemplary associated guidelines are presented in ascending order of effort.

1. Implementation by the game engine: Besides guidelines, which have to be implemented manually, there are also accessibility features, which can be implemented by pre-developed templates of the chosen game engine (in our case Unreal Engine), such as: "Representation of the controllers in the virtual environment" [12]. In order for the players to have a reference to the real controllers during the game and to simplify their use, a virtual copy of the controllers should be displayed (see Figure 7). This not only shows the position of the buttons on the controllers, so that the players do not have to remember them, but also marks the position of the controllers in the real space, and thus simplifies their findability [12]. The game engine Unreal also provides this feature in the engine's own VR-template.

2. Implementation based on prior knowledge of accessibility: Further, there are such guidelines that can be implemented simply and with small expenditure, if there is knowledge of their necessity. One of these guidelines being: "Ensure no essential information is conveyed by a color alone" [8]. Since not everyone can perceive information through color, an alternative form of communication must be implemented [8]. This can be in the form of patterns, icons, or text.

In *Access to Escape*, a combination of these approaches is used. At one point, color signals the activation of a button,

Fig. 9. Visualization of captions of spoken dialogue of the Guiding Character.

which is additionally symbolized by sound and changing text. Another example are color-coded blocks that are equipped with patterns, so that they can be clearly differentiated without the visibility of color.

3. Implementation through elementary game design: A subset of the guidelines can be grouped under features that every common game design includes to make the application fundamentally playable, for example: "Placing UI elements in a user-friendly way" [12]. For an unrestricted gaming experience, the elements of the user interface must be easily accessible and visibly positioned, otherwise the game flow suffers [12]. The chosen position should indicate the relation of the element to the rest of the room.

In our VR-Escape Room, the guideline was planned into the visual conception of the games. The previous considerations about the positioning of individual UI elements have greatly simplified the fulfillment of this guideline.

4. Implementation through high effort: The guidelines sets also include policies that require costly implementation, such as "Provide subtitles for all important speech" [8]. Purely auditory instructions and narrations exclude persons with hearing impairments or persons who are more likely to take in written information from a full game experience [8]. To counteract this, the use of subtitles can be considered.

However, the implementation of these is not possible without further effort using Unreal Engine. The option to add subtitles to audio tracks is offered, but these are displayed in a font size that is too small and in an unsuitable position in the game. During our research, no option could be found to change font size and position, so another approach had to be taken: The subtitles are currently displayed as a separate text field based on predefined time frames (see Figure 9). Due to the complexity of this approach, the subtitles in the prototype were only implemented as an exemplary feature in one scene of the game.

5. Implementation not possible: Lastly, there are policies that have not been implemented. In our case this had several reasons; for one, the guidelines may not be in accordance with the game rules or the game form: "Provide details of accessibility features on packaging and / or website" [8]. To benefit from the implemented accessibility features, players must first be made aware of them [8]. If these are implemented but not advertised, players may overlook them and, therefore, assume that the game is not playable for them. In addition, advertising the features can increase search engine traffic and distinguish the application from other games of the same kind.

However, since *Access to Escape* is only a prototype and currently no public deployment is planned, this policy was not implemented for the current application.

For another, the reason for the lack of implementation may be resource constraints, as some implementations of policies may require additional expertise or time:

"Personalization of Controller-Based Movements" [12]. For example, players who have difficulty holding a game-required arm position for an extended period of time should have the opportunity to personalize controller-based movements [12]. If a position, such as an outstretched arm, cannot be achieved in the real world, it should nevertheless be possible to personalize the parameters of size, rotation or distance, so the virtual arm can be fully extended or moved to a different position. Due to different mobility abilities, these "hand profiles" should be implemented individually for the left and right hand. This guideline was not implemented within *Access to Escape* due to its extensive implementation work and project time restrictions.

V. Evaluation

The evaluation study was conducted with the support of eleven participants from the field of computer science, as they are the primary target audience for the planned learning concept. Among the participants, there were two former students and nine individuals currently pursuing their studies. Over a period of three weeks, they were invited to play the VR-Escape Room in person. After completing the game, the participants were asked to take part in an online survey on-site. This survey was created using the survey and examination software *evasys*, which is used at the Goethe University Frankfurt, among other places, for quality management purposes. The survey primarily consists of two questionnaires: the User Experience Questionnaire (UEQ) [18] and the Course Evaluation Questionnaire (CEQ) [19]. In addition, open feedback was collected, and observations were documented. A comprehensive elaboration of the evaluation results can be found in [17]. Following, the results concerning Accessibility Education collected by the CEQ will be presented.

For the establishment of the VR-Escape Room as a learning offer, it is necessary to evaluate it as such. The CEQ is employed to gather feedback from learners, enabling the identification of positive aspects of the learning offering as well as the investigation and improvement of negative aspects. The CEQ is structured into three sections: *General*, *Educational Objectives* and *Learning Format*. Out of a total of 17 items, 15 are assessed using a 6-point Likert scale (1: strongly agree - 6: strongly disagree). The remaining two items consist of open questions.

As Table I shows, the implemented learning format has the potential to increase knowledge regarding accessibility by understandably conveying content. A somewhat diverse

TABLE I. CEQ - General: Mean values (1: strongly agree - 6: strongly disagree).

Statement (translated from German)	Mean	Standard deviation
The completion of the Escape Room leads to an increase in knowledge.	1.5	0.5
The content is presented in an understandable manner.	1.5	0.7
The relevance of the topics covered is evident.	1.8	1.0

TABLE II. CEQ - Educational Claim: Mean values (1: strongly agree - 6: strongly disagree).

Statement (translated from German)	Mean	Standard deviation
The learning experience makes me see things differently and makes me recognize new connections.	1.5	0.7
The covered topic is comprehensively explored and reflected upon.	1.5	0.5
The learning offer helps me develop my own perspective.	1.5	0.7

range of opinions follows the statement "The relevance of the topics covered is evident." The majority fully agrees with this statement, but one person each chose the options "somewhat agree" and "somewhat disagree". This feedback is significant as a primary focus of the learning offer is to convey the importance of the topic of accessibility and exhibits a matter for further inspection.

The items "The learning experience makes me see things differently and makes me recognize new connections." and "The learning offer helps me develop my own perspective." both receive identical and mostly positive ratings, suggesting that this goal has been achieved (see Table II). The positive agreement with the statement "The covered topic is comprehensively explored and reflected upon" supports the hypothesis that initial steps towards addressing the educational objective of teaching about accessibility and initiating a sense of sensitization have been taken.

The results of the last section of the CEQ show the advantage of an innovative learning format. The participants stated interest in the learning offer due to the use of VR and the Escape Room format even though it was a voluntary learning session about a rather unknown topic (see Table III).

Additional free-text feedback, analyzed using the Summative Qualitative Content Analysis according to Mayring [20], particularly emphasizes awareness of the topic of accessibility.

TABLE III. CEQ - Learning Format: Mean values (1: strongly agree - 6: strongly disagree).

Statement (translated from German)	Mean	Standard deviation
VR has sparked my interest to take part in this offer.	1.5	0.7
I participated because I am interested in Escape Rooms.	1.2	0.4

In five free-text responses, it is highlighted that the VR-Escape Room, for example, "creates attention for a topic that often seems intangible to outsiders" (translated from German) and that "the feeling of having a disadvantage in everyday life becomes practical" (translated from German). Additional benefits of the VR-Escape Room for teaching Accessibility Education can be summarized under the advantages of playful learning, originality, appealing aesthetics, and simplified learning.

VI. Discussion & Limitations

Access to Escape covers accessibility in two kinds of ways: The VR-Escape Room was implemented following the GAG workflow to achieve a low-barrier application (Game Accessibility). Further, *Access to Escape* is supposed to educate about accessibility, so the players experience sensitization for the topic and develop an understanding of different kinds of barriers and how to avoid them (Accessibility Education).

Focusing on the first goal of *Access to Escape*, creating a low-barrier application, challenges need to be addressed. The discipline of Game Accessibility deals with eliminating avoidable barriers for people with disabilities or impairments within the framework of game rules [7]. This creates a dilemma between adhering to the game rules and making the game as accessible as possible. Game rules typically require overcoming intended barriers that are presented in the form of game challenges.

For example, a digital chess game where each move is timed cannot fulfill the guideline of variable game speed without violating the game rules [11]. Furthermore, not every guideline is relevant to every game. For example, the guideline that requires the use of subtitles cannot be applied to a game that does not have audio. Therefore, developers must be aware that a game may not be entirely accessible due to the game rules but also that a game can still be accessible even if not every single guideline is met. Thus, developers are faced with the challenge of recognizing which guidelines are feasible and relevant for the game.

Within the scope of this work, the GAG workflow has proven to be a suitable approach, especially for the needed structured exploration of the guidelines. Furthermore, the transfer of this workflow to other guidelines has also been successful and can be recommended. However, developers must consider that a resource-based prioritization, as suggested in phase 3 of the GAG workflow, cannot produce an accessible application. This goal can only be achieved by implementing all applicable guidelines. The EU Directive 2016/2102 (39) also emphasizes this fact: "Only legitimate reasons should be taken into account in any assessment of the extent to which the accessibility requirements cannot be met because they would impose a disproportionate burden. Lack of priority, time, or knowledge should not be considered as legitimate reasons." Therefore, while the GAG workflow provides a structured approach to developing a low-barrier application, it is only suitable for implementing an accessible application if prioritization within the workflow does not lead to the exclusion of other applicable policies. This is crucial as each guideline ensures the access to the presented content for a specific target group and further, as confirmed by our results, they can improve the game experience for everybody. To comply with all applicable guidelines, it is necessary to schedule enough time to implement accessibility features that were not achieved to the desired extent in the discussed implementation. In retrospect, it could be recognized that a classification of guidelines into categories is possible, which could support better time management during the development process. Another aspect that must be addressed early on during the development process is the cooperation with people affected by impairments or disabilities. Since no test person stated that they are affected, the question of inclusion can only be answered theoretically, not practically.

