

Article

An Iterative Design Method from Products to Product Service Systems—Combining Acceptability and Sustainability for Manufacturing SMEs

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Abstract: Manufacturing small- and medium-sized enterprises (SMEs) play a crucial role in the economic development and resource consumption of most regions. Conceptually, a product-service system (PSS) can be an effective way to improve the sustainability of manufacturing SMEs. However, the construction of PSSs requires enterprises to integrate a large number of product and service resources. Moreover, current PSS design methods mostly construct a new set of highly service-oriented PSS solutions based on customer needs while seldom considering the combination of acceptability and sustainability for manufacturing SMEs at the initial stage of design, which may lead to the difficulties in applying PSS solutions beyond enterprise integration capacity or result in the waste of existing product resources. Instead of constructing a new PSS solution, this paper proposes the treatment of existing product modules as the original system. The PSS solution is iteratively constructed with the upgrade of the original system in a gradual way, which is driven by systematic performance (this process can be suspended and repeated). Phased iterative design solutions can be applied by manufacturing SMEs according to their development needs. The analytic hierarchy process (AHP), Lean Design-for-X (LDfX), design structure matrix (DSM), and Pearson correlation coefficient (PCC) are combined in an iterative design process from customer needs and system performances to PSS solutions. The feasibility of the proposed method is verified through the iterative design case from electric pallet trucks to warehousing systems. It is proved that this method is more sustainable and easier to be accepted by manufacturing SMEs than existing PSS design methods through in-depth interviews with entrepreneurs.

Keywords: manufacturing SMEs; product-service systems; an iterative design method; existing components; acceptability and sustainability



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1. Introduction

Manufacturing SMEs comprise a vital part of the manufacturing industry. In Asian countries, manufacturing SMEs play a crucial role in improving national economic efficiency [1]. However, manufacturing SMEs are responsible for a considerable part of the world's resource consumption, air and water pollution, and waste generation [2]. According to Asian Development Bank data for 2017, some countries in the Asia-Pacific region continue to struggle with reaching their sustainable development goals in terms of responsible consumption and production patterns [3]. As a result, manufacturing SMEs are under greater pressure to carefully consider their use of limited resources and to strike a balance between economic growth and environmental sustainability [4].

In this context, the servitization of manufacturing has gained increased attention, as manufacturing SMEs need new methods to increase customer satisfaction and sustainability [5–8]. To meet these demands, the manufacturing industry has proposed a new concept

denoted the PSS [9]. The PSS definition proposed by Mont, “PSS is a system of products, services, supporting networks and infrastructure that is designed to be: competitive, satisfy customer needs and have a lower environmental impact than traditional business models”, is one of the most cited PSS definitions [10,11]. Based on previous literature analysis, PSSs which consist of product and service elements can lead to an increase in customer satisfaction and customer value. Moreover, PSSs can reduce the environmental impact in connection with delivery of customer needs and offer a new business model which includes shifts in product ownership [11]. PSSs have been recognized as having great potential for sustainability through reducing the costs of materials by using fewer, using them longer, etc. in the life cycle [12–14].

In the modern global economy, the PSS strategy is increasingly popular among manufacturers [15], including IBM (from hardware to software supplier and then to service provider), Apple (from personal computer manufacturer to high-end consumer electronics and service provider), and Monetti S.P.A of Italy (from refrigerator manufacturer to integrated service provider of cold chain logistics based on refrigerator manufacturing) [16]. Although PSSs enhance customer acceptance and market success [17], manufacturing SMEs faces a number of challenges in the servitization transition [18–20]. These unexpected difficulties are known as the Service Paradox [21]. It often proves more difficult than expected to recoup the expected level of return from services [22]. Moreover, present scientific approaches generally focus on case studies based on large companies [23]. Current PSS design theories lack comprehensive consideration of combining acceptability and sustainability for manufacturing SMEs. Based on these theories, enterprises often get a highly service-oriented new system solution, which means that manufacturing SMEs need to waste a lot of existing product resources. Moreover, the highly service-oriented system solution is costly and risky for manufacturing SMEs, which have limited resources and serviceability [24].

This study proposed to take the existing product modules as the original system of PSS. Manufacturing SMEs can gradually construct PSSs with better performance through iteration design. The resource waste can be reduced by making full use of existing products. On the other hand, iteration design splits the design process into iterative design cycles, reducing prevailing uncertainties [25] and validating solutions fast with low input [26]. The remaining sections of this study are arranged as follows. Section 2 discusses the limitations of the existing PSS design methods in SME applications. Section 3 introduces an iterative PSS design method based on AHP, LDfX, DSM, and PCC. In Section 4, the feasibility of the proposed iterative PSS design method is verified through a case study of an actual warehousing system in a manufacturing SME. Section 5 discusses the advantages on combining sustainability and acceptability for manufacturing SMEs. Finally, Section 6 provides a summary and brief overview of future work.

