Classifying different types of modularity for technical system

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Abstract:

Modular design is regarded as an effective approach to reduce production cost and increase mass customization and personalization in industries. The implementation of modularization requires the support of the entire technical system, including product, service and supply chains. However, most modularity studies only focus on product modularity. There is a need for comprehensive understanding of modularity in product, service and supply chains. This paper addresses this need by defining the modularity of the technical system, including product, service and supply chains; and providing classifications for modularity across product modularity, service modularity and supply chain modularity separately. The contributions of this paper are: (a) a review on the classification of technical system modularity; (b) the analysis of internal relationship among different types of product modularity, (c) a proposal for different types of service modularity and supply chain modularity. This study can assist manufacturing companies to improve modular design and management of technical system.

Key words: technical system; product modularity; service modularity; supply chain modularity

1. Introduction

Modular design is regarded as an effective approach to reduce production cost and increase mass customization and personalization in industries. [Miller & Pedersen, 1998]. Modularity thinking appeared firstly almost 2000 years ago in the building sector, for example, modular brick and tile were used as the basic building blocks in Chinese Qin dynasty [Gu, 2014], and laws on proportions and symmetry in temples and columns were made in ancient Roman times [Routio, 1998]. From the early 20th century, modularity appeared in many fields, such as in construction, biology, networks, ecology, artifact product design and manufacturing, computer science, etc. [Starr, 1965; Miller & Pedersen, 1998; Newman, 2006]. Modularity has created great benefits across the manufacturing sector: 1) reduction of manufacturing cost due to the use of components across product families, 2) reduction of risk and improvement of efficiency by decomposing a complex system into more manageable modules, 3) ease of product updating and maintenance, 4) increased product variety from a smaller set of components, and 5) decreased order lead-time via fast combination of modules [Parnas,1972; Ulrich,1991; Gershenson,1997; Baldwin,2000]. Based on these advantages, modularity has become an important research area in manufacturing system and other fields in recent 20 years.

Since 1980s, modularity has been defined by several scholars. Although the definitions are different, they all share common features, such as function independence, interchangeability, physical and functional similarity. Modularity is explained as a systematic process where a product or system is composed of various modules, and these modules can be combined in different ways which become different products.. The whole process needs to follow certain industrial rules and standards [Walz,1980; Ulrich and Tung,1991; Ulrich,1995; Gershenson,1999; Tong, 2000; Starr, 2010].

At the beginning of the 20th century, the idea of standardization with functional thinking and industrial production in building construction and building blocks were introduced in architecture and construction in Germany [Miller & Pedersen, 1998]. In 1920s Germany, modularity thinking began to be applied in machine design. Several components in milling machine were decomposed into modules based on functions, which were easily assembled into modular products to meet customers' demands [Gu, 2014]. In 1960s, modular industrial turbines, modular container and modular weapon systems appeared in the market [Gu, 2014]. In 1965, Starr discussed the concept and potential benefits of using modular production, and emphasized modular design of product "parts" that could be combined in the maximum number of ways to create new products for sale [Starr, 1965]. Then, Pahl & Beitz directly linked the definition of modules to functionality and defined different types of modules based on a range of functions [Pahl & Beitz, 1996]. In 1991, Ulrich linked modularity to structure, and proposed different types of modular structures and interfaces [Ulrich, Tung, 1991,1995]. In recent years, the research on modularity has been extended to a number of other areas, such as product life cycle stages and their interaction with the system environment [Gershenson,1997; Ishii,1998], product domain, service domain, organization domain [de Aguiar Corrêa L., 2013; Bask, 2010], and product family architecture for mass customization [Jiao & Tseng, 1999]. The research object also expands from a single product to product family and technical systems.

This paper identifies the gap that exists in the types of modularity for technical system. Therefore, this paper analyses the relationships among different types of product modularity, and proposes classifications orf service modularity and supply chain modularity separately.

In this paper, the 2nd section provides a definition and analysis on the modularity of technical system; the 3rd section analyses the classification of product modularity in technology system; the 4th section mainly classifies the types of service modularity in technical system; the 5th section mainly classifies the types of supply chain modularity in technical system; and the final section summaries the contribution and future work of technical system modularity.

2. The modularity of technical system

2.1 The definition of technical system and its modularity classification

Several definitions on technical system have been proposed by scholars. Their common points are that a technical system contains structured activities and actions that are necessary to fulfill a certain purpose (function), and it usually includes several elements such as organizations and artifacts, and their interactions [Altshuller, 1984; Hughes, 1987; Ehrlenspiel, 1994; Salamatov, 1996]. Based on the above definition, in order to clarify the boundary and basic constitution of technical system, we define that aiming to a kind of product, from product design, manufacturing, transportation to service, in which the related things, such as people, materials, and supply chains are known as a technical system. Therefore, a technical system consists of three basic parts: product, service and supply chain. The three parts are brought together to fulfill certain customer demands (product and service functions), product and service in the technical system run in product life cycle with the support of system's supply chain.

The classification of product modularity has been studied by many researchers, however, the classification of service modularity, supply chain modularity, and technical system have not yet been studied [Pahl & Beitz, 1996; Ulrich & Tung, 1991, 1995; Gershenson, 1997; Ishii, 1998; Leonardo de Aguiar Corrêa, 2013; Bask, 2010; Jiao & Tseng, 1999; Chen & Crilly, 2014]. We argue that it is important to reclassify different types of modularity for technical system due to three reasons.

(1) The implementation of modularity in enterprises needs to consider not only product modularity, but also services modularity and supply chain modularity. All these elements fuse into a seamless organic whole, interacting and restraining each other. Therefore, research on the

modularity of technical system is the practical base whereupon modular design theory is implemented effectively in a firm.

(2) To fully understand the relationships among the three parts (product, service and supply chain) in a technical system. For a technical system, the relationships among product, service, and supply chain are complex in any modular process, and they are still not studied. So studying relationships among units is very important for the modular design of technical system.

(3) There are lots of existing types of modularity that deliver product modularity, but the relationships among them are ambiguous. It is important to analyse the relationships among them. For the classification of service modularity, the current classification criterions in literature cannot support service modular design well, so there is a need to reclassify service modularity. For the supply chain modularity, there is no existing classification.

2.2 The relationships among different parts of technical system modularity

Technical system includes product, service and supply chain. Technical system modularity cannot be totally carried out by a particular method, because it consists of the three parts, and each part has its special types of modularity. Therefore, technical system modularity must be classified considering relationships among different objects and life cycle stages. Fig.1 shows the relationship of technical systems modularity at different layers. Technical systems modularity can be described in two layers. The first layer is product modularity and service modularity, which are in certain stages of the product life cycle; the second layer is supply chain modularity. In the first layer, product modularity includes several types of modularity in the product life cycle: design-oriented modularity, manufacture-oriented modularity, assembly-oriented modularity, service-oriented modularity, and recyclable-oriented modularity. Service-oriented modularity refers to product modular design oriented to service, and recyclable-oriented modularity refers to product modular design oriented to material or components recyclability, they also belong to product modularity. However, in service stage, some service business, retirement business and resources can be carried out in modules, so they belong to service modularity. In the second layer, supply chain modularity exists in whole product and service life cycle, and supports the running of modular products and services, Otherwise product and service will not work effectively.