Having addressed Game Accessibility, we shift our focus to the objectives regarding Accessibility Education.

To clearly define the scope and objectives of the learning offer, Kerres' guide provided a supporting framework [13]. Contexts, stakeholder, teaching objectives and many more components could be specified on a common understanding of the terms and their attributes. Considerations and challenges regarding the learning format and the learning content could be identified.

As defined in Subsection III-D, learners are supposed to acquire competences to remember and understand encountered barriers as well as apply that knowledge by identifying and removing similar ones. The attainment of this goal cannot be answered definitely as there was no examination conducted. This poses a gap that needs to be closed. To do that, the challenges regarding the format of a potential examination need to be addressed (see Subsection III-L), e.g., with the help of long-term participants who could be examined after a longer period of time.

However, tendencies regarding the teaching objective concerning the attitudes of the learners could be identified. The majority of learners stated that they recognized the importance of digital accessibility (see Section V). They experienced a newfound perspective on everyday barriers and felt more aware of otherwise intangible challenges [17], which emphasizes the suitability of the format for this competence dimension.

Another advantage a novel learning format [17] like a VR-Escape Room holds, can be defined by the intrinsic motivation it is able to evoke (see Section V). Students voluntarily registered to participate in the learning session, even though it covered a rather theoretical topic like accessibility. Their motives can be defined by the use of VR and the interest in Escape Rooms.

In conclusion, the development of an accessible VR game requires enough resources and a well-defined time schedule. To plan these factors, the GAG workflow offers a supporting guide but is not sufficient on its own, which is why thorough research and more tangible implementation templates are needed. Moreover, Kerres' guide provided a common foundation for the definition of the learning offer. Expanding on this, the considerations taken in the conception phase simplified the merge of the didactic and technical design. They reported a sense of sensitization and understanding of barriers. A research gap left open states the examination for learning success regarding the competence dimensions of knowledge and cognitive skills. Overall, *Access to Escape* represents a learning format that has the potential to effectively raise awareness among students, and its development process can be replicated through the proper utilization of support resources such as those provided by GAG or Kerres.

VII. Conclusion and Future Work

As a result of the development of *Access to Escape*, approaches to create accessible and innovative learning offers in fields like Accessibility Education could be identified. While *Access to Escape* provides a foundation for tackling the challenge of delivering learning content in an engaging manner, numerous opportunities for further enhancement and expansion were formulated.

A. Conclusion

Summarizing, the research question "What does the design process for creating an accessible VR game entail and what implementation steps are necessary to achieve this goal?" can be answered supported by Kerres' guide and the GAG workflow.

The former offers guidance throughout the development process of a didactic design for a learning offer. It highlighted various aspects that need to be taken into account to create a game that can be used in educational settings.

Based on the results of the developed didactic concept, the game can then be designed accessible using the GAG. The GAG workflow provides a suitable starting point for developing accessible games and a structured approach to working with large sets of accessibility guidelines like the GAG and the Oculus manual. The workflow is especially useful for identifying and prioritizing policies that can be implemented in a first implementation cycle. But here, the examination of the guidelines alone is not sufficient for a sustainable assessment of which prioritization these features should take. A retrospective view of the implemented features shows that preceding steps are needed, like the consideration of the features that the chosen game engine already offers, as well as the documentation of existing implementations. Here, the classification into the categories presented in this paper could benefit the development process. They offer the possibility of assessing the workload that would be needed to meet each guideline. However, since many guidelines fall under the category of "Implementation through high effort" or "Implementation not possible", our VR-Escape Room *Access to Escape* cannot meet the requirements of an accessible VR game. Our research phase indicated that there is a need for low-level solutions for accessible games and VR applications so that accessibility features that were classified under the

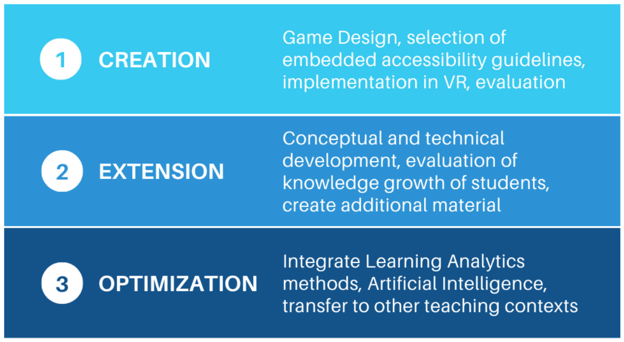

Fig. 10. Three phases of development and research: creation, extension, and optimization.

mentioned categories can ideally be classified into "Implementation by game engine". Since this is not the case yet, the guidelines were implemented in an exemplary manner at various points in our VR-Escape Room, but not consistently, which is unsatisfactory and needs to be addressed in future design iterations. Another aspect that needs to be included in future work is the evaluation of *Access to Escape* by people with impairments or disabilities to get reliable insights into the accessibility of the VR game.

B. Future Work

The evaluation of *Access to Escape* in the first development phase shows that the selected format of a VR-Escape Room is suitable for sensitizing students to digital barriers that may arise (see Section V). This subsection gives an overview of the further development, the related research questions, and discusses different approaches for future work. Figure 10 shows three phases, being creation, extension and optimization of development and research.

With a focus on accessibility [1] and the implementation in VR [17] the first phase has been completed and the results have been published. The initial work is about the game design of the VR-Escape Room, the definition of the topics covered, a state-of-the-art analysis, the implementation of *Access to Escape*, and a first evaluation.

The next steps of development and research are divided into two further phases (see Figure 10), which may overlap in time. In the second phase, the VR-Escape Room will be further developed and improved, and in the third phase, an expansion and integration of learning analytics approaches and AI will be considered.

Following, the conceptual and technical development, game accessibility, possible integration into teaching, and the examination of the learning success are described in detail.

1) Further technical development:

Development environment: After the first development cycle, the question is whether to migrate the VR-Escape Room from Unreal to Unity. A main argument is that it can then be integrated into an overall concept of new learning and teaching spaces as part of other ongoing projects such as *fuels* [21]. However, this step would involve considerable effort.

Improvements based on evaluation results and user feedback The evaluation has shown that the current state of development still needs adjustments and improvement (see Section V). Besides bugfixing, one improvement would be that the Guiding Character provide more assistance, e.g., through time-independent hints.

Multiplayer mode: The current single-player game could be enhanced by a multiplayer mode, increasing the players' motivation. This would also be in line with the typical game mechanics of an Escape Room, which includes team play to encourage the discussion of different approaches.

Learning Analytics & Artificial Intelligence: By integrating learning analytics methods into the VR-Escape Room, learning data can be analyzed. The identification of the relevant data and appropriate collection methods are subject to future projects. Further research will address the elaboration of different scenarios for the application of Artificial Intelligence (AI) such as interactive and adaptive assistance.

Transfer to other topics: Access to Escape was implemented for Accessibility Education. The transfer of the designed learning format to other topics will be approached. This includes the development of an easy replication process and the evaluation of learning success in different fields. Here, projects like UEmbed [22] could allow users without programming knowledge to create a game using the Unreal Engine. Since the tool is modifiable, it could be integrated into the VR-Escape Room project and expanded with new features. For example, options for the type of in-game navigation can be enabled or disabled in advance.

2) Conceptual development:

Cooperation with accessibility stakeholders In further development, increased cooperation with accessibility experts and organizations is sought, and people with disabilities or impairments should be involved in the development process.

Addition of in-depth learning content Access to Escape currently covers the content of five WCAG success criteria. Approaches to the integration of more information on these criteria need to be discussed. However, the presentation of information within the game should not disturb the game flow. Therefore, one strategy would be to create additional material, including explanations of the barriers encountered within *Access to Escape*.

Addition of new learning content In the first version of *Access to Escape*, success criteria were selected from the WCAG and conveyed through puzzles. The goal of future iterations is to include additional success criteria.

3) Game Accessibility:

Using the GAG workflow, a clear prioritization of the guidelines was made, making it possible to identify a first set of guidelines that were implemented within the project scope of *Access to Escape*. However, this can only be a starting point as an accessible application requires the implementation of all applicable guidelines. In future development, the integration of remaining guidelines is a main goal.

4) Integration into educational context:

Currently, *Access to Escape* is not integrated into any university courses. Following the optimization of the VR-Escape Room during phases two and three, it should be considered how to integrate it into courses and curricular planning. One possibility is to develop a module as an addition to an existing course or to create a new, stand-alone course focused on accessibility, e.g., as part of Open Educational Resources (OER).

5) Evaluation:

User testing and feedback User testing with people from different backgrounds, including people with disabilities or impairments is planned to gather feedback on the accessibility of *Access to Escape*. This feedback can be used to iterate and improve accessibility features and the overall user experience. *Evaluation of impact* Further, studies are planned on how to assess the effect of the learning offer on the awareness and knowledge of digital accessibility among participants.

REFERENCES

[1] S. Mateen, P. Wiesemüller, and S. Voß-Nakkour, "Design of an Accessible VR-Escape Room for Accessibility Education," *SMART ACCESSIBILITY, IARIA*, 2023.

[2] S. Lewthwaite and D. Sloan, "Exploring pedagogical culture for accessibility education in computing science," in *Proceedings of the 13th International Web for All Conference*, 2016, pp. 1–4.