2. Related Work

Over the past decade, research has found that, in theory, PSSs can benefit many different stakeholders and the environment [27]. However, the application of PSSs in the manufacturing industry has not yet reached its full potential [28], and many SMEs are still hesitant regarding the adoption of a PSS model.

From the perspective of enterprise implementation, this occurs because PSSs are radical innovations, demanding huge challenges in different aspects of society, such as current customer habits, organizations’ capabilities, and regulatory systems [29]. In other words, enterprises often adopt a conservative attitude when the implementation of PSSs has a high risk of failure or failure will make it difficult for enterprises to survive. Therefore, how to reduce the investment in PSS transformation to improve acceptability of PSSs is a crucial first step.

From the perspective of the PSS design method, the main directions of existing studies are customer needs analysis and solution configuration through parallel design process. (1) In regard to customer needs analysis technologies, Song et al. [30] proposed a method

for evaluating customer needs in the early stages of PSS design, the concept of a customer activity cycle, and the use of a rough group analytic hierarchy process to extract customer needs. The limitation of this method is that it often fails the consistency test due to the subjectivity of the industry stakeholder. Carreira et al. [31] conducted a comprehensive in-depth study of customer experiences to guide the design process. This research allowed for the active participation of multidisciplinary experts from different partnering companies to jointly support the development of the PSS. However, this research remains in the initial theoretical stage and lacks a verifiable quantitative model. Schuh et al. [32] proposed a new model consisting of a descriptive model visualizing variety within the integrated product-service system and an explanatory model quantifying the cost of PSS. Enterprises can select configurations of PSSs that have an optimal cost-benefit ratio resulting under the premise of customer's price acceptability. However, it is not enough to measure customer satisfaction with PSSs from an economic point of view. (2) In regard to solution configuration technologies, Trevisan and Brissaud [33] proposed a PSS design framework to provide a tool for an integrated PSS design, involving the cooperation of both product and service designers. By integrating the existing models of product and service engineering into a single framework, any component in the solution design process could be expressed from both product and service perspectives, thereby facilitating the integration of products and services. Durugbo [34] adopted a method that combined multi-case logic and expert interviews to develop a collaborative PSS design system for assisting in the management of collaborative design. However, additional research is still required on some key aspects of PSS design, such as role conversion and structured dialogue. Zhou et al. [35] reconstructed a PSS based on behavior and functionality, thereby providing a new approach for PSS design through functional activity mapping. The PSS design method does not guarantee environmental improvements if it is not specifically designed for sustainability [36].

Pieroni et al. [37] proposed the adoption of PSS strategies which appears to be a promising solution. However, the practical application of PSS sustainable approaches is still limited. Kjaer et al. [38] proposed that PSSs are not necessarily environmentally benign compared to conventional systems as well as integrating the life cycle assessment into the environmental evaluation of PSSs. This method of adding the sustainability evaluation at the later stage of design makes it difficult to have a positive impact on the PSS solution itself. Pigosso and McAloone [39] proposed integrating PSS best practices with ecodesign best practices to ensure increased environmental performance. However, this method guarantees sustainability, not success for manufacturing SMEs. Maccioni et al. [40] constructed the correlations between specific ecodesign principles and success through an exploratory study. This paper mainly discusses the relationship between sustainability and customer behavior (interact with and choose to pay for). Enterprises that are important stakeholders in the PSS design are not considered.

Chen et al. [41] proposed making minor modifications to existing products to satisfy customer needs through an evolutionary design approach. Riesener et al. [42] proposed meeting priority customer needs through iteration to shorten development cycles and increase customer focus. Moreover, iterative design can not only improve the design efficiency in the early stage, but also quickly adjust in the later stage with the change of customer needs [43]. Therefore, iterative design is considered in this paper to improve the acceptability for manufacturing SMEs.

3. Method

This paper presents the iterative design method from products to product service systems. The specific procedure is as follows: (1) establish a mapping relationship between system performance and customer requirements and translate customer needs into system performance as the iterative driver based on AHP; (2) rank the weight of system performance according to the weight of customer requirements, which is used as a driver in iterative design; (3) modularize existing product components as the original system based on LDfX; (4) modularize service components through analysis of internal informa-

tion flow of service components based on DSM; (5) construct correlation ranking between each module and system performance based on PCC to determine the module priority corresponding to the system performance in the iterative process; (6) combine product and service modules to meet each system performance gradually, and PSS solutions get iterative upgrades each time system performance is met.

The existing product is defined as the original system. The combination of product and service modules in system iteration is regarded as a horizontal cross section. The system performance-weighted ranking is regarded as an ordinate axis. The design process of the PSS solution reflects a spiral iterative state, as shown in Figure 1. Manufacturing SMEs can suspend the iterative process and put phased plans into the market. Moreover, this iteration can be repeated by taking the existing PSS solution as the original system when customer needs change. The original system in Figure 1 can be an existing product module or an existing PSS module solution.