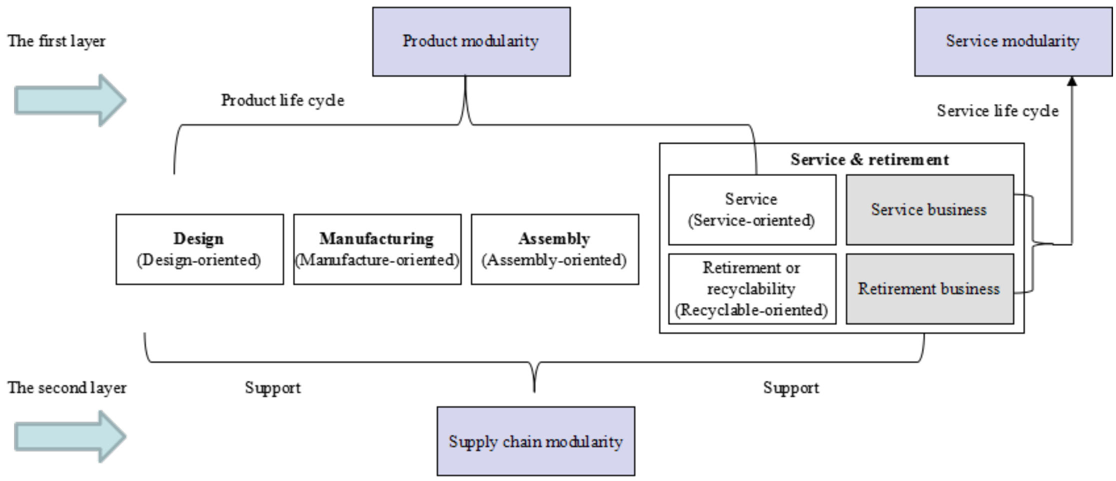

Fig.1 Relationships among different parts of technical system modularity

3. The classification of product modularity in technology system

3.1 Research review on the classification of product modularity

The study on the classification of product modularity dates from the definition of different types of modules based on a range of functions (i.e. basic, auxiliary, special, adaptive, customer-specific) [Pahl & Beitz, 1996]. Ulrich and Tung focused on the structure of modularity, and divided it into six types [Ulrich & Tung, 1991, 1995]. Later, product life cycle design became very popular. Different types of modularity based on product life cycle were proposed [Gershenson,1997; Gershenson,1999; Salvador, 2002]. These classification criterions have been summarized by Chen and Crilly in 2014 [Chen & Crilly, 2014]. However, there are still some other classification criterions in product modular design process, such as different operating modes in modular configuration design, modularity in principal domains, according to the level and granularity of the module partition, and product family architecture for mass customization [Jiao,1999; Qi,2009; Duray, 2000; Baldwin & Clark, 2000; de Aguiar Corrêa, 2012; Gu, 2014].

Chen and Crilly [Chen & Crilly, 2014] proposed three classification criterions: component function role in the system, component structural assembly and interface compatibility, and life cycle stage or interaction with the system environment. Based on the three criterions, we have categorized the existing classification criterions into seven types, as shown in Table 1. The classification criterions are proposed from one stage to the whole product life cycle, from product modularity to service and supply chain modularity, and from product modularity to product family architecture for mass customization. This provides different types of modular design, and it can fully express the operating category in the modular design process and deepen the understanding on the modular design. However, these classification criterions still have some deficiencies. For example, there are some different types of modularity for the classification criterions of life cycle stage or interaction with the system environment that these classification cannot be unified; and that the relationships among different classification criterions are still ambiguous in logic.

Table 1 Literature review on types of product modularity

NO.	Classification criterion	Types of modularity	Authors(Year)	Benefits of classification criterion
P1	Component function role in the system	Production modules, function modules (basic function module, auxiliary function module, special function module, adaptive function module and customer-specific function module)	Pahl & Beitz (1996)	For the classification of function modules it seems advantageous to define the various types of function that recur in modular systems and can be combined as sub-functions to fulfill different overall functions (overall function variants).
		Non-physical module	Miller (1998)	The software domain has thus also benefited from utilizing the concept of modularity for handling complex systems and rationalization of design tasks.
P2	Operating mode in modular configuration design	Splitting, substituting, augmenting, excluding, inverting, and porting	Baldwin &Clark (2000)	Most complex changes in modular design can be represented as combination of these operators.
P3	Component structural assembly and interface compatibility	Component-swapping modularity, component-sharing modularity, fabricate-to-fit modularity, bus modularity, sectional modularity, slot modularity	Ulrich (1991,1995)	These types of modularity is used in industrial practice to exploit component standardization and to achieve product variety, and shows different component interaction ways of organizing.
		Combinatorial modularity	Salvador (2001)	Helps to avoid confusion from terminological ambiguities and to prevent misunderstandings regarding the unit of analysis and the level of analysis.
P4	Life cycle stage or interaction with the system environment	(1) Product modularity, characteristic modularity: design-oriented modularity, manufacturing-oriented modularity, use-oriented modularity, service-oriented modularity and retirement-oriented modularity; (2) manufacturing modularity; (3) service modularity	Gershenson (1997)	The benefits of manufacturing modularity include reduced inventory, fewer works in process, faster process time, as well as component economies of scale, ease of product update, increased product variety from a smaller set of components, and decreased order lead-time. Modularity allows the designer to control the degree to which changes in service [or manufacturing] processes affect the product design. By promoting interchangeability, modularity also gives designers more flexibility, with decreased cycle time, to meet these changing processes.
		Manufacturing perspective on modularity, service perspectives on modularity, recyclability perspectives on modularity	Ishii (1998)	Manufacturing perspective on modularity provides the customers their desired customized products at an affordable price and in a timely manner, service perspective for modularity addresses serviceability and reliability (design for ownership quality), recyclability focuses on one dimension of environmental compatibility.

		Manufacturing modularity, product use modularity, limited life modularity, data access modularity	Arnheiter (2005)	Manufacturing modularity mainly emphasizes design for mass customization, flexibility, and supplier integration. Product use modularity mainly design for appearance, durability, and ergonomics. Limited life modularity mainly design for accessibility, low cost, recycling. Data access modularity mainly design for reliability, durability and soft module protection.
P5	Modularity in principal domains	Modularity in design, modularity in production, and modularity in organization (Sako, 1999; Camuffo, 2001; Doran, 2003) or modularity in organization and supply chain (Bask, 2010), modularity in use (Pandremenos, 2009)	de Aguiar Corrê a (2012)	Modularity in design has been investigated to reduce design process complexity, modularity in production is to facilitate both manufacturing and assembly to meet product variety, production flow, cost and quality requirements.modularity in organization is to improve definitions in managerial activities and tasks among organizations or within a company itself. Modularity in use is a consumer driven decomposition of a product with a view to satisfying the ease of use and individuality.
P6	The layer and granularity of the module partition	Complete equipment layer modularity, product layer modularity, component layer modularity, part layer modularity, structural unit (or logical unit) layer modularity	Qi (2009) Gu (2014)	In the structural design process, according to different levels to determine the granularity.
P7	Product family architecture for mass customization	Functional modularity, technical modularity, manufacturability	Jiao (1999)	The goal of functional modularity is to map customer needs in different market segments, technical modularity is to address the technical feasibility of design. Manufacturability is a major concern in physical modularity, where the interaction is measured by engineering costs derived from available process capabilities and estimated volume.
		Modularity through fabrication, modularity through standardization	Duray (2000)	Modularity through fabrication reflects modularity issues involving design or changes to the components for a specific customer, it can be considered a measure of modularity in the design or fabrication of a product. Modularity through standardization addressed modularity in the form of options to standard products or interchangeability of components.