[3] Y. N. El-Glaly, "Teaching Accessibility to Software Engineering Students," in *Proceedings of the 51st ACM Technical Symposium on Computer Science Education*, 2020, pp. 121–127.

[4] C. Putnam, M. Dahman, E. Rose, J. Cheng, and G. Bradford, "Teaching Accessibility, Learning Empathy," in *Proceedings of the 17th International ACM SIGACCESS Conference on Computers & Accessibility*, 2015, pp. 333–334.

[5] D. Kletenik and R. F. Adler, "Let's Play: Increasing Accessibility Awareness and Empathy Through Games," in *Proceedings of the 53rd ACM Technical Symposium on Computer Science Education V. 1*, 2022, pp. 182–188.

[6] S. Kavanagh, A. Luxton-Reilly, B. Wuensche, and B. Plimmer, "A systematic review of virtual reality in education," *Themes in Science and Technology Education*, vol. 10, no. 2, pp. 85–119, 2017.

[7] T. Westin, J. J. Ku, J. Dupire, and I. Hamilton, "Game Accessibility Guidelines and WCAG 2.0 – A Gap Analysis," in *International Conference on Computers Helping People with Special Needs*. Springer, 2018, pp. 270–279.

[8] I. G. D. Association. (2021) "Game Accessibility Guidelines - A straightforward reference for inclusive game design". Last visited: 2023.09.15. [Online]. Available: https://gameaccessibilityguidelines.com/

[9] R. Ossman, "Guidelines for developing accessible games," *Retrieved August*, vol. 12, p. 2011, 2006.

[10] J. R. Porter and J. A. Kientz, "An empirical study of issues and barriers to mainstream video game accessibility," in *Proceedings of the 15th international ACM SIGACCESS conference on computers and accessibility*, 2013, pp. 1–8.

[11] B. Yuan, E. Folmer, and F. C. Harris, "Game accessibility: a survey," *Universal Access in the Information Society*, vol. 10, no. 1, pp. 81–100, 2011.

[12] Oculus. (2022) "Designing Accessible VR". Last visited: 2023.09.15. [Online]. Available: https://developer.oculus.com/resources/design-accessible-vr/

[13] M. Kerres, *Didaktik. Lernangebote gestalten. (engl. 'Didactics. Designing learning offers.')*. Waxmann, 2021.

[14] German Bundestag, "Verpflichtung von privatwirtschaftlichen Unternehmen zur Herstellung von Barrierefreiheit in den USA, Österreich und der Schweiz. (engl. 'Obligation of private sector companies to create accessibility in the USA, Austria and Switzerland.')," 2018.

[15] I. for Computer Science (Goethe University Frankfurt). (2021) Modulkatalog Bachelorstudiengang Informatik (engl. 'The module catalog for the bachelor's program in computer science'). Last visited: 2023.09.15. [Online]. Available: https://www.uni-frankfurt.de/104692860.pdf

[16] C. Palmer and J. Williamson, *Virtual Reality Blueprints: Create compelling VR experiences for mobile and desktop*. Packt Publishing Ltd, 2018.

[17] P. Wiesemüller, S. Mateen, S. Voß-Nakkour, and A. Dengel, "Access to Escape - An Immersive Game-Based Learning Experience for Accessibility Education in Virtual Reality," in *2023 9th International Conference of the Immersive Learning Research Network (iLRN)*. IEEE, 2023.

[18] M. Schrepp, "User experience questionnaire handbook," *All you need to know to apply the UEQ successfully in your project*, 2015.

[19] studiumdigitale. (2022) Qualitätsentwicklung durch Evaluation (engl. 'Quality development through evaluation.'). Last visited: 2023.09.15. [Online]. Available: https://www.studiumdigitale.uni-frankfurt.de/58533111/Evaluation

[20] P. Mayring, *Qualitative Inhaltsanalyse (engl. 'Qualitative content analysis')*. UVK Univ.-Verl. Konstanz, 1994, vol. 14, ch. 4.

[21] fuels. (2023) fuels – future learning spaces. Last visited: 2023.09.15. [Online]. Available: https://futurelearning.space/

[22] I. Hossain, L. Weist, and S. Voß-Nakkour, "UEmbed: An Authoring Tool to Make Game Development Accessible for Users Without Knowledge of Coding," *SMART ACCESSIBILITY, IARIA*, 2023.

Digital Transformation after Covid-19 and the Balancing Act of Digital Teaching

A Qualitative Study

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***Abstract*—With the Covid-19 pandemic, academic teaching changed fundamentally and university teachers across the board came into contact with the opportunities and challenges of digital teaching. The impact of this change, with both positive and negative consequences, requires adjustments at different levels of the university system, ranging from re-design of learning formats, to the expansion of qualification offers for teachers, to new rules for what is credited towards the teaching load. An exploratory study was conducted to examine the impact of the pandemic on university faculty attitudes toward digital teaching and reflect on the advantages and disadvantages that have arisen as a result of digital teaching and what benefits the independence of location and time as well as the possibilities of digitalization have yielded for teachers and students. Additionally, the study aimed to analyze perceptions of and opinions on digital teaching as well as statements about future teaching. For this purpose, 13 semi-structured interviews with higher education teachers and deans of studies at a large German university were conducted and analyzed using inductive categorization. One result is that teachers describe the use of digital tools and methods as more natural and perceive a digital culture change, also thanks to improved infrastructure. Furthermore, four positions could be identified that describe the different perspectives of higher education teachers on the possibilities of digital teaching and the value of on-site teaching. When assuming a certain degree of heterogeneity among students, this results in a tension field of advantages and disadvantages for students, depending on the chosen teaching formats and preferences of the teachers. In this article, reasons behind these four different perspectives are discussed as well as recommendations given for the future design of post-pandemic teaching.**

Keywords-culture change; digital transformation; digital learning and teaching; higher education; digital accessibility.

I. Introduction

During the Covid-19 pandemic, academic teaching changed fundamentally and university teachers across the board came into contact with the opportunities and challenges of digital teaching. The impact of this change brought both positive and negative effects [1]. Teaching was largely maintained and many teachers experienced an increase in digital teaching skills, but the dynamics of the transition often led to emergency solutions that only insufficiently exploited the didactic potential of digital media [2]. The question arises whether, beyond this emergency remote teaching [3], teachers today perceive a stronger anchoring as well as more natural use of digital media in teaching. Such a digital culture shift requires instructors to (voluntarily) move away from familiar teaching strategies and practices [4], which many instructors are hesitant towards [5]. Conversely, culture change also requires students to adapt their learning habits [6]. Graf-Schlattmann et al. [7] describe a prerequisite for culture change as social acceptance in the teaching environment. All stakeholders share the conviction that the changes associated with transformation are necessary and are associated with both individual and organizational benefits.

The first reaction of many universities after the end of the full lockdown was to return entirely to on-site teaching. However, as experience reports show, this also has many disadvantages for students and teachers, and especially the aspect of (digital) accessibility [8][9][10]. The (forced) experiences with digital teaching, without the possibility to meet in presence, were perceived very differently on several levels. With regard to study organization, flexibilization, study performance and learning success, communication and interaction, motivation and competencies, both positive and negative experiences were made by students and higher education teachers [8]. During the pandemic, it also became clear that what is a relief for some can be a complication for others [11]. It can be seen that educators must operate in an area of tension with respect to post-pandemic digital teaching. Considering their own needs and the needs of a heterogeneous student body is a particular challenge. Although higher education recognizes the diversity of students as reality in its mission statements, in reality heterogeneous learning situations are rarely taken into account in the conception of teaching scenarios, or are only taken into account by teachers when students articulate individual needs and request support [9].

An explorative, qualitative study was used to investigate the impact of the pandemic on university teachers' attitudes toward digital teaching and whether the experiences during the pandemic have led to a digital culture change in teaching. This involves a more detailed analysis of the patterns of argumentation found among teachers with regard to the selection and design of teaching formats and scenarios and how they justify their decisions for and against digital teaching. Section II describes the conducted qualitative study.

We asked about consequences of the pandemic on teaching, experiences during the pandemic related online semesters, about changing attitudes and possible reservations about digital teaching, and the advantages teachers see in digital teaching, in order to illuminate a possible area of tension caused by different needs and teaching requirements. This results in the following three research questions for analysis:

RQ1: What are the perceived impacts and consequences of the pandemic on academic teaching for higher education teachers in the post-pandemic period?

RQ 2: What reservations do higher education teachers express about digital teaching and how does this impact the future conception of their courses?

RQ 3: What advantages do teachers see in digital teaching and what should be retained after the pandemic induced online semesters?

Section II describes the research design, the data collection methods, the selection of participants and the methodological approach to data analysis. In Section III, the findings from the interviews conducted are presented in detail and discussed in Section IV Some teachers prefer on-site teaching and have concerns about digital methods, while others recognize the benefits, such as increased motivation and organizational ease. It is emphasized that a balance must be found between the advantages and disadvantages of both approaches in order to create inclusive and effective teaching. Finally, the last Section V, conclusion and future work, highlights the four positions that describe the tension between digital and face-to-face teaching. It emphasizes the importance for teachers to consider these different perspectives at both an institutional and individual level.

II. Methodological Approach

In order to answer the research questions, a total of 13 individual interviews were conducted with teachers from a large German university. Eight interview partners were from faculties of the natural sciences and medicine, three from social sciences, and two from the humanities. Among the 13 interview partners, 10 were simultaneously acting deans of studies of their respective faculties. The interviews were carried out in German language and the transcripts of the interviews were translated into English. The guiding questions were slightly modified for this group of persons. The individual interviews were carried out between 07/01/2022 and 08/02/2022 via videocall using Zoom videoconferencing software. To ensure the anonymity of the interviewees, no further personal data was collected.