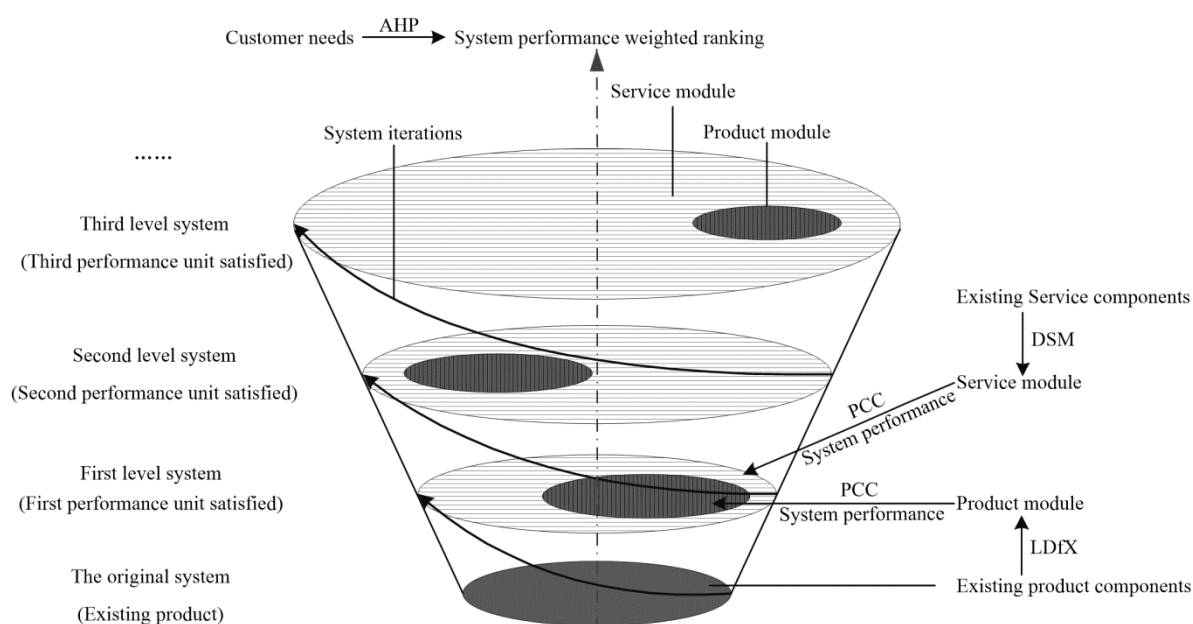


Figure 1. An iterative design method from products to PSSs.

3.1. System Performance Weighted Ranking

The transformation process from customer needs to system performance is a step-by-step mapping process from the target layer of customer demand satisfaction to customer value index and finally to system performance index. In this process, the weight of customer value and system performance should be ranked by multiple stakeholders. Saaty [44] proposed that AHP provides the objective mathematics to process the inescapably subjective and personal preferences of a group in making a decision. AHP is considered one of the most popular and powerful multicriteria, decision-making methods [45,46], which is a suitable method to more objectively obtain the weight of the indexes [47]. Lu et al. [48] demonstrated how a particular company can decide on which strategic marketing orientation to adopt based on AHP.

This study aims to establish an AHP-based model for transforming customer needs to system performance and rank their weights. Based on the "SERVQUAL" model (a service evaluation tool) [49] and a generalized comprehensive performance analysis [50], customer needs are categorized into the following six types (C1 to C6): reliability, timeliness, credibility, interactivity, social, and economic. The corresponding 17 system performances are also categorized (SP1 to SP17), as shown in Figure 2.

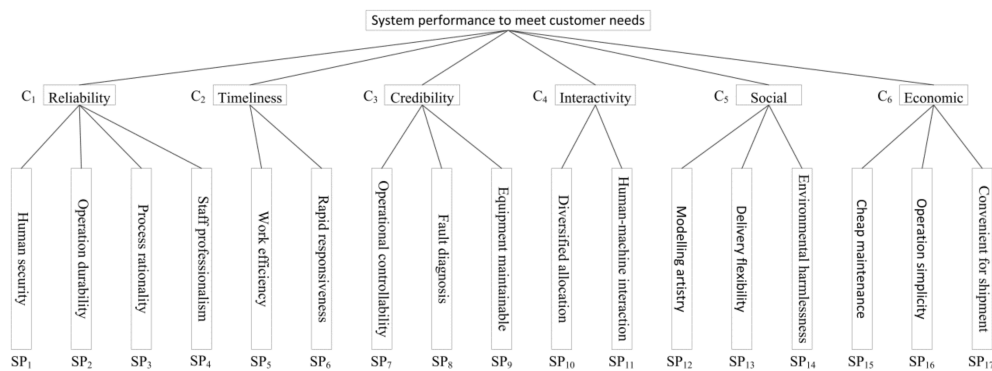


Figure 2. Hierarchical model of PSS system performance.