3.2 Understanding relationships among main classification criterions in product life cycle

Based on the review of product modularity, we have categorized existing product modularity into seven types. Even though the seven classification criterions are clear, the relationships among them are ambiguous across the product life cycle. We therefore explain the relationships among the classification criterions in the product life cycle under different manufacturing modes, shown in Figure 2. There are four types of manufacturing modes: ETO (Engineer to Order), MTO (Make to Order), ATO (Assemble to Order), and MTS (Make to Stock) [Bozarth & Chapman, 1996]. In product life cycle, ETO focuses on design stage; MTO focuses on manufacturing stage; ATO focuses on assembly stage; and MTS focuses on service stage. This describes the different separation points of orders.

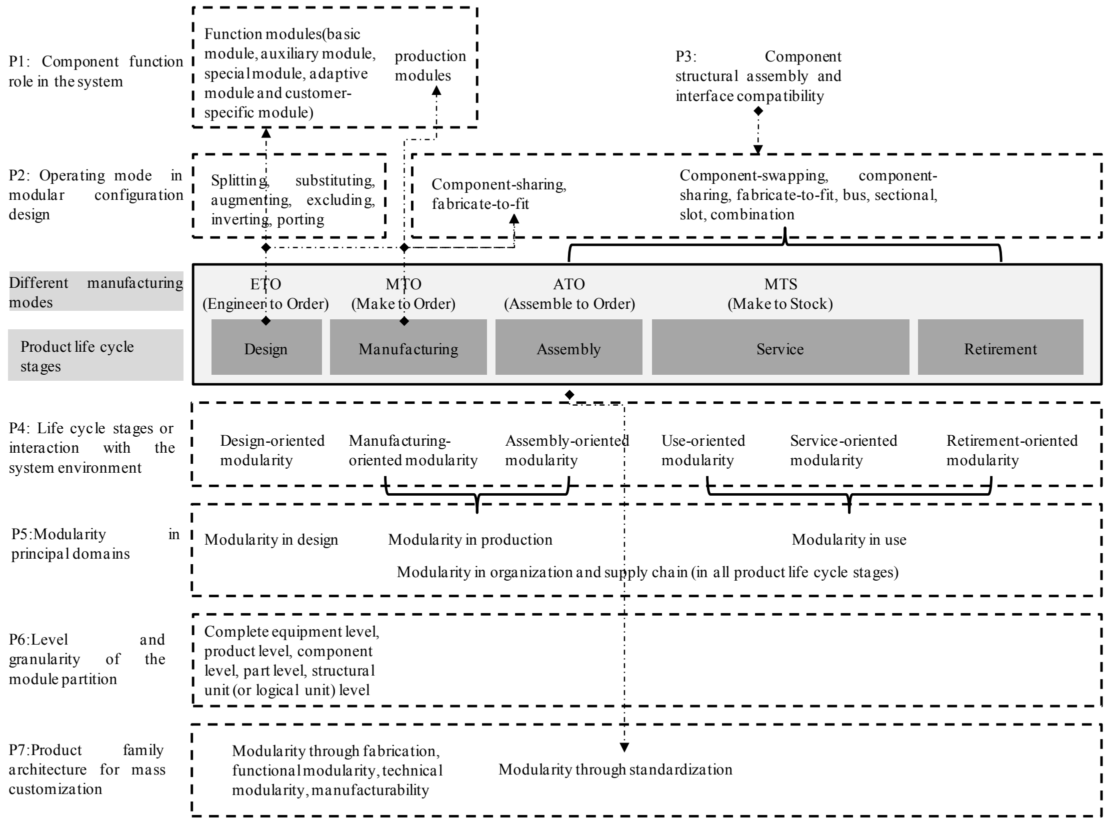

Fig.2 Relationships among different classification criterions in product life cycle under different manufacturing modes

In Fig.2, each classification criterion consists of several types of modularity, and each type of the modularity corresponds to a certain life cycle stage or manufacturing mode. For example, In the type P1, modules are divided into two domains: function modules in design stage, and production modules in manufacturing stage. For the type P3, the component sharing modularity and fabricate-to-fit modularity focus on design and manufacturing stages; component swapping modularity, bus modularity, sectional modularity, slot modularity and combinatorial modularity focus on the assembly, service and retirement stage.

3.3 Understanding relationships among classification criterions of product modularity in four domains of design world

Suh in 2001 proposed four domains of the design world: customer domain, functional domain, physical domain, and process domain; and mapped the relationships between two adjacent domains [Suh, 2001]. In order to understand the relationships among different classification criterions, we compare the classification criterions of modularity with the four domains. These classification criterions include component function role in the system, component structural assembly and interface compatibility, modularity in principle domains, and product family architecture for mass customization [Pahl & Beitz, 1996; Ulrich,1991,1995; Salvador, 2001; Gershenson, 1997; Ishii, 1998; Jiao, 1999; Duray, 2000; de Aguiar Corrêa, 2013; Chen & Crilly, 2014].

We analysed the relationships among different classification criterions of product modularity in four domains, as shown in Fig.3. The types of modularity based on P1 mainly focus on functional domain. The types of modularity based on P3 mainly focus on physical domain. The types of modularity based on P5 mainly focus on function domain, modularity in production and use focus on the physical domain, and modularity in supply chain focus on process domain. For the types of modularity based on P7, the functional modularity focuses on functional domain, and technical and manufacturability modularity belongs to the physical domain.