The interview procedure chosen was the problem-centered interview according to [12]. This method tries to let interview partners speak as freely as possible to come as close as possible to an open conversation. At the same time, however, the interview is oriented toward a previously determined problem, the details of which are compiled in advance in an interview guide. For the study, two guides for research questions were developed (deans of studies and higher education teachers). To avoid the interviewees formulating their assessments of reservations and advantages of digital teaching too broadly or too abstractly, they were asked to describe their experiences and impressions from different phases of the COVID-19 pandemic in each case. This is reflected in the wording of the questions in the interview guides, which respectively refer to the lockdown phase of the pandemic with Emergency Remote Teaching [13] and the post-pandemic phase, in which teaching returned to a "New Normal" [14]. The two interview guides included the following questions:

Interview guiding questions for deans of studies: How did faculty members perceive virtual teaching during the past three online semesters? Are the teaching experiences from this time viewed more positively or negatively? To what extent? / What do you think are the reasons for this?

In your estimation, inasmuch did the Corona pandemic change attitudes toward digital teaching among faculty members, if at all?

What were the reactions of faculty members this semester when the "back to on-site teaching" tendency emerged?

What reservations about digital teaching do you currently perceive on behalf of the faculty? (technical problems, social problems, didactic limitations, etc.). In your estimation, to what extent are these reservations related to the experiences from the Corona semesters?

Interview questions for teachers: How do you assess your experiences with digital teaching during the past Corona semesters? What are the reasons for your assessment?

What negative effects of digitalization processes in teaching do you see? What kinds of downsides emerge from them?

Has your attitude towards digital teaching changed as a result of the pandemic? In what way?

Have you used digital teaching practices, methods and tools from the Corona semesters in this semester? - If not, what are the reasons for this?

The recorded interviews were automatically transcribed with the software Amberscript and completely anonymized so that no more conclusions can be drawn about persons or subject discipline. Subsequently, the material was analyzed in a Qualitative Content Analysis (QCA) according to Mayring [15] with the software QCAMap. An inductive evaluation method was chosen, in which the category system is developed from the material concurrently with the analysis and evaluation process, guided by the research questions. The coding of the interviews was done in an inter-coder procedure with two coders each. The reliability of the overall result was ensured by checking all codes during an evaluation conference with all four coders. In this session, major categories were also formed from the individual categories, which are described in the following section.

III. Results of the qualitative content analysis

The qualitative content analysis of the transcripts was conducted along the three research questions RQ1, RQ2 and RQ3 (see Section I) and the results are presented separately below.

A. *Perceived impacts and consequences of the pandemic on academic teaching for higher education teachers in the post-pandemic period (RQ1)*

With regard to the perceived impact on post-pandemic teaching (RQ1), a total of 32 categories were identified during the analysis of the interviews, which could be assigned to five superordinate categories (cf. Tab. I). Along these upper categories, a selection of the most relevant categories will be discussed in more detail below.

1) *Digital Normality*

Nearly all interview partners (12 of 13) describe that in the course of the pandemic distance learning, a new normality of using digital media in teaching has emerged. This digital cultural shift toward a New Normal [14] has led to changes in the design of teaching that are currently still ongoing and have lingering effects. In particular, faculty cite the decreased skepticism toward digital teaching due to the growth in experience (RQ1-01) during the pandemic. Even if the turn to online-supported teaching was not entirely voluntary, in retrospect it is seen as valuable, as described by interviewee 8, for example:

> *"So that has definitely been a positive side effect of the fact that you were forced to teach digitally. That one has acquired the techniques and then also seen the advantages, which of course also exist." (IP08)*

In the course of the positive experiences, the willingness of the interviewed teachers to increasingly use digital elements in teaching grew (RQ1-19) and to offer events hybrid, i.e., both synchronously and asynchronously (RQ1-17). The fact that the use of digital media has become more natural for the lecturers and that the initial skepticism has decreased is also observed by interviewee 9. In his function as Dean of Studies, he describes the development thus:

> *"I think it was an experience and development work for many lecturers. So, I perceived that as a dean of students, [there] was a lot of rejection in the beginning. So, people wanted to stick close to their usual format, the lecture or seminar. So, in the beginning, people didn't get along well with asynchronous, but thought that if anything, then synchronous. And at that time I'm standing in my lecture hall as usual and well, then a camera is running if it has to be. And that was, that was a lot of voices at the beginning. And then in the three semesters, already in the second semester, I noticed that there was a development that people got involved in offering more and more asynchronous lectures. This means that lectures and seminars are first recorded and then made available at another time. So, all in all, after the three semesters, I would say that the overwhelming majority or the vast majority of the faculty have found this to be an enrichment." (IP09)*

As faculty became more willing to engage in teaching with digital media, interviewees also became more eager to try out new technologies and experiment with digital elements and tools (RQ1-21). At the same time, faculty reported how the new digital normal emerged outside the teaching context as well. For example, videoconferencing became a natural means of communication (RQ1-24) even beyond the Covid19 pandemic. As further evidence of the incipient cultural change towards a new digital normality, attitudes of lecturers towards their own digital teaching actions can be seen: The respondents are very satisfied with their own digital teaching (RQ-3) and, as individual teachers report, would also like to continue using digital elements (RQ-8). Even if these teachers are still a minority at the moment, interviewee 6 nevertheless emphasizes

> *"[...] that it's still a minority, but maybe not a very small one, that would say 'Well, even if it's not required at all because of the pandemic, I'll definitely turn on online elements.'" (IP06)*

Instructors also observe the newly normalcy of digital university teaching in changing and continuing student behavior. For example, faculty report that students increasingly view face-to-face and online teaching as equally valid alternatives. On the one hand, while instructors note a decreased willingness of students to be mobile due to the pandemic (RQ1-6), as well as an increased expectation among students that content be additionally offered digitally (RQ1-27). Students would also prefer to use recordings instead of attending face-to-face lectures (RQ1-9) and would be more likely to stay away from face-to-face lectures if digital alternatives were offered (RQ1-20). On the other hand, students do not seem to want the digital normality of university teaching to be complete digitization. Rather, students expect digital offerings to be available as a matter of course in order to be able to adapt their studies as flexible as possible to individual circumstances, as interviewee 9 notes:

> *"I think it looks different for students than for teachers, yes. With students, you hear more often that they really want to have a choice, presence or digital. For different reasons, personal reasons." (IP09)*

TABLE I.
EFFECTS OF COVID 19 REGARDING DIGITAL TEACHING (RQ1)

CATEGORY ID	CATEGORY NAME	ABSOLUT COUNT
Digital becomes normal - cultural change		53
RQ1-1	Increased experience and less scepticism towards digital teaching	19
RQ1-3	High satisfaction with own digital teaching during C19 among teachers	4
RQ1-6	Students less willing to move after C19	2
RQ1-8	Teachers would like to continue teaching digitally	3
RQ1-9	Students want to make more use of recordings instead of attending face-to-face lectures as a result of their experience during the pandemic	3
RQ1-17	Teachers offer hybrid courses (synchronous & asynchronous)	5
RQ1-18	Students use face-to-face courses despite online offers	2
RQ1-19	Teachers more willing to use digital elements	7
RQ1-20	Students stay away from face-to-face courses if digital alternatives are available (e.g., recording, streaming etc.)	2
RQ1-21	Teachers start experimenting with digital elements and tools	2
RQ1-24	Video conferencing has become normal and is no longer a hurdle	1
RQ1-27	Adoption of digital teaching practices and methods in face-to-face teaching	2
RQ1-30	Students increasingly use digital devices in the courses	1
Experience gain		21
RQ1-4	Increased experience and more scepticism towards digital teaching	3
RQ1-10	Teachers more willing to make content available digitally	4
RQ1-14	Teachers felt confirmed in their opinion regarding digital teaching	3
RQ1-15	Teachers are positively surprised by the possibilities of digital teaching	2
RQ1-16	Teachers could gain experience with digital teaching	6
RQ1-22	Teachers feel prepared for future disruptions to face-to-face teaching	2
RQ1-31	Students increasingly work with digital tools (e.g., for seminar recordings etc.)	1
Establishment of new organisational structures and digital infrastructure		8
RQ1-12	Contributes to learning success	1
RQ1-25	Is popular among students	3
RQ1-26	Good online offers are used and replace face-to-face offerings	4
Improvement of teaching		7
RQ1-11	More care in the creation of teaching-learning materials	1
RQ1-13	Teachers are more concerned with the needs of students	2
RQ1-23	Increased student participation and collaboration	1
RQ1-28	Establishment of innovative teaching formats (e.g., flipped classroom)	2
RQ1-29	Teachers were happy to return to face-to-face teaching	1
Lowered motivation and willingness to perform		6
RQ1-2	Students have agreed on online examinations	1

RQ1-5	Drop in student performance due to C19	3
RQ1-7	Corona used as an excuse by students for poor academic performance	1
RQ1-32	Indiscipline of students with digital teaching	1
		95

2) Increase in experience of Teachers in Higher Education

As a further effect of the pandemic on university teaching, an increase in experience can be identified in the interviews. The interviewees observe this increased experience in dealing with digital teaching (RQ1-16) primarily in themselves as well as in their colleagues. In this context, they report on the special circumstances of the pandemic, which led them to methodological-didactic experiments that they would not have attempted in normal face-to-face operations:

> *"A lot of things during that time, from a didactic point of view, were also exciting at times, because we had to try things that we might never have taken on otherwise, or might not have even dared to try." (IP11)*

The teachers interviewed would like to continue to use the skills they acquired during the pandemic in dealing with digital media. This is expressed, for example, in a greater willingness to provide content in digital form in addition to traditional classroom teaching (RQ1-10):

> *"I have learned something and I am very happy about that because I can now continue to use it. So now I know how to make videos and I will certainly continue to do that, offer videos or Yes, you can also do that for exercises. So that's definitely been a positive side effect of being forced to teach digitally." (IP08)*

The assessments of the teachers regarding the possibilities of digital teaching differ greatly. Some teachers report in the interviews that they are positively surprised by the didactic possibilities of digital teaching (RQ1-15), whereas others feel rather confirmed in their opinion of digital teaching (RQ1-14). This assessment is shared especially by those interviewees who already had a positive attitude towards digital teaching before the pandemic, such as interviewee 10:

> *"[...] I would say I was open-minded about it before. I am now, too. In that respect, the real attitude has not changed." (IP10)*

However, individual teachers also repeatedly express their skepticism about the possibilities of digital teaching in the interviews (RQ1-4). Based on their experiences during the pandemic, these teachers have a rather negative assessment of the effectiveness of digital teaching and, like interviewee 4, are rather disillusioned:

> *"[...] the reservations have become greater. [...] we know how it works, but it works badly." (IP04)*

Even if the instructors have different assessments of the potential of digital media for university teaching, most of the interviewees see themselves as well prepared for future interruptions of face-to-face teaching at the university (RQ1-22), as interviewee 6 also states:

> *"And there I would say, however, so even if there is once again, let's say, forced, a considerable transition is necessary, there I would already say, based on the experience we have gained there, we should actually be quite well equipped." (IP06)*

3) Establishment of new organizational structures and digital infrastructure

The perception of a common usage of digital tools and methods is accompanied by the perception of a surge in digitalization that has facilitated the uncomplicated and low-threshold use of digital tools due to an improved infrastructure (RQ1-25). The establishment of this infrastructure enables straightforward digital working for students as well as instructors, as an example statement shows.

> *“I cannot remember bringing printed-out slides either; rather the students bring their tablets and practically take notes on my slides. That is very noticeable for me. It seems like there was a technology boom among the students.” (IP13)*

Moreover, since the onset of the pandemic, digitalization services are available at the university, for example at the library or in laboratories, making the production and distribution of digital materials easier (RQ-26).

> *“Using the university library for very quickly available scans, for example, as digital data. You know, after the university library was closed down. Everybody perceived that very positively.” (IP12)*

These digital materials are then made available asynchronously online or used for on-site teaching (RQ1-26). As an example of application, interviewee 12 goes on pointing out:

"And of course, at least that is also the case at our department, there has been a bit of a shift towards […] well, we developed teaching elements, developed digital elements, that can then be used in on-site teaching." (IP 12)

However, an improved infrastructure and the provision of digital services are not the sole outcome of this surge in digitalization. It has also had an impact on the establishing of new organizational structures, such as working groups at departments that function as Communities of Practice and provide cooperative support for the use of digital tools and methods (RQ1-12).

"So, in early April we already established a working group on digital teaching that I was a member of." (IP05)

4) Improvement of teaching

Beyond the infrastructural and organizational changes, faculty members also perceive a qualitative improvement of teaching to be a result of the pandemic. Firstly, instructors report being more diligent in creating teaching-learning materials for digital scenarios (RQ1-11). Secondly, also during the pandemic, they thoroughly attended to the students' concerns (RQ1-13).

"During the Corona times, many instructors engaged with their students quite intensively, so that the social aspects were never fully lost." (IP05)

That intensive interaction between instructors and students is also possible during asynchronous learning phases and results in high quality teaching (RQ1-23) can be seen in a statement of interviewee 11.

"So, we've reached a higher level, which we noticed in the students' inquiries, in the participation and the joint work on the material that was previously provided online." (IP11)

Instructors also acknowledge the increased flexibility of their day-to-day business due to the possibilities opened up by digitalization (RQ1-29). As an example, interviewee 12 mentions the practical and flexible option to digitally communicate with students via video conferencing.

"And right now I find that, I don't find that inconvenient or impractical at all, the scheduling of, of appointments and of supervision meetings, I have in fact held several of those via zoom, of course also during the past semesters after the pandemic. And I believe that this is well-received, if you're just a bit flexible." (IP12)

5) Decreased motivation and willingness to perform

In addition to the aforementioned improvements, instructors also perceive negative impacts of the pandemic on teaching and learning in higher education. Some instructors report a drastic decrease in student performance during the pandemic (RQ1-5), which manifests in a higher percentage of weak exam performances and a lacking willingness to perform (RQ1-7). Instructors also observe that some students struggle with bridging gaps and making up for deficits as they have difficulty motivating themselves to resume their studies, thus widening the gap between high- and low-performing students.

"But the low-performing students don't read anymore at all. And then you notice, it's drifting apart." (IP05)

Furthermore, individual instructors reported negative behavior on behalf of the students during the pandemic. They mentioned students colluding during online exams (RQ1-2) as well as how some students' lack of discipline impaired their teaching.

„First you turn off the video, to still keep the sound, which keeps working. But once it is sound only, suddenly there is no reply anymore […] or then the mobile phone rings. You know these effects. And of course we can always attribute this to a lack of discipline. We can say, okay, he should come to Frankfurt, given that being a student is his main occupation, he should already get proper equipment and a proper DSL connection and so on. That's something you can expect, it doesn't cost much these days. But sadly we also always have to deal with the students' lack of discipline." (IP04)

B. Reservations about digital teaching (RQ2)

The reservations about digital teaching expressed by the teachers in the interviews address social, didactic, organizational and technical aspects. The statements of the teachers were assigned to a total of 56 different subcategories, which in turn can be summarized in 10 main categories (See Tab. II). A selection of the most relevant categories will be discussed in more detail in the next section.

1) Social aspects: Lack of contact and absence

Frequent concerns expressed by teachers about digital teaching relate to social aspects of the teaching-learning process, such as a lack of social contact, insufficient contact with the subject and also (physical) absence from the learning location. The interviewees complain that there is no direct contact in online scenarios (RQ2-1) and thus no real discourse and dialogue as well as no sufficient interaction (RQ2-2). Interview partner 3 (IP03) describes it like this:

> *“Even in the lectures we try to include as many practical elements as possible. And even if it’s just a matter of discussing problems and getting the students involved in the dialogue, so to speak, so that they have to think about it and follow the train of thought and not just sit there and let it wash over them. Of course, that doesn’t work in the digital world.” (IP03)*

Digital teaching would also lack the spontaneous small talk before and after the lecture (RQ2-23). As online lectures end abruptly, student communication is assumed to suffer (RQ2-39) due to a lack of opportunities for exchange, discussion and reflection (RQ2-24, RQ2-25). This is regretted by interview partner 5:

> *“On the way to the seminar, they talk about the content of the seminar, as well as about the lecturer. But they reflect in the process. This reflection is lost.” (IP05)*

2) Pedagogical-didactical reservations and motivational aspects

Some of the reservations expressed in the interviews relate to the didactic design possibilities of digital teaching. In the eyes of some interview partners, these are less effective than those available in face-to-face teaching (RQ2- 36). Likewise, the willingness and ability of students to perform presumably decreases in online teaching (RQ2-22). Several of the interviewees also point out that digital teaching- learning formats are didactically flawed and generally do not correspond to their ideas of "good" teaching (RQ2-11). Interview partner 6 says, for example, videos would tend to prevent engagement with texts (RQ2-38):

> *“To understand the digitization of teaching as a bit of an alternative to text-based teaching, so to speak, in the direction of, let’s say, video or audio content, that would also be a problem from our specialist point of view" (IP06)*

Teachers are also dissatisfied with the didactic possibilities of the existing systems. In their opinion, the systems and tools are not very appealing in design and could be more playful (RQ2-31). Teachers also perceive the “digital divide” associated with online teaching as problematic, i.e. the effect that high-achieving students benefit more from digital teaching than lower-achieving students, who tend to be disadvantaged by the use of online teaching (RQ2-53). Interview partner 8 describes their experience as follows:

> *“I think that to those who are good didn’t matter that much because they dealt with it well. But those who are not so good, you lost them to a certain extent because you couldn’t nudge them directly." (IP08)*

The respondents attributed this effect to the fact that lower- performing students in particular were less motivated in online teaching (RQ2-10). Due to the lack of scheduled learning opportunities in presence as well as the lack of social exchange, students partly lose the structure for their daily study routine (RQ2-47) and learn less as well as less independently (RQ2-42).

3) Organizational and legal barriers

In addition to concerns about the didactic reservations of digital teaching, the interview partners also mention organizational and legal reservations about the increased use of virtual and hybrid teaching formats. Digital teaching is above all time-consuming (RQ2-5) and expensive (RQ2-32), as teachers sometimes have to familiarize themselves with new tools first (RQ2-45), must first create or prepare additional materials or provide additional online support. According to the interviewees, the additional workload then leads to work intensification and deadline pressure (RQ2-27). Teachers see it as particularly problematic that the amount of work they invest in producing and supporting additional digital courses is not remunerated (RQ2-37). Interview partner 6 said:

> *“Well, I’m basically doing face-to-face teaching, but I’m also doing a lot of nice digital stuff on top of it, a bit of personal commitment that you do because it’s close to your heart. But the effort is somehow not compensated in a certain way." (IP06)*

In addition to the extra effort, respondents also raise legal concerns about the use of digital teaching. For example, Interview partner 3 argues that online is rarely compatible with legal regulations such as the licensing regulations for medical professions (RQ2-18):

> *“If we do not return to real practical content, we are not educating future doctors properly. That is a very clear fact. So we are in breach of the licensing regulations, so to speak, if we continue to keep them away from the hospital bed." (IP03)*

Last but not least, respondents also fear that their digital course material will be distributed uncontrolled and illegally on the web (RQ2-13).