Next, the impacts of each indicator on the indicators in the level above are evaluated. A pairwise comparison is performed on the same-level indicator so that one middle-layer matrix (the weighted judgment matrix of the middle- and top-layer indicators) and six bottom layer matrices (the weighted judgment matrices of the bottom-level and middle-level indicators) can be constructed through the decision matrix. The relative importance of SPU pair comparison in the base layer is denoted as r , and for n , number of system performance (SP), the weight judgement matrix can be obtained according to the aforementioned scales:

$$M = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n1} & \cdots & r_{nn} \end{bmatrix} \quad (1)$$

The formula for calculating weight is expressed as follows:

$$W_i = \frac{\sum_{j=1}^n r_{ij} + \frac{n}{2} - 1}{n(n-1)}, (1 \leq i \leq n) \quad (2)$$

The consistency ratio is verified as follows:

$$\lambda_{max} = \frac{1}{n} \sum_{j=1}^n \left(\frac{\sum_{i=1}^n r_{ij} W_i}{W_j} \right) \quad (3)$$

$$CR = \frac{(\lambda_{max} - n)RI}{n - 1} \quad (4)$$

In this equation, the random consistency index, RI , can be obtained from a lookup table. When the consistency index $CR \leq 0.1$, the consistency test is passed, and the normalized feature vector becomes the weight vector.

3.2. Modular Approach to Existing Product and Service Components

PSS modularization facilitates product and service upgrades, adaptations, modifications, and product assembly and disassembly and also helps to increase product diversity, achieve economies of scale, and reduce manufacturing time [33]. The modularization of product and service components can also greatly improve the efficiency of PSS design, while simultaneously making it convenient for customers to select and customize products and services.

As the PSS design considers the entire operating cycle of the system, this study adopts the LDfX-based modularization of product components. The diversity of X in LDfX makes it adaptable to multiple product types and enterprise modularity requirements, which is consistent with the enterprise and product diversity in PSS design. Through a lean thinking approach, it also focuses on decreasing waste resources within the product

(for all life cycle phases), which is particularly important for manufacturing SMEs [51]. Products can be modularly analyzed efficiently and accurately based on LDfX which has been applied and verified by Baptista et al. [52] on a press-brake machine tool. The term LDfX describes a design philosophy or methodology focusing on product improvement at different stages of a product life cycle [53]. In LDfX, X can represent the entire life cycle of the product or one of its phases, such as manufacturing, assembly, utilization, disassembly, maintenance, recycling, and scrapping; it can also represent factors that determine product competitiveness, such as quality, time, and cost [54], as shown in Table 1. The LDfX-based modularization of product components is particularly versatile in applications of manufacturing SMEs. It can be implemented based on the industry's actual needs and conditions; for example, for low-end-market products, the modularization focus is on cost, and for construction machinery (which has a high rate of damage), the modularization should focus on disassembly and repair.

Table 1. LDfX-based modular partitioning.

X	Characteristic Index
Assembly	Size, geometry, weight, material, assembly process, etc.
Manufacturing	Structure, geometry, material, manufacturing technology, manufacturing equipment, etc.
Disassembly	Structure, assembly method, disassembly process, disassembly tools, etc.
Disassembly	Ease of disassembly, ease of reassembly, reliability, repair cost, maintenance tools, etc.
Recycling	Ease of disassembly, material, etc.
Quality	Dimensional tolerance limits, ease of testing, standard type, standardization, etc.
Reliability	Material, durability, etc.
Environmental	Recyclability, maintainability, reliability, eco-safety
Cost	Purchase cost, manufacturing cost, assembly cost, etc.

Owing to the intangible nature of services, manufacturing enterprises often use services tailored to specific customer groups. The modularization of services allows manufacturers to customize services and enables them to use (to a certain extent) economies of scale at the modular level to control costs. Considering the automotive industry as an example, many automakers have established modularized service platforms to reuse, modify, standardize, and selectively combine individual modules to meet different customers' needs and to provide services in different business environments [55].

Existing or planned service components in the manufacturing SMEs also need to be modularized. DSM is a versatile method that can be used for modeling, mapping, and analyzing the relationships and interactions between different elements of a complex system [56]. Compared with the structured analysis and design technique and quality function deployment, DSM is more efficient and accurate [57]. Sakao et al. [58] proposed five steps of a service modularization method based on DSM and proved its feasibility through the case of an elevator service module modularization. The existing and planned service processes are constructed into service modules, as shown in Figure 3, based on the following three steps [59]. First, the relationships between the service components are represented. The service components can have one of three types of relationships: independent, unidirectional, and two-way reciprocal. Binary interactions (input or output) between different components were created based on DSM. If information is input from component A into component B, then the vector points from A to B. The second step comprises matrix construction. If service component A points to component B, then the element in row B and column A is one; if there is no interdependence between components A and B, then use zero; the black blocks along the matrix diagonal indicate "no meaning." There will be asymmetry in the matrix when there is only information flowing from A to B and no information flowing from B to A in the information exchange. The third step

concerns matrix segmentation. The matrix is rearranged based on matrix segmentation rules [60] so as to cluster the service components to the possible extent.