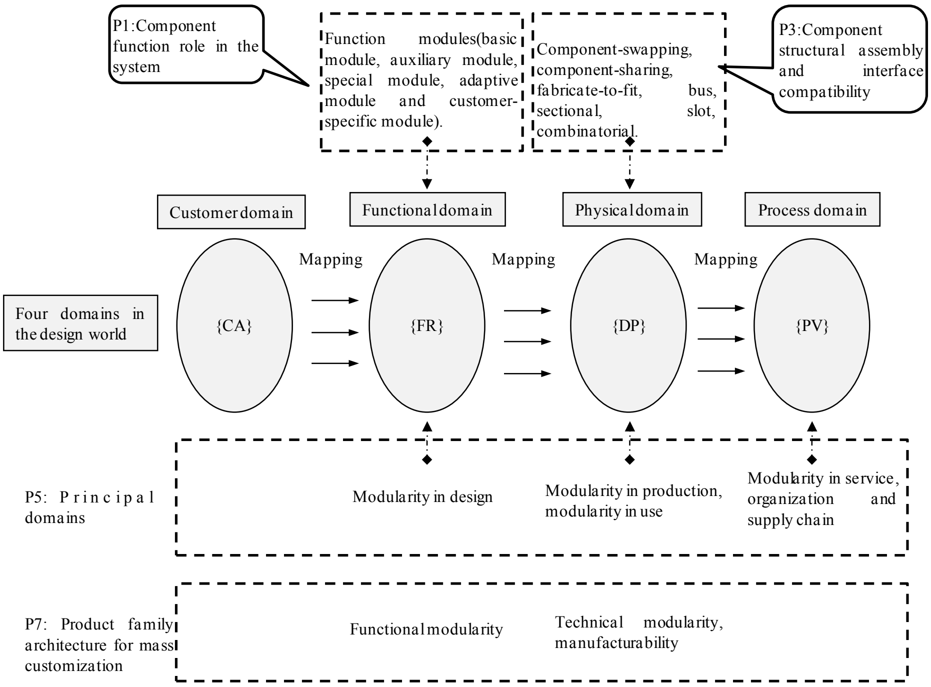

Fig.3 Relationships among different classification criterions of product modularity in four domains

4. The classification of service modularity in technology system

4.1 Research review on the classification of service modularity

In logistics services, modularity was defined as the integration of various functions in a company in order to decrease service complexity and achieve better responsiveness to service variety [Bask, 2010]. Service modularity is the abstraction from tangible or intangible services with independent functions, and it realizes service functions through the interaction of physical modules and services process [Li, 2012;Li,2017]. A service module can be seen as one or more service elements offering one service characteristic, and a modular service can be combined from one or more service modules [Bask, 2010]. Understanding the service process can provide help on the classification of service modularity. There are five generic types of process: project, jobbing, batch, line and continuous process operations [Hill, 1991]. These processes have become a part of classic production management. Silvestro proposed three types of service process: professional, service shop and mass [Silvestro, 1992]. Hyötyläinen argued that in the case of human-intensive activities, hard, soft, and hybrid technologies should be used to systematically industrialize services, which provided guidance to the classification of service modularity [Hyötyläinen, 2007]. We therefore proposed classification criterion of service modularity with three types in Table 2,. They are service industry modularity (S1), component function, structure and process role in the system (S2), and oriented to service customization (S3).

Three levels of service industry modularity were suggested by Xu: service product system or design modularity, service-oriented manufacturing and service production modularity, service organization or service function modularity [Xu, 2007]. The service modularity is classified according to different service life cycle and organizations.

According to the component function, structure and process role in the system, Deng analyzed a variety of module combination modes in the financial service industry, and divided the financial service module into three types: the base module, structural module and function module [Deng, 2008]. Li divided the service module into content modularity and process modularity, and pointed that the interfaces between different modules more loosely coupled than manufacturing modularity [Li, 2008]. Li proposed three forms of service modules, which are: independent function service module, “class” service module and process service module [Li, 2012].

Under the mode of service customization, Voss proposed that service customization can be either combinatorial or menu driven [Voss, 2009]. Cai proposed a menu-based manufacturing services module matrix according to the manufacturer's service business category [Cai, 2013].

Table 2 three types of service modularity

NO.	Classification criterion	Types of service modularity	Authors(Year)
S1	Service industry modularity	The service product system or design modularity, service-oriented manufacturing and service production modularity, service organization or service function modularity	Xu (2007)
S2	Component function, structure and process role in the system	The base module, structural module, function module	Deng (2008)
		Content modularity, process modularity	Li (2008)
		Independent function service module, “class” service module, process service module	Li (2012),Li(2017)
S3	Oriented to service customization	Combinatorial (the combination of a set of service processes and products to create a unique service) or menu driven (the selection of one or more services from a set of existing services/products to meet customer needs)	Voss (2009)

We address that an in-depth understanding on the nature of service modularity is crucial for service design and innovation Existing studies on the classification of service modularity (shown in Table 2) provide support on the service characteristic, module partition and modular design. However, in a technical system, the classification of service modularity is affected by product, service offerings organization and the entire network, which will make the types of service modularity more complex and diversified. It therefore needs further study.

4.2 Understanding the relationships between product and service

According to the correlation degree of physical product and service, service can be divided into functional service and non-functional service, as shown in Fig 5. A functional service is a type of service which needs to be carried out with the support of specific physical components, such as maintenance service and remote monitoring service. These services will directly affect the function and structure of physical product. Non-functional service is (largely) independent of function physical module, for example, consulting service, installation service, transportation service, and training service. As shown in Fig.5, functional services can only be carried out when the special optional physical component assembled in physical product; but the non-functional service can be carried out without the support of physical components [Li, 2012; Li, 2018].

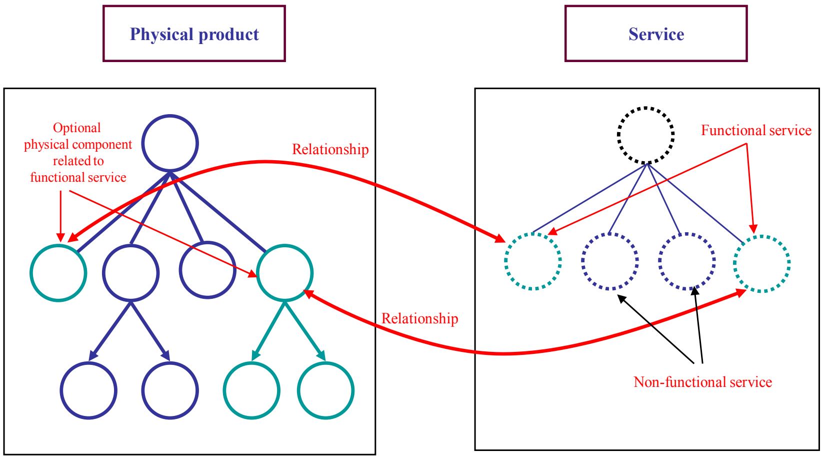

Fig.5 The relationship between product and service [Li, 2012]

4.3 Classification of service modularity

4.3.1 Function oriented service modularity

A function independent service module is an independent function corresponding to a physical module or service module. There is a 1:1 relationship between function and module, such as the service module of spare parts [Li ,2012].

Case study: sea cruise services [Voss, 2009]

The cruise industry consists of at least four levels of service architecture decompositions (see Fig.6), all cruise service modules are divided based on function [Voss, 2009]. The first level includes several kinds of modules, such as cruse companies, airlines, travel agents, etc. The second level only focuses on an individual cruise company. The company operates a number of cruise ships, marketing services and port operations services. Some of these modular services are outsourced. The third level focuses on the ship itself. Each kind of ship has swimming service (pools), entertainment, food and beverage services, cabin services, etc. At the final level, each of these services can be broken down into a further set of service modules, from cabin design to specific service personnel.