4) Technical barriers

The implementation of digital teaching is inextricably linked to the use of different digital tools, systems and technologies. Thus, various reservations are also mentioned in the interviews that are closely related to the use of technology as well as the specific characteristics of the respective technologies used. In addition to infrastructural problems such as an inadequate WLAN connection (RQ2-54), the usability of the available digital systems is criticized as being inadequate, especially for "beginners" and digitally less inclined teachers (RQ2-9). Interview partner 10:

> *“Where the eLectures are recorded and where you can also upload things yourself as a user. [...] I also used that once, I have to say at the beginning, and then found it complicated after all." (IP10)*

It is often the university’s own systems that do not work well (RQ2-46). Another reservation is the fact that some technological solutions (such as AR or VR applications) offer didactic advantages, but cannot be used properly on a broader scale at present (RQ2-19) as interview partner 3 argues:

> *“VR is indeed quite nice, but as I said, it is still a long way from being usable for all students. There are not enough devices." (IP03)*

In addition to these points, which relate more to the teachers themselves, the interviewees also bring up technical barriers on the part of the students that limit or even prevent their participation in digital teaching. First and foremost, an insufficient internet connection of the students is mentioned (RQ2-17) as well as a general uncertainty of the teachers due to the technical challenges on the part of the students (RQ2-41).

5) Personal reservations and lack of teaching skills

While the reservations about digital teaching described so far tended to be of an external nature, the respondents also mentioned internal reasons. These include, on the one hand, personal sensitivities and preferences of the teachers, but, on the other hand, also their own teaching competence levels, which are perceived as insufficient. The personal reservations mentioned include fear of the unknown (RQ2-49) or the uncomfortable feeling of communicating with students via camera and microphone (RQ2-40). For example, interview partner 12 reports that

> *“the tiles were black, and speaking to a black screen, especially in the first semester, for example, was considered by many to be very unusual or difficult to get used to and not very advantageous." (IP12)*

Furthermore, some teachers have the opinion that a majority of their colleagues would prefer face-to-face teaching to online teaching (RQ2-34) or they themselves could not imagine teaching online (RQ2-48). However, there were also complaints about the lack of support from the university, especially with technical problems (RQ2-51), which prevented them from incorporating more digital elements into teaching. Interview partner 11 is disillusioned, given that

> *“the technical support was rather poor and we had to work out a lot on our own." (IP11)*

Last but not least, the teachers also surveyed a lack of competences as a reason for not offering more digital teaching. The main reason cited here is the lack of digital skills among teachers (RQ2-4), which made it difficult to deal with the tools needed, as interview partner 5 explains:

> *“Of course, there were enormous difficulties in dealing with a digital format, for example. So how do I actually do an online session or something?" (IP05)*

Similar problems in the use of technologies for digital teaching are described by interview partner 2:

> *“But I have no idea how to create these videos in a visually different way and maybe put them on another page. [...] Or what is a Scorm learning content. These are all things that you normally have no idea about" (IP02),*

and interview partner 13

> *“How does zooming work? What is the best way to do it? [...] There was a lot of uncertainty on all sides." (IP13)*

A lack of didactic skills is also cited as a further obstacle to the more extensive use of digital teaching (RQ2-20). Interview partner 5 recognizes the greater deficit here.

> *“For me, it was relatively clear that the know-how was still lacking on the part of the teachers, both from a didactic and a technical point of view. Above all from a didactic point of view." (IP05)*

In addition to the competence deficit, the interviewees also mention the problems caused by the introduction of new technologies (RQ2-6) and insufficient guidance and instruction on new digital systems as further barriers to the use of digital teaching (RQ2-52).

TABLE II.
RESERVATIONS ABOUT DIGITAL TEACHING (RQ2)

CATEGORY ID	CATEGORY NAME	ABSOLUT COUNT
Lack of contact with the subject matter		**32**
RQ2-3	Blackboard notes difficult to transfer into digital format	3
RQ2-7	Experiments and practicals not transferable to digital	13
RQ2-8	Lack of haptics, lack of contact with real-world objects	10
RQ2-15	certain course is not suitable for digital teaching	4
RQ2-56	Teaching at the bedside not transferable to digital	2
Missing competencies		**35**
RQ2-4	Lack of digital competence of teachers	15
RQ2-6	Introduction of new technology causes problems	8
RQ2-20	Teachers lack didactic competencies for digital teaching	4
RQ2-21	Available tools are too complicated	6
RQ2-52	Insufficient guidance/instruction for new digital systems	2
Lack of social contact		**56**
RQ2-1	Lack of direct contact/social contact	23
RQ2-2	Online no dialogue/no argumentation/no interaction possible	24
RQ2-22	Organizational questions can be clarified faster and easier in presence	1
RQ2-23	In the digital world, "small talk" is missing / events end abruptly	1
RQ2-24	Without e.g., walking together to the place of learning, there are no opportunities for discussion and reflection of the contents	4
RQ2-25	Lack of exchange with colleagues	1
RQ2-39	Communication between students suffers in the digital world in comparison to the presence.	1
RQ2-50	Lack of body language in video conferences	1
Organizational reservations		**29**
RQ2-5	Organizational reservations	13
RQ2-14	Digital teaching is time-consuming	3
RQ2-27	Infrastructure operated in parallel causes additional effort	1
RQ2-29	Digital teaching leads to increased workload and time pressure	2
RQ2-32	Digital teaching must be well prepared	2
RQ2-37	Good digital teaching is expensive	7
RQ2-45	(Additional) digital teaching offers cause unpaid additional work for the teachers	1
Technical reservations		**25**
RQ2-9	Usability of systems for "beginners" insufficient	8
RQ2-17	Insufficient Internet connection for students	5
RQ2-19	Technical solutions not widely applicable (e.g., VR)	2
RQ2-28	Affinity for digital teaching / digital technologies among teachers very heterogeneous	1
RQ2-33	Lack of system freedom (e.g., when using an LMS)	1
RQ2-41	Uncertainty due to technical challenges on the part of students	2
RQ2-46	University's own solutions do not work so well	2
RQ2-54	Technical hurdles	4
Motivation & learning success		**18**
RQ2-10	Lack of motivation of (lower-performing) students for online teaching	13
RQ2-16	Students put off digital teaching and do not manage to work it up	1
RQ2-42	Students learn less/do not learn as independently as before	2
RQ2-47	Students lose fixed structures for their daily study routine	2
Didactic reservations		**27**

RQ2-11	Digital formats have shortcomings/do not correspond to ideas of good teaching	9
RQ2-12	Performance of average students decreases with online teaching	5
RQ2-30	Teachers no longer teach but just recycle their old screencasts/slides	2
RQ2-31	Systems and tools could be more playful	2
RQ2-36	digital teaching is less effective than face-to-face teaching	1
RQ2-38	digital teaching (especially videos) hinders engagement with texts	2
RQ2-43	Students have inhibitions to participate	2
RQ2-44	Digital teaching is dull/boring	1
RQ2-53	Digital teaching favors high-achieving students and disadvantages low-achieving students	3
Legal reservations		**5**
RQ2-13	Content from digital events ends up on the web	1
RQ2-18	Digital teaching violates legal regulations (e.g., licensing regulations for medical professions)	4
Absence		**9**
RQ2-26	Character of the university as a presence university is lost	1
RQ2-35	Students no longer come to face-to-face courses with digital offerings	7
RQ2-55	Students have become accustomed to online teaching and stay away	1
Personal reservations		**10**
RQ2-34	A majority of lecturers prefer face-to-face teaching to online teaching	1
RQ2-40	Uncomfortable feeling of communicating via camera and microphone	2
RQ2-48	Teachers can't imagine teaching online	0
RQ2-49	Fear of the unknown	1
RQ2-51	Lack of support from the university for technical problems	6

C. Advantages of digital teaching (RQ3)

In addition to the reservations, the teachers were also asked in the interviews about the advantages of digital teaching. In their experiences, teachers report on the pedagogical-didactical and technical-organizational advantages of digital teaching as well as positively perceived effects on students' motivation and learning success. In addition, they talk about advantages that compensate for individual disadvantages, as well as about increasing their own digital skills. The statements of the teachers were assigned to a total of 26 different categories, which in turn can be summarized in six main categories (See Tab. III).