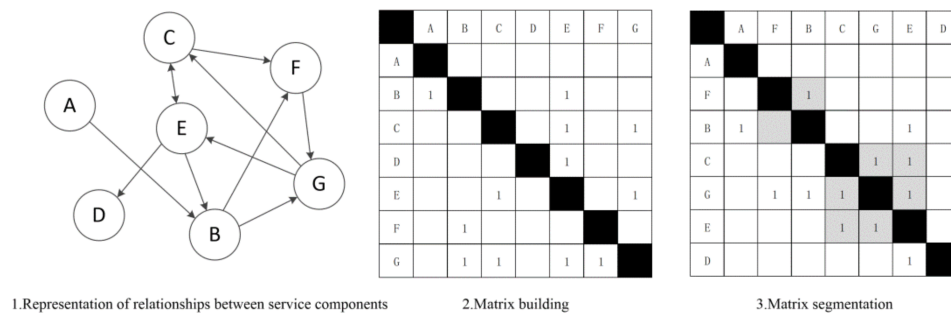


Figure 3. Module partition method based on design structure matrix (DSM).

3.3. Correlation Analysis of System Performance and Modules

Each system performance is satisfied by combining various modules. The correlation between each performance and module is different. It is necessary to rank the correlations between each system performance and the different modules during the design process. After determining the ranking of each system performance, the modules that are highly related to important system performances can be prioritized as design and implementation goals so as to maximize customer satisfaction with minimal resource.

First, the relationships between the different system performances and module attributes are mapped, as shown in Figure 4. For example, for a warehousing system, customer satisfaction with the system performance can be mapped onto the full-load lifting speed of the handling module, maximum full-load driving speed of the power module, turning radius of the mobile module, rationality of the control layout of the control module, rationality of the operating specifications of the training guidance module, and rationality of the diagnostics and maintenance specifications for the maintenance module.

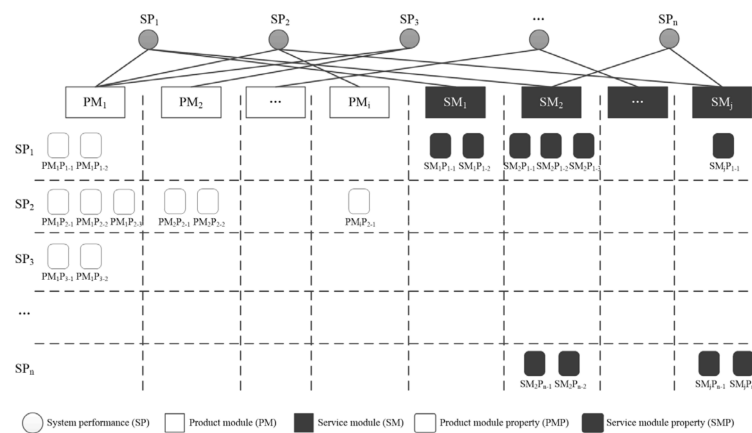


Figure 4. Relationship mapping of system performances and module attributes.

Next, the correlation between each module attribute and system performance is calculated using the PCC. The PCC is a linear correlation coefficient, which is used to reflect the linear correlation of two normal continuous variables [61]. The PCC is recognized as a classical and arguably more popular tool to measure the degree of correlation between groups of data [62]. The PCC value is in the interval $[-1, 1]$; a value of 1 indicates a

complete positive correlation, and a value of less than or equal to 0 means that the two variables are not correlated. The Pearson coefficient formula [63] is as follows:

$$r = \frac{\sum_{i=1}^n (M_i - \bar{M})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^n (M_i - \bar{M})^2} \sqrt{\sum_{i=1}^n (P_i - \bar{P})^2}} \quad (5)$$

Here, n is the number of modules; M_i and P_i are the observed values of point i corresponding to M and P , respectively; $\bar{M}$ is the average number of M samples; and $\bar{P}$ is the average number of P samples.