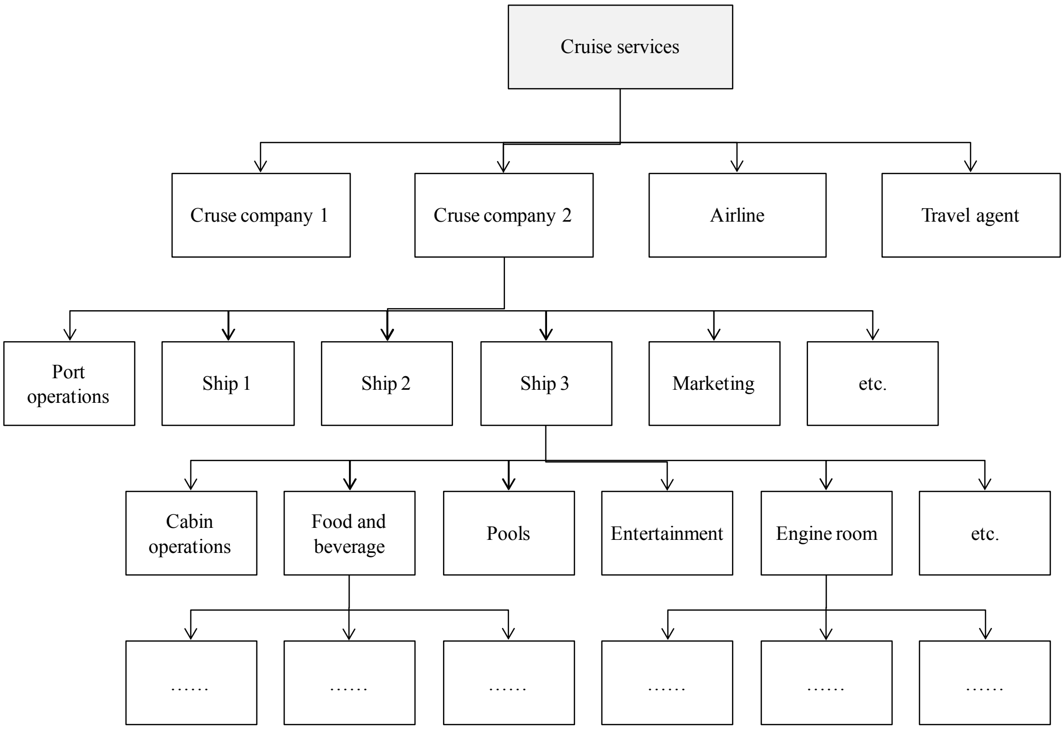

Fig.6 Module decomposition example of sea cruise services [Voss, 2009]

4.3.2 Physical product oriented service modularity

According to the relationship analysis on different elements of technical system based on product life cycle (see Fig.2), service modularity includes serviced-oriented modularity and service business modularity. For the service-oriented modularity, all service modules are divided according to the physical modules. These service modules are called functional service modules (service can be divided into functional service and non-functional service). It has 1:1 mapping relationships between physical modules and service modules, replace or upgrade the parts are functional services.

Case study: power transformer

The functional service of power transformer mainly includes measurement, control, testing, monitoring, protection service.

Functional service module includes: temperature rise test analysis, thunder impact test (full wave, carrier wave), temperature rise and insulation oil chromatographic analysis, mechanical strength test of oil tank, transition characteristic test of on-load tap-changer switching, winding degeneration, zero sequence impedance measurement experiment of three-phase transformer, no-load current harmonic measurement sound level measurement, bear ability test of short circuit, gas gathered quantity, the top oil temperature, bottom oil temperature, winding temperature, environmental temperature, earth current of magnet core, cooling device, on-load tap-changer m30, master IED of monitoring function group, partial discharge monitoring IED, the dissolved gas monitoring IED (chromatography), the dissolved gas monitoring IED (electrochemical), the hot temperature measurement IED of winding, non-electricity protection and merge unit [Li, 2012].

4.3.3 Process oriented service modularity

One of the characteristics of services is that they are produced and consumed at the same time. Thus, a service can often be a process as well [Voss & Hsuan, 2009]. A process service module is a set of service processes in a specific phase, which completes some service tasks in a certain period of time or certain stage, such as the lubricating oil company's overall chemicals management module, and full performance service module of ABB [Li, 2012].

Case study: total chemical management

China Petrochemical Corporation (Sinopec Group) is a super-large petroleum and petrochemical enterprise group in China. In Fig.7, the chemicals are managed in modules. The horizontal axis represents different service stages, and the vertical axis represents the different types of lubricants. For example, in Fig.7, the module 1.4, module 2.4 and module 3.4 are different auxiliary modules, because they are used in different service process stages [Sinopec,2016].

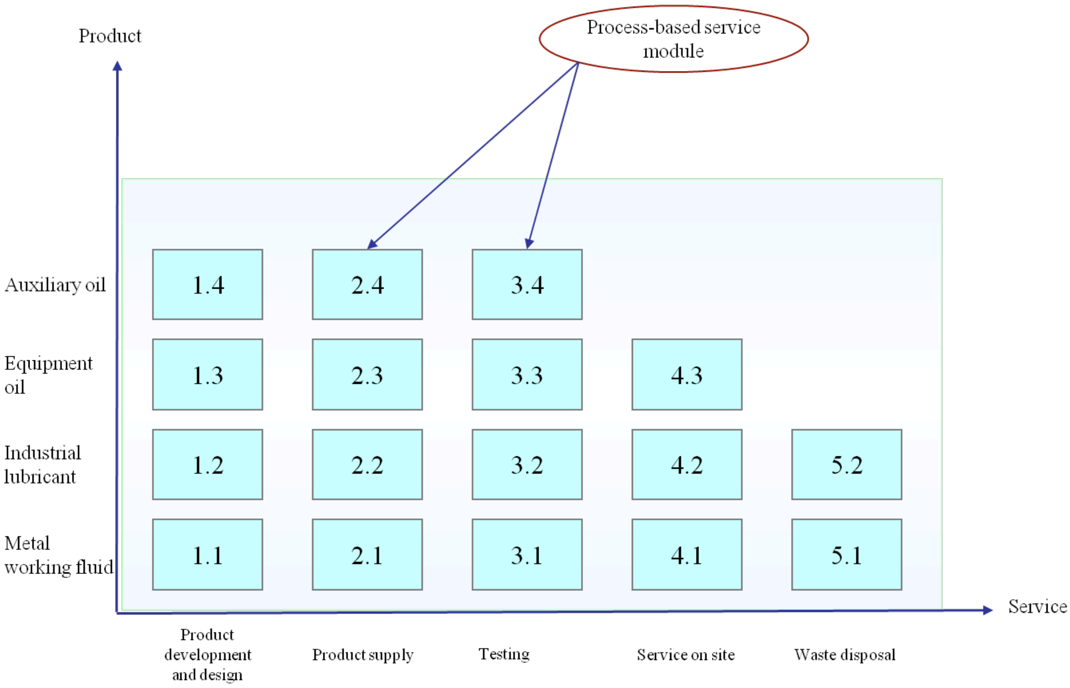

Fig.7 modular total chemical management in China Petrochemical Corporation [Sinopec,2016]

4.3.4 "Class" oriented service modularity

A class service module is a class of services with the same characteristics. This type of services form a "class" services module, such as the main components maintenance service package in maintenance services [Li, 2012].