1) Pedagogical-didactical, motivational and performance- related advantages

The temporal and spatial flexibility of digital, asynchronous teaching (RQ3-7) in connection with the possibilities of uncomplicated repetition of the learning materials at one's own learning pace (RQ3-8), also for the preparation and follow-up of synchronous phases, are repeatedly mentioned in the interviews as advantages and a way to self-determined learning. The following two statements are representative of several statements about these advantages:

"So some like it, appreciate it very much, that they can schedule things themselves, that they can work independently at home, when they want to." (IP11)

and

"Asynchronous elements, especially now, when students are supposed to work on their own, alone or in study groups or so, you can design that well or even better with virtual tools." (IP12)

Teachers also perceive that digital teaching is popular with students (RQ3-4), motivates students (RQ3-22), and contributes to learning success (RQ3-3). Students' desire to have digital teaching as a choice is reported several times. Representative of this apparently frequently expressed wish are the following two statements:

"Can't we also have the material virtually as well?" (IP01)

and

"With students you also hear more often that they really want to have a

choice, face-to-face or digital. For different reasons, personal reasons." (IP09)

In addition, the high motivational effect of digital teaching was also reported during the pandemic:

"They all turned on their cameras and they had a very intense exchange that 30 minutes were usually not enough for because everyone was so engaged in it." (IP05)

And they also perceived an increase in performance among some students, as interview partner 4, among others, states:

"We've made the observation that high-performing students actually show performance improvement from online teaching." (IP04)

For the future design of teaching, teachers take with them the insight from pandemic times that the mixture of digital and face-to-face offers is important, (RQ3-23) as the following quote of interview partner 9 illustrates:

"We cannot replace face-to-face teaching with digital offers, but only expand and supplement it. That's something that was a clear takeaway." (IP09)

In this context, the development of one's own competencies (RQ3-14) and the further development of one's own teaching (RQ3-1) were also perceived as positive effects of the pandemic, as described by interview partner 10 and 2 as representative of several statements in this direction:

"But I have now become acquainted with many more opportunities and possibilities. In this respect, the attitude has changed a little. I think so, because now I will also use blended learning formats more readily. And in this respect, it has changed somewhat, because I now take the opportunity more easily or more frequently, even in a seminar that does not take place virtually, but to incorporate real work phases that use virtual tools." (IP10).

"So the bottom line after the three semesters, I would say, among the colleagues the vast majority or a great majority have found this to be an enrichment. And as yes [...] now looking back at the possibility to develop one's teaching further." (IP02)

With regard to the further development of their own teaching, teachers also emphasize that the analysis of data generated by digital teaching could be used for a more precise didactic evaluation (RQ3-16).

2) Organizational advantages

In the interviews, a whole series of arguments for digital teaching came up, which concern advantages for the organization of teaching. Emphasis is placed on the easier and increased provision of learning content (RQ3-18) and recordings (RQ3-6), temporal and spatial independence (RQ3-13), and the reusability of digital materials (RQ3-2). For some programs, such as teacher education, these organizational advantages are of particular importance, as interviewee 05 makes clear:

"I have a lot of teacher trainees who have a lot of problems with overlap in their curriculum. For them, of course, it was a blessing that now in the lecture, that they can also participate asynchronously." (IP05)

In addition to making it easier for students to organize their studies, teachers also see advantages of digital asynchronous teaching for their own work (RQ3-24):

"Yes, because of course it gives teachers the opportunity to create new freedom for themselves through the asynchronous offers." (IP09)

The initially high effort to produce digital materials is now, after the creation seen as an advantage for students and as a relief for themselves, as interviewee 08 states:

"And I now have digital materials for all three semesters. If I teach this course again, then in principle I could profit from it or I would profit from it, then I could make all the digital things that I already have, I could then make them accessible again. And then, of course, that's very luxurious for the students." (IP08).

3) Advantages of digital teaching that compensate for individual disadvantages

Two interviewees also describe aspects of digital teaching that can reduce individual disadvantages for both students and teachers. With the help of digital teaching, teachers with health risks due to the pandemic were still able to offer and conduct courses (RQ3-25). In addition, one interviewee also perceives benefits for students whose personality traits allow them to overcome disadvantages of face-to-face formats through digital teaching (RQ3-26):

> *"And yes, there are students who find it convenient when they can turn off their camera and then speak quasi-anonymously." (IP12)*

TABLE III.
ADVANTAGES OF DIGITAL TEACHING (RQ3)

CATEGORY ID	CATEGORY NAME	ABSOLUT COUNT
Didactic advantages of digital learning		**27**
RQ3-1	Digital revision leads to improvement	5
RQ3-7	Time independence of students (asynchronous participation)	8
RQ3-8	Repetition of the material is possible in an uncomplicated way (e.g., multiple viewing)	2
RQ3-9	Observation/monitoring of students more easily	1
RQ3-10	Virtual simulation enables new learning experiences	2
RQ3-16	Digital evaluation enables more accurate didactic evaluation	1
RQ3-17	New didactic possibilities	8
Organizational advantages of digital learning		**41**
RQ3-2	Reusability of digital material	13
RQ3-6	Lectures can be made available later	5
RQ3-11	Division into small groups enables intensive collaboration	4
RQ3-12	Asynchronous lectures prevent overlapping schedules	1
RQ3-13	Digital teaching enables spatial independence	11
RQ3-18	Increased provision of content	3
RQ3-20	Basic courses would not need to be held permanently	1
RQ3-21	Organization of courses becomes easier with digital tools (e.g., LMS)	1
RQ3-24	Asynchronous possibilities create freedom	2
Motivation and learning success		**29**
RQ3-3	Contributes to learning success	8
RQ3-4	Is popular among students	10
RQ3-5	Good online offers are used and replace face-to-face offerings	3
RQ3-15	Continued use through hybrid offerings ("The mix makes the difference!")	5
RQ3-22	Motivation among students	1
RQ3-23	Mix of digital and face-to-face offerings are important	2
Increasing digital competencies		**3**
RQ3-14	Increase of the own digital competence of teachers	3
Advantages that lie in the technology itself		**1**
RQ3-19	Digital tools are easy to use	1
Advantages that compensate for individual disadvantages		**2**
RQ3-25	Digital teaching preferred for health problems	1
RQ3-26	Digital anonymity makes it easier for some students to participate	1

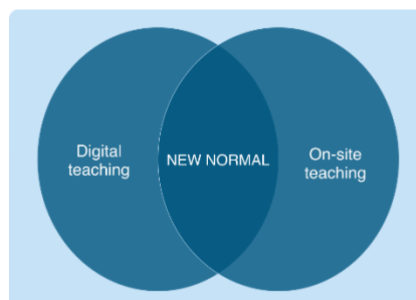

Fig. 1. The transformation toward a New Normal, with the interpenetration of digital media and methods of on-site teaching.

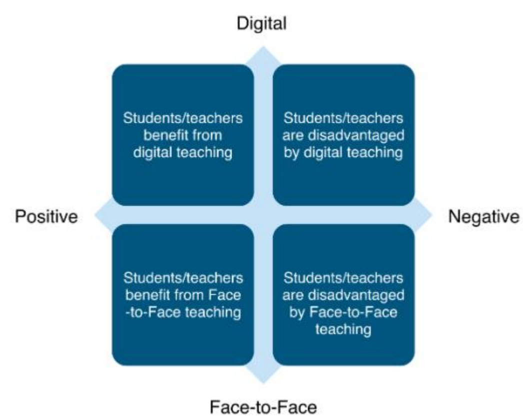

Fig. 2. The Tension field of digital and face-to-face teaching. The four positions of a teacher's view on the benefits and disadvantages regarding both settings.

IV. DISCUSSION

The results for RQ1 show that teachers perceive changes in their own teaching practices as well as in those of their colleagues, which they attribute to their experiences during the pandemic. These changes can be interpreted as an incipient digital culture change. Thus, the teachers observe a stronger anchoring of digital media in teaching. The use of digital tools in planning and conducting teaching is also becoming more natural. Instructors describe how they are changing their previous teaching strategies by incorporating lessons learned during the pandemic and incorporating their newly acquired digital teaching skills. The transformation toward this New Normal, with the interpenetration of digital media and methods of on-site teaching (Figure 1), means that the disadvantages of one or the other form of teaching (on-site versus online) can be offset to some extent. If teaching is thus set up more broadly in terms of methods (e.g., synchronous and asynchronous) and media (e.g., LMS, eLectures, videoconferencing), the needs of a heterogeneous student body are much more likely to be met. The balance act then shifts more to the question of how much resources teachers want to or can invest in differentiated teaching. The teachers interviewed also recognize changes in the learning actions of students in the sense of a cultural shift. Students are adapting their previous learning habits and are increasingly demanding the integration of digital elements and the provision of digital content. It remains to be said, however, that although digital cultural change can already be observed in various places, the process of change toward post-digital university teaching is far from complete. In their assessment of the pandemic experience, teachers come to very different conclusions. By no means all teachers are convinced of the didactic possibilities and the effectiveness of digital teaching and are prepared to change their teaching practices. This mixed picture is also reflected in the statements of the teachers regarding the advantages as well as the concerns about the use of digital media in university teaching (RQ2 and RQ3).

The results show that, after the experience of the pandemic, some teachers emphasize the desire for on-site teaching and the associated direct contact with students and colleagues. This goes hand in hand with teachers' concerns and reservations about digital teaching. Besides the pedagogical and didactic difficulties of digital teaching, they also see motivational and performance-related problems. In addition, there are personal reservations in connection with their own lack of competence and perceived organizational, technical or legal hurdles. On the other hand, however, some advantages of digital teaching are also perceived, for example with regard to motivation, pedagogical-didactical possibilities and potentials, and organizational facilitation. These different perceptions are not necessarily contradictory, but rather reflect the individual situation and perspective of teachers and students. There is a tension between the advantages and disadvantages of face-to-face and digital teaching, which poses a dilemma for the design of teaching (as illustrated in Figure 1). Advantages of a format for some may represent disadvantages for others.