4. Case Analysis

Company H is a warehousing equipment manufacturing SME that produces electric pallet trucks and provides training guidance, on-site maintenance, and other services for this product series. Company H hopes to gradually establish its PSS based on its existing products and services to meet the needs of household appliance supermarket managers. First, the customer value (middle layer) judgment matrix, M_C , and system performance (bottom layer) judgment matrices, M_{P1} , M_{P2} , M_{P3} , M_{P4} , M_{P5} , and M_{P6} , were constructed based on a user survey questionnaire of supermarket managers and evaluations from an expert group.

$$M_C = \begin{bmatrix} 1 & C1C2 & C1C3 & C1C4 & C1C5 & C1C6 \\ C2C1 & 1 & C2C3 & C2C4 & C2C5 & C2C6 \\ C3C1 & C3C2 & 1 & C3C4 & C3C5 & C3C6 \\ C4C1 & C4C2 & C4C3 & 1 & C4C5 & C4C6 \\ C5C1 & C5C2 & C5C3 & C5C4 & 1 & C5C6 \\ C6C1 & C6C2 & C6C3 & C6C4 & C6C5 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 2 & 5 & 4 & 5 & 3 \\ 1/2 & 1 & 3 & 2 & 4 & 2 \\ 1/5 & 1/3 & 1 & 1/2 & 1/2 & 1/3 \\ 1/4 & 1/2 & 2 & 1 & 2 & 1/2 \\ 1/5 & 1/4 & 2 & 1/2 & 1 & 1/3 \\ 1/3 & 1/2 & 3 & 2 & 3 & 1 \end{bmatrix} \quad (6)$$

$$M_{P1-4} = \begin{bmatrix} 1 & P1P2 & P1P3 & P1P4 \\ P2P1 & 1 & P2P3 & P2P4 \\ P3P1 & P3P2 & 1 & P3P4 \\ P4P1 & P4P2 & P4P3 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 2 & 4 & 3 \\ 1/2 & 1 & 3 & 2 \\ 1/4 & 1/3 & 1 & 1/2 \\ 1/3 & 1/2 & 2 & 1 \end{bmatrix} \quad (7)$$

$$M_{P5-6} = \begin{bmatrix} 1 & P5P6 \\ P6P5 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 3 \\ 1/3 & 1 \end{bmatrix} \quad (8)$$

$$M_{P7-9} = \begin{bmatrix} 1 & P7P8 & P7P9 \\ P8P7 & 1 & P8P9 \\ P9P7 & P9P8 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 4 & 3 \\ 1/4 & 1 & 1/2 \\ 1/3 & 2 & 1 \end{bmatrix} \quad (9)$$

$$M_{P10-11} = \begin{bmatrix} 1 & P10P11 \\ P11P10 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 1/2 \\ 2 & 1 \end{bmatrix} \quad (10)$$

$$M_{P12-14} = \begin{bmatrix} 1 & P12P13 & P12P14 \\ P13P12 & 1 & P13P14 \\ P14P12 & P14P13 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 1/3 & 2 \\ 3 & 1 & 5 \\ 1/2 & 1/5 & 1 \end{bmatrix} \quad (11)$$

$$M_{P15-17} = \begin{bmatrix} 1 & P15P16 & P15P17 \\ P16P15 & 1 & P16P17 \\ P17P15 & P17P16 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 1/2 & 2 \\ 2 & 1 & 3 \\ 1/2 & 1/3 & 1 \end{bmatrix} \quad (12)$$

Next, the λ_{max} , CI , and CR values were calculated for all eight normalized matrices, as shown in Table 2.

Table 2. Definition linguistic terms of fuzzy numbers.

Matrix	λ_{max}	CI	RI	CR<0.1
M_C	6.1542	0.0308	1.24	0.0249
M_{P1-4}	4.0313	0.0104	0.90	0.0116
M_{P5-6}	2	0	0.00	0
M_{P7-9}	3.0184	0.0092	0.58	0.0159
M_{P10-11}	2	0	0.00	0
M_{P12-14}	3.0038	0.0019	0.58	0.0033
M_{P15-17}	3.0093	0.0047	0.58	0.008

Next, the total weight of each system performance was calculated, as shown in Table 3.

Table 3. System performance weights.

System Performance	C1 0.3821	C2 0.224	C3 0.0574	C4 0.1056	C5 0.0703	C6 0.1606	Weight
SP ₁	0.4658						0.178
SP ₂	0.2771						0.1059
SP ₃	0.096						0.0367
SP ₄	0.1611						0.0615
SP ₅		0.75					0.168
SP ₆		0.25					0.056
SP ₇			0.6232				0.0358
SP ₈			0.1373				0.0079
SP ₉			0.2395				0.0137
SP ₁₀				0.3333			0.0352
SP ₁₁				0.6667			0.0704
SP ₁₂					0.2299		0.0161
SP ₁₃					0.648		0.0456
SP ₁₄					0.1221		0.0086
SP ₁₅						0.2972	0.0477
SP ₁₆						0.539	0.0866
SP ₁₇						0.1638	0.0263

Based on the calculated weights, the system performances were ranked from the highest to the lowest weight, as follows: SP₁, SP₅, SP₂, SP₁₆, SP₁₁, SP₄, SP₆, SP₁₅, SP₁₃, SP₃, SP₇, SP₁₀, SP₁₇, SP₁₂, SP₉, SP₁₄, and SP₈. Among them, the most important system performances (with a weight greater than 10%) were SP₁, SP₅, and SP₂; the secondary importance system performances (with weights between 5–10%) were SP₁₆, SP₁₁, SP₄, and SP₆; the inconsequential system performances (with weights of less than 5%) were SP₁₅, SP₁₃, SP₃, SP₇, SP₁₀, SP₁₇, SP₁₂, SP₉, SP₁₄, and SP₈.