Case study: Maintenance service modules

Little Swan is a Chinese leading air conditioner and washing machine manufacturing company, which is also the first home appliance company providing menu-style maintenance services in China [Littleswan, 2016]. Little Swan proposed "menu services" and comprehensive modular service processes of air conditioner. The 'menu services' consist of common services (i.e. basic free services and optional paid services) and personalized services. The personalized services are based on consumer's demands (called as "additional paid services"). Optional paid services and additional paid services belong to "class" service modules, as shown in Fig 8.

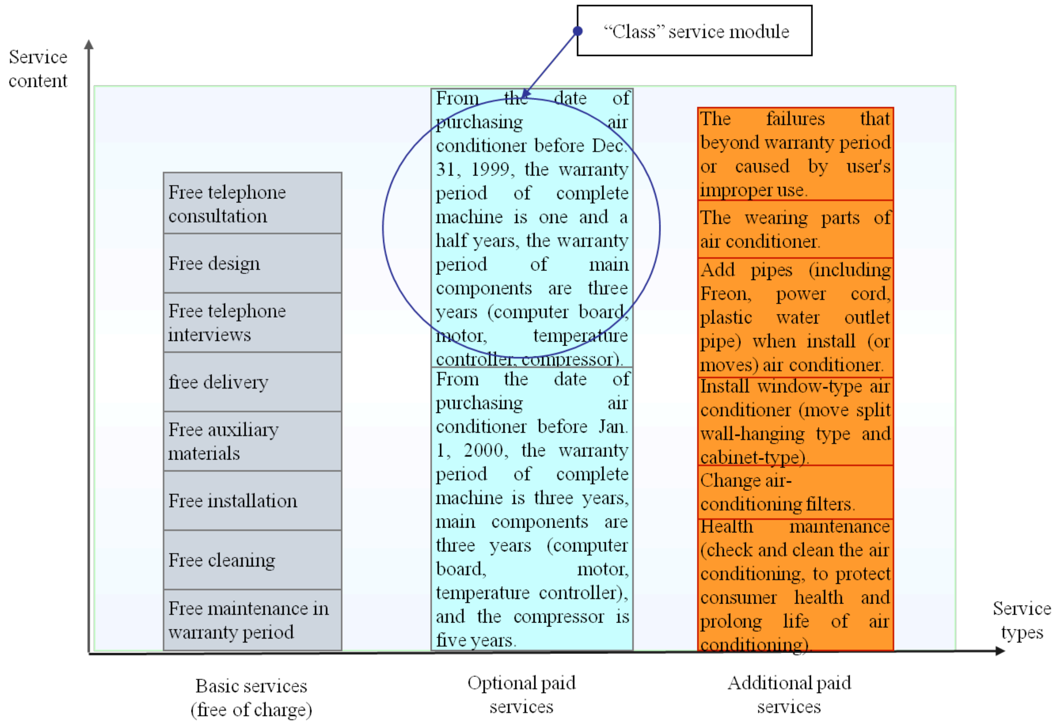

Fig.8 Maintenance service modules of Little Swan air conditioner[Littleswan, 2016]

5. The classification of supply chain modularity in technology system

5.1 Research review on supply chain modularity

The decomposability into modularity results in a series of chain reactions across product design, production, internal organization external organizations and other aspects. The creation of a modular product not only increases the flexibility of product design, but also brings loosely coupled product design, and flexible and modular structure [Sanchez, 1996]. Fisher (1997) recognized the importance of coordination between product and supply chain. He proposed that innovative products should have responsive supply chains, and functional products should be arranged with efficient supply chains [Fisher, 1997]. Tu [2004] thought that a general principle is that standardized processes should be ordered first and customization sub-processes should occur later to allow for the most cost-effective customization. Process modularity makes it possible to break down the process into standard sub-processes and customization sub-processes, and to place the standard sub-processes before the customization sub-processes to achieve maximum flexibility. Postponed manufacturing extends the final modular assembly to distribution centers and even customer sites. This makes it possible to respond quickly to changing customer requirements [Bask, 2010]. In modular assembly lines, workstations and units can be flexibly added, removed, or rearranged to create different process capabilities [Tu, 2004]. Lau demonstrated the positive relationship between product modularity and supply chain integration in selected Hong Kong manufacturing industries [Lau, 2007].

Hoetker found that while product modularity leads to more reconfigurable organizations, it contributes less or not at all to the development of outsourcing activities [Hoetker, 2006]. Supply chain modularity has been associated with certain kind of modular product architectures, even leading to modular structures at the industry level [Bask, 2011]. Chiu found that during supply chain execution, rearrangement of an existing supply chain network based on product characteristics can markedly improve system performance [Chiu, 2014]. Therefore, modularization is an important element for both product design and supply chain design as it affects the selection of component and module suppliers in the assembly sequence. However, the impact of modularity level on supply chain performance is still unclear, and the classification of modularity in supply chain still needs further study.

5.2 the classification of supply chain modularity

5.2.1 Product-oriented supply chain modularity

Product-oriented supply chain modularity is mainly based on different levels of granularity. Corresponding modules can be outsourced to different supplier for designing, manufacturing or supply, so it forms a modular manufacturing network. According to the level and granularity of the module partition, product modularity consists of complete equipment level modularity, product level modularity, component level modularity, part level modularity, and structural unit (or logical unit) level modularity[Gu,2014]. Based on the level of the module granularity, supply chain is designed correspondingly. Fig.9 shows the relationships between product modularity and supply chain modularity. In product modularity, complete equipment forms a completely modular tree structure. Each module corresponds to one supplier node in the supply chain. One node may consist of more than one supplier, representing that one function module may be provided by different suppliers with the same module interface. Different levels of product modules can find the appropriate supplier nodes in the modular supply chains. These supplier nodes form an organization network oriented to product structure. This approach is called product-oriented supply chain modularity.

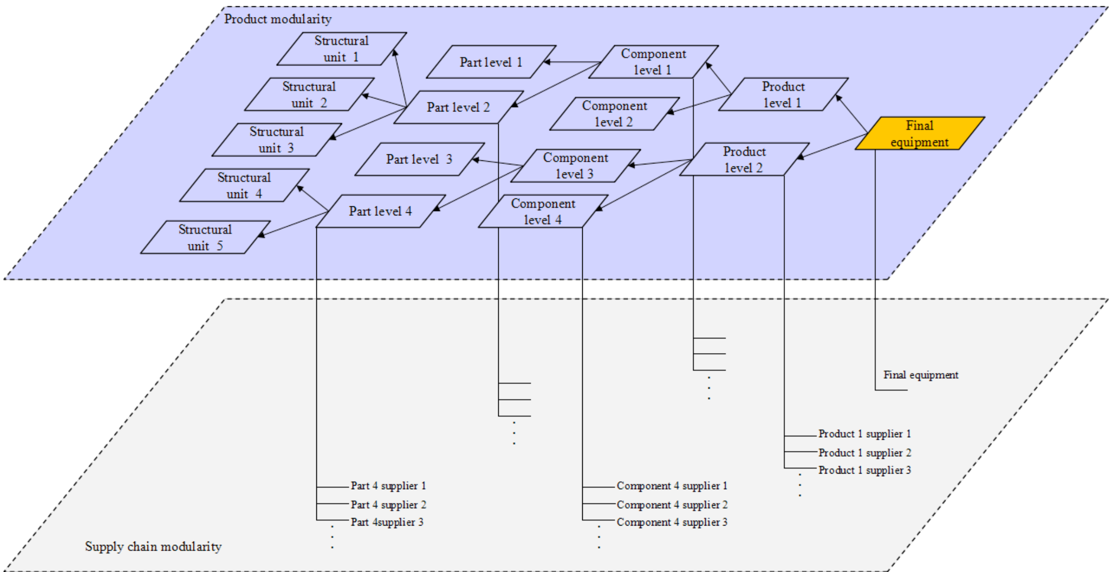

Fig.9 mapping relationships between product modularity and supply-chain modularity [Chiu, 2014]