A. *The Tension field of digital and face-to-face teaching*

In addition to aspects of isolation and loneliness or difficulties for lower-performing students, the perceived disadvantages of digital teaching relate primarily to the lack of direct exchange and dialog with students. This perception leads to a strong desire on the part of some teachers to return to the former face-to-face teaching formats rather than to maintain digital ones. This reaction risks overlooking the fact that "back to face-to-face" may well be associated with disadvantages for some students and teachers. Assuming a broad understanding of heterogeneity, respectively diversity [12], in which heterogeneous (learning) starting points are acknowledged, with different prior knowledge, interests, cognitive, motoric and sensory abilities, motivations as well as social and cultural backgrounds of students, digital elements play an eminently important role with regard to diversity-sensitive, inclusive teaching. Disadvantages of a purely verbal and fluid face-to-face teaching offer arise, for example, for students who have difficulties following due to auditory perception disorders, physical hearing impairments, reading/spelling difficulties, grief or ADHD/ADS [9] or have problems actively participating in presence due to shyness or anxiety. Advantages of digital teaching can provide significant support. A continuous asynchronous learning offer or the possibility to make use of it in addition to face-to-face teaching would be very helpful for these students. For example, students with reading and spelling difficulties have enough time to read texts, use reading programs and apps for written assignments, and enter their own written submissions, e.g., using text-to-speech software, and have them automatically checked for spelling and grammar. In the case of concentration difficulties or simply different discussion and learning speeds, an asynchronous learning offer can provide relief by allowing contributions and tasks or asynchronously conducted discussions to be worked on autonomously at one's own pace or in smaller units, so that the working memory is less burdened. In addition, for some students in special life situations, e.g., when they are prevented from attending due to illness, parenthood or other care work, a continuous asynchronous learning offer makes it possible to maintain their studies in the first place.

V. CONCLUSION AND FUTURE WORK

The qualitative study identified four positions that can be used to describe the tension between the perspectives with which teachers view the specific opportunities and threats of digital teaching and face-to-face teaching (see Figure 2). In the future, these different perspectives must be considered on two levels when designing contemporary teaching. For one, on the institutional level, in strategic decisions about the goals and orientation of academic teaching at the university. For another, on the individual level of the single teachers, in the planning and realization of their own teaching, but also in the reflection of their own teaching activities. In this context, it will be crucial to always have different possible solutions in mind in a multiperspective sense and to choose solutions that take several of these positions into account and lead to a synthesis through dialogue [16]. Interview partner 9 also argues in favor of such an approach by speaking out against thinking in either/or categories:

> *"So it's neither a demonization of digital possibilities, but also not a clear prioritization of face-to-face presence. Yes, perhaps not just prioritization, but really the mix, it's the mix that makes it. Both have their place, digital teaching, face-to-face teaching, and you can't replace one with the other."*

In the future more research is needed to further explore this tension field of digital teaching. On the one hand, the perspective of the students is important, whose needs and wishes must be taken into account when designing digital teaching. On the other hand, the group of persons with special needs due to e.g., visual, hearing or motor impairments or with care work is interesting. Even if all students (and teachers) benefit from digital accessibility in principle, it is this group whose needs should be given special attention. Further work will focus on the question of how university teaching can become more inclusive by incorporating the possibilities of digitization [2] and in what form the multi-perspective approach described can support this process. One approach could be the creation, systematic preparation, and distribution of learning designs for inclusive, digital teaching. These patterns, which require both individual teachers (individual level) and institutes for academic development (institutional level) to create, would provide teachers with a valuable source of inspiration for designing contemporary teaching.

References

[1] A. Tillmann, S. Voß-Nakkour, M. Eichhorn, and F. Kuhn, 'The Tension Field of Digital Teaching From the Perspective of Higher Education Teachers', in *IARIA - SMART ACCESSIBILITY 2023, The Eighth International Conference on Universal Accessibility in the Internet of Things and Smart Environments*, Venice, Italy, 2023. [Online]. Available from: http://personales.upv.es/thinkmind/dl/conferences/smartaccessibility/smart_accessibility_2023/smart_accessibility_2023_3_20_88010.pdf (accessed Dec. 18, 2023)

[2] M. Eichhorn, A. Tillmann, R. Müller, and A. Rizzo, 'translated: Teaching in times of Corona: practice-theoretical investigation of teaching action during school closure. Unterrichten in Zeiten von Corona: Praxistheoretische Untersuchung des Lehrhandelns während der Schulschließung', in *Medien in der Wissenschaft: Band 77. Seamless Learning – lebenslanges, durchgängiges Lernen ermöglichen*, C. M. Werder and J. Erlemann, Eds., Waxmann Verlag GmbH, 2020, pp. 81–90.

[3] 'The Difference Between Emergency Remote Teaching and Online Learning'. [Online]. Available from: https://er.educause.edu/articles/2020/3/the-difference-between-emergency-remote-teaching-and-online-learning (accessed Dec. 18, 2023).

[4] D. Euler and S. Seufert, 'translated: Change Management in University Teaching: The Sustainable Implementation of e-Learning Innovations. Change Management in der Hochschullehre: Die nachhaltige Implementierung von e-Learning-Innovationen', 2007, doi: 10.3217/ZFHD03/02.

[5] M. Kerres, 'translated: Introduction of learning innovations . Einführung von Lerninnovationen', in *Mediendidaktik. Konzeption und Entwicklung digitaler Lernangebote*, M. Kerres, Ed., Berlin: De Gruyter, 2018, pp. 491–511.

[6] D. Euler, 'translated: Designing the implementation of e-learning innovations: Promoting the readiness of teachers and learners to innovate as central players in implementation. Gestaltung der Implementierung von E-Learning-Innovationen: Förderung der Innovationsbereitschaft von Lehrenden und Lernenden als zentrale Akteure der Implementierung', in *E-Learning in Hochschulen und Bildungszentren*, D. Euler and S. Seufert, Eds., Berlin, Boston: DE GRUYTER, 2004. doi: 10.1515/9783486593754.561.

[7] M. Graf-Schlattmann, D. M. Meister, G. Oevel, and M. Wilde, 'translated: Collective Willingness to Change as a Key Success Factor of Digitization Processes at Universities. Kollektive Veränderungsbereitschaft als zentraler Erfolgsfaktor von Digitalisierungsprozessen an Hochschulen', 2020, doi: 10.3217/ZFHE-15-01/02.

[8] C. Arndt, T. Ladwig, and S. Knutzen, 'translated: Between curiosity and uncertainty : internal university surveys of students and faculty in the virtual summer semester 2020 : results of a qualitative content analysis. Zwischen Neugier und Verunsicherung : interne Hochschulbefragungen von Studierenden und Lehrenden im virtuellen Sommersemester 2020 : Ergebnisse einer qualitativen Inhaltsanalyse', Nov. 2020, doi: 10.15480/882.3090.

[9] F. A. Rüscher, E. Buchminskaia, S. Chilla, and C. Filk, 'translated: Digital accessibility and the university: STUDYasU - a proactive approach to barrier-sensitive digital university teaching. Digitale Barrierefreiheit und die Hochschule: STUDYasU – ein proaktiver Ansatz für barriere-sensible digitale Hochschullehre', in *Digitale Barrierefreiheit in der Bildung weiter denken. Innovative Impulse aus Praxis, Technik und Didaktik*, S. Voß-Nakkour, L. Rustemeier, M. M. Möhring, A. Deitmer, and S. Grimminger, Eds., Frankfurt am Main: Universitätsbibliothek Johann Christian Senckenberg, 2023, pp. 90–100. Accessed: Mar. 09, 2023. doi: 10.21248/gups.62773.

[10] G. Marinoni, H. van´t Land, and T. Jensen, 'The Impact of COVID-19 on Higher Education around the World', IAU, Paris, 2020. Accessed: Mar. 09, 2023. [Online]. Available from: https://www.iau-aiu.net/IMG/pdf/iau_covid19_and_he_survey_report_final_may_2020.pdf (accessed Dec. 18, 2023)

[11] D. Frohwieser, S. Gaaw, S. Hartmann, K. Lenz, and J. Möller, 'translated: Between "what's missing most is time." and "thank you for making studying possible." survey of lecturers and students on the corona-induced conversion to virtual teaching in the summer semester 2020. results of the first survey wave in april 2020. Zwischen „Was am meisten fehlt, ist Zeit." und „Danke, dass ein Studium möglich gemacht wird." Befragung von Lehrenden und Studierenden zur coronabedingten Umstellung auf virtuelle Lehre im Sommersemester 2020'. [Online]. Available from: https://tudresden.de/zqa/ressourcen/dateien/publikationen/hochschulmonitoring/Virtuelle_Lehre_2020_Schnellauswertung_erste_Welle.pdf (accessed Dec. 18, 2023)

[12] A. Witzel, 'translated: The problem-centered interview. Das problemzentrierte Interview', in *Qualitative Forschung in der Psychologie : Grundfragen, Verfahrensweisen, Anwendungsfelder*, G. Jüttemann, Ed., Weinheim: Beltz, 1985, pp. 227–255.

[13] M. K. Barbour, R. LaBonte, K. Kelly, C. B. Hodges, S. Moore, B. B. Lockee, T. Trust, and M. Bond, *Understanding Pandemic Pedagogy: Differences Between Emergency Remote, Remote, and Online Teaching*. 2020. doi: 10.13140/RG.2.2.31848.70401.

[14] P. Jandrić *et al.*, ‘Teaching in the Age of Covid-19—The New Normal’, *Postdigital Sci. Educ.*, vol. 4, no. 3, pp. 877–1015, Oct. 2022, doi: 10.1007/s42438-022-00332-1.

[15] P. Mayring, ‘translated: Qualitative Content Analysis: Basics and Techniques . *Qualitative Inhaltsanalyse: Grundlagen und Techniken*’, 12., Überarb. Aufl. Weinheim u.a.: Beltz, 2015.

[16] D. Bohm, ‘translated: The open conversation at the end of the discussion. *Das offene Gespräch am Ende der Diskussion*’. Klett-Cotta, 1999