After ranking the system performances, the next step is to modularize the existing product and service components. As the warehousing system required that the manufacturing enterprise was responsible for the product during its entire life cycle, except for its daily use, the modular partitioning of the warehousing equipment principally involved product components used in product assembly, manufacturing, and post-maintenance. In addition, as Company H purchased some of its warehousing equipment components, such as the drive motor, control system, suspension system, and hydraulic system, these components were not further subdivided into separate components in the modular partitioning. Figure 5 shows the product module partition of the storage device.

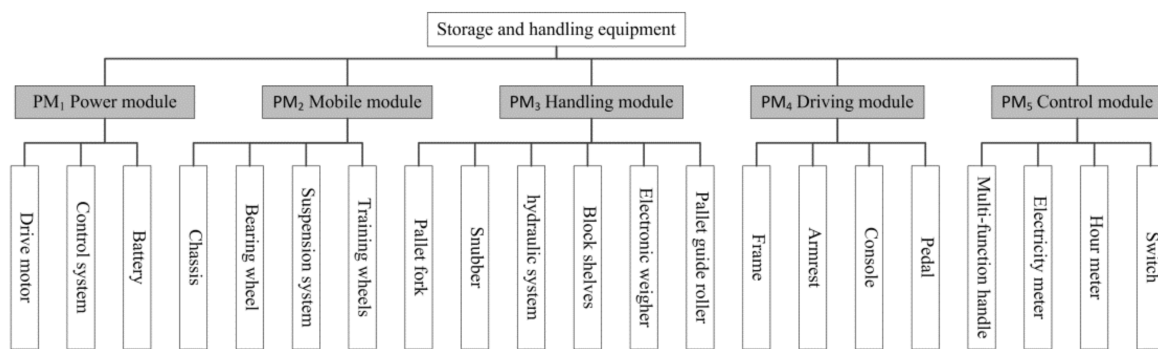


Figure 5. Relationship mapping of system performances and module attributes.

Next, the services and components involved in the entire life cycle of the warehousing system were analyzed. The existing service components are shown in Figure 6.

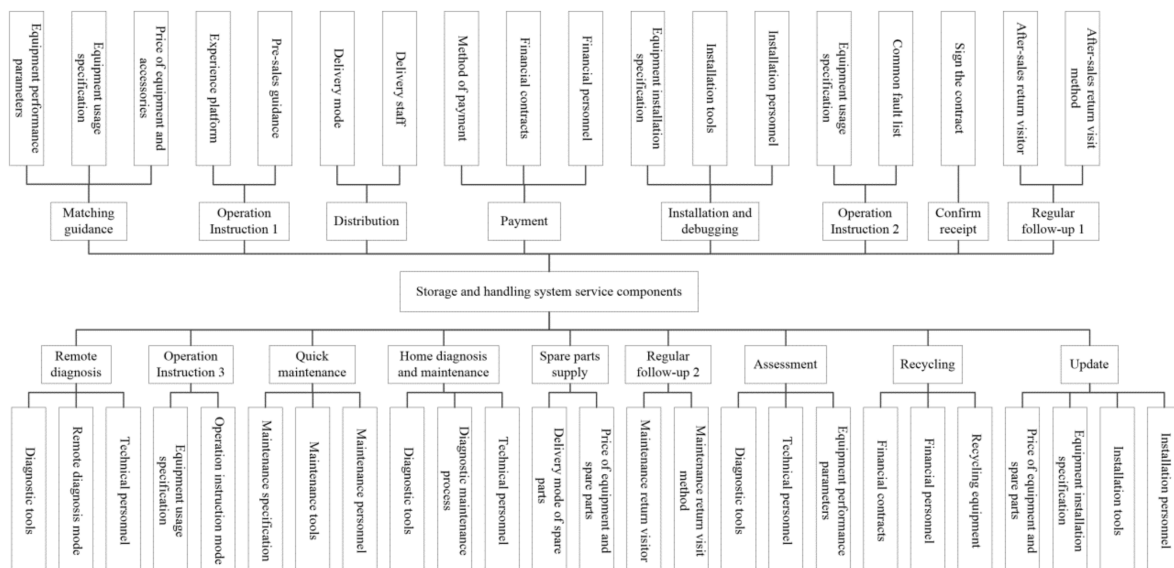


Figure 6. Service components of the warehousing system.

The service components were modularized and ranked based on their relevance so as to facilitate the subsequent preferential design. The service components are divided (using the DSM method) into the following six service modules: training guidance, purchased service support, system to deliver, operating support, repair and maintenance, and recycling/updates, as shown in Figure 7 (indicated by gray shading).