Case study: Smart car

Smart is made by MCC (Micro Compact Car) , a joint venture between the Mercedes-Benz of German and Swatch of Switzerland. MCC focuses on the key components of Smart, other functions being performed by partners and service providers. Fig. 10 shows the Smart's supply chain in production process. five modules implemented based on the product structure model in the design and assembly, five modules including product platforms, powertrain, body, automotive electronics and seats. It has 7-10 system partners, and 5 supply chains and service provider, and 15 direct suppliers and 25 second-tier service providers. 90% of the stocks can be provided in one hour, and product delivery period is three days. MCC not only gets added value through postponement and customized supply, but also reduce the production cost greatly through the supply chain integration and control [Qi, 2009].

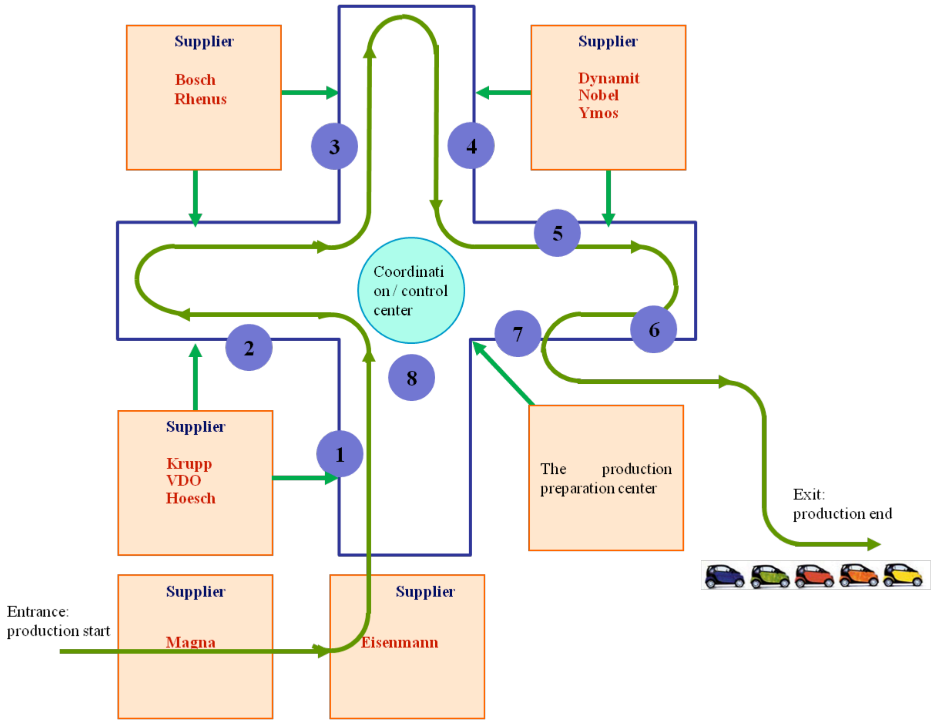

Fig.10 The Smart's modular supply chain in production process [Qi, 2009]

5.2.2 Service-oriented supply chain modularity

Based on service modules, the supply chain can be divided into several modules with independent functions. Each sub-module has a relatively close convergence, and each sub-module has clear standard, interface and structure, by which they can be configured into an organic whole. In the process of service-oriented supply chain modularity, service needs are regarded as the main line, and calls the service process using service integrators to achieve customer's personalized services. The establishment process of service-oriented modular supply chain is that the service continues to be decomposed, searched, filtered, integrated and called.

Case study: the modular service supply chain structure [Fang, 2013]

A port company in Hong Kong cooperates with several service providers such as terminals, warehouses, transportation, packaging and distribution processing service provider, and forms a supply chain service provider offering international logistics services. The business process is shown in Fig. 11.

In Fig.11, the port service consists of four steps. Firstly, accepting customer's requests, and giving a detailed description on the customer's needs. Second, designing customer's service process according to the specific needs. Thirdly, each service process comes from different service modules, therefore, only call the combined service process modules can satisfy the customer's needs. Finally, carrying out the customer service evaluation. The evaluation result is regarded as one of the performance evaluation index for each service provider.

In the process of service-oriented supply chain modularity, each service process module consists of four parts: service activity, service resources, service interface, and service standard. These process modules are service providers, the combined service process modules consists of a series of service providers.

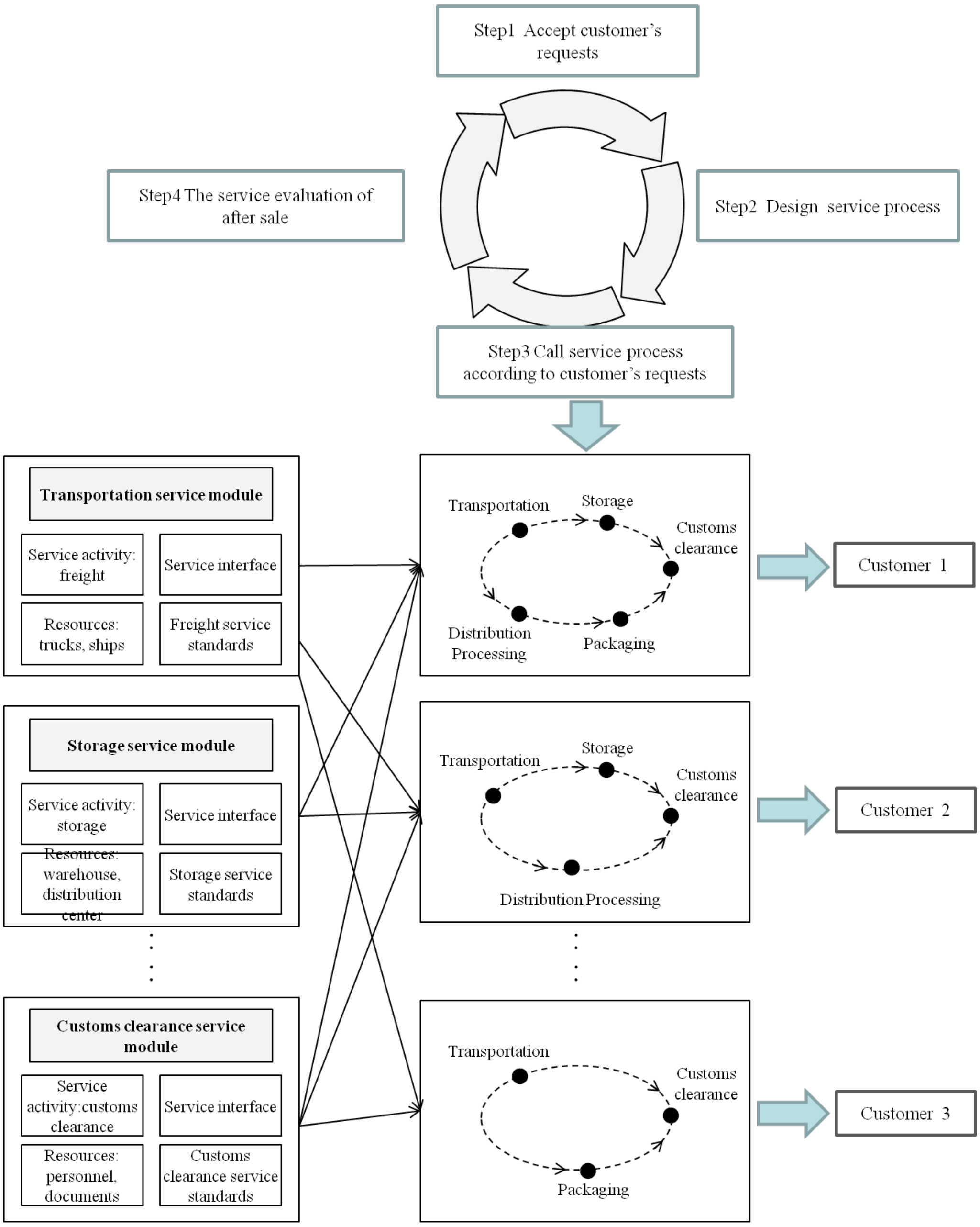

Fig. 11 The modular service supply chain structure of a port company in Hong Kong [Fang, 2013]

5.2.3 Process-oriented supply chain modularity

Process-oriented modularity: in the product life cycle, the supply chain process of the technical system is regarded as a number of modular sub-processes. The supply chain process is divided into modules with standardized operating rules and non-standardized operating parameters, sub-processes become sub-modules with specific functions, each having relative independence in their operations, and form a complete modular supply chain of technical system through standardized operating rules.

Case study: Process-oriented supply chain modularity [Ni, 2004]

X group's materials procurement was originally scattered in various departments and subsidiaries. The department was divided into two types after integration: centralized materials procurement sector and decentralized materials procurement sector. The company established its standard procurement process. In Fig.12, the assembly processing process was divided into stamping, welding, painting and assembly, after standardization it formed relatively independent process modules, which could be used in a variety of car types in parallel. Sales modules included two process modules which were customer assistance center and technical assistance center, standardized operating procedures made sales agents of X group follow a uniform format and standards to provide services to customers. After-sale service modules included two sub-modules: maintenance and automobile sale finance, which provided maintenance services for buyers, and provided credit loan financial services for buyers. The third-party logistics company Y provided most of the logistics services for the subsidiaries of S group. R&D module was divided into two sub-modules: basic technology R&D and specific technology R&D, which provided technical supporting services for all vehicles and specific vehicles respectively. The quality control module is divided into two sub-modules: group ISO certification and department quality control system, implemented quality control functions in two levels [Ni, 2004].

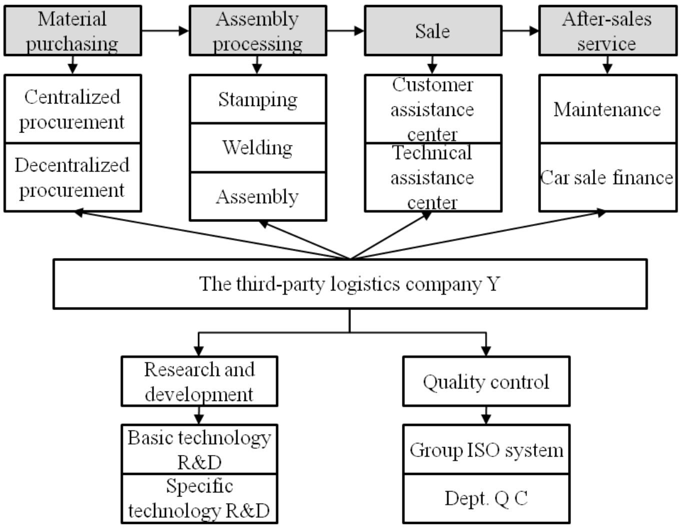

Fig.12 The modular supply chain framework of X group [Ni, 2004]

6. Discussion

In this paper, we address the research and industrial need for the classification of modularity in a broader range. This paper has proposed a definition of modularity of technical system, to include product modularity, service modularity and supply chain modularity. We reviewed the classification of modularity in product, service and supply chain separately, and then considered them as an entire technical system and analysed their relationships.

We found that the structures of product, service and supply chain are different, which determines that the classifications of the modularity of the three parts should be different. There is no united classification which can fit all three modularities. Therefore, we investigated and analysed the classifications of product modularity, service modularity and supply chain modularity separately.

However, we found that there are strong relationships between product modularity, service modularity and supply chain modularity. We also investigated their interrelationships. For example, the P4 (life cycle stage or interaction with the system environment) and P5 (modularity in principal domains) in product modularity classification are closely connected to the service structures as well. The physical product oriented service modularity also links service to physical products; and in supply chain modularity classification, the product-oriented and the service-oriented supply chain modularity hugely rely on products and services.

This paper addresses this need by defining the modularity of technical system, including product, service and supply chains within that defintion; and by providing the classification of modularity in product modularity, service modularity and supply chain modularity separately. The contributions of this paper are: (a) a review on the classification of technical system modularity; (b) the analysis of internal relationship among different types of product modularity, (c) proposal of different types of service modularity and supply chain modularity. This study can assist manufacturing companies improve their modular design and management of technical system.

7. Conclusion

This paper proposes a new classification of the modularity of technical system, including product, service and supply chain. There are already a number of existing studies on the classification of product modularity in the literature; however, the relationships among them are ambiguous. We analysed the relationships among the main classification criterions from the perspectives of product life cycle and in four domains (customer domain, functional domain, physical domain, and process domain). There are even fewer existing studies on the classification of service modularity. We argue that the three types emerging from literature cannot support the service module partition and modular design well, so we analysed the relationships between product and service modularities, and proposed four new types of service modularity oriented to technical system. We also provided cases for each type of service modularity. For the supply chain modularity, there is no existing classification in literature. We analysed related studies, and proposed three types of supply chain modularity and cases separately.

The novelty of this paper consists of three aspects. The first is an overview on the classification of technical system modularity, the second is the analysis of the relationships among different types of product modularity, and the third is the proposal of the classifications of service modularity and supply chain modularity. Further work is needed to study the modular process of technical system based on the above relationships and proposed types of modularity.

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