Next, the correlation between each module and system performance was calculated based on the PCC. Take the correlation between system performance SP_5 and each module of the warehousing system as an example. The customer satisfaction with SP_5 was set as the dependent variable, and the relevant attributes of each module are set as the independent variable (respectively). Based on a focus group discussion involving 28 experts and the results of a questionnaire survey, SP_5 was mapped into the maximum full-load driving speed of the power module (PM_1P_{5-2}), the turning radius of the mobile module (PM_2P_{5-1}), the maximum full-load lifting speed of the handling module (PM_3P_{5-1}), the functionality of the controls layout of the control module (PM_5P_{5-1}), the rationality of the operating specifications of the training guidance module (SM_1P_{5-1}), and the rationality of the diagnostic and maintenance specifications of the maintenance module (SM_5P_{5-1}). The survey questionnaire investigated the user's satisfaction with SP_5 in the process of a module attribute change. After averaging the evaluation results, the correlations between each module and SP_5 were obtained. The calculation results are shown in Table 4. Based on the PCC results, the

relative order of the SP₅-related modules, from strong to weak, is determined as follows: power module (PM₁), control module (PM₅), handling module (PM₃), training guidance module (SM₁), maintenance module (SM₅), and mobile module (PM₂).

SM ₁ Training guidance																					SM ₂ Purchased service support						SM ₃ System to deliver						SM ₆ Recycling update			
	Equipment performance parameters	Equipment usage specification	Price of equipment and accessories	Experience platform	Pre-sales guidance	Contact platform	Delivery mode	Delivery staff	Method of payment	Financial contracts	Financial personnel	Equipment installation specification	Installation tools	Installation personnel	Common fault list	Sign the contract		Recovery update tool	Recovery and Renewal staff	Recovery process and specification																
Equipment performance parameters		1	1																																	
Equipment usage specification	1		1		1																															
Price of equipment and accessories	1																																			
Experience platform	1	1	1		1	1																														
Pre-sales guidance	1	1	1	1		1						1			1																					
Contact platform		1	1	1	1			1			1			1					1																	
Delivery mode									1	1																										
Delivery staff		1					1		1		1																									
Method of payment							1	1		1	1																									
Financial contracts	1		1				1	1	1		1																									
Financial personnel			1				1		1	1																										
Equipment installation specification	1												1	1	1	1																				
Installation tools												1		1																						
Installation personnel	1	1										1	1		1	1																				
Common fault list													1																							
Sign the contract	1									1	1	1		1	1																					
.....																		1																		
Recovery update tool																			1	1																
Recovery and Renewal staff	1																	1		1																
Recovery process and specification																		1																		

Figure 7. Service module partitioning of the warehousing system.

Table 4. Correlations between customer satisfaction with SP5 and module attributes.

	PM ₁ P ₅₋₁	PM ₂ P ₅₋₂	PM ₃ P ₅₋₁	PM ₅ P ₅₋₁	SM ₁ P ₅₋₁	SM ₅ P ₅₋₁
Degree of satisfaction with SP5	0.987 **	−0.630 *	0.776 **	0.784 **	0.755 **	0.666 *
Significance (two-tailed)	0.000	0.016	0.001	0.001	0.001	0.009

** significant correlation at the 0.01 level; * significant correlation at the 0.05 level.

Finally, the iterative design sequence of the system performance and each module in the warehousing system were determined, as shown in Figure 8 (the serial numbers represent the sequence).

		SP ₁	SP ₅	SP ₂	SP ₁₆	SP ₁₁	SP ₄	SP ₆	SP ₁₅	SP ₁₃		SP ₁₄	SP ₈
Product module	PM ₁		3	1				3		5	...	1	2
	PM ₂	5	5	4					5		...		
	PM ₃	4	1	3				4	4		...		
	PM ₄	1		5		2		2	6	5	...		
	PM ₅	2	2	2	1	1			3		...		
Service module	SM ₁	3	6	4	2	3	1				...	4	3
	SM ₂						4	7		4	...		
	SM ₃				5		5		2	1	...		
	SM ₄	6		7		5	6	5		6	...		1
	SM ₅	7	4	8	4	4	2	6	1	3	...	3	
	SM ₆			9	5		5			7	...	2	

Figure 8. Iterative design sequence of system performance and each module.

In the initial stage of servitization, Company H planned to meet the most important system performance requirements. Therefore, it needed to implement three incremental designs to satisfy the customer needs for SP₁, SP₅, and SP₂. To reduce the cost of the transformation, Company H chose the most relevant module (at the 0.01 level) as the design object to maximize system performance through fewer component combinations. A warehousing system solution satisfying the requirements for SP₁, SP₅, and SP₂ was obtained after three iterations, as shown in Figure 9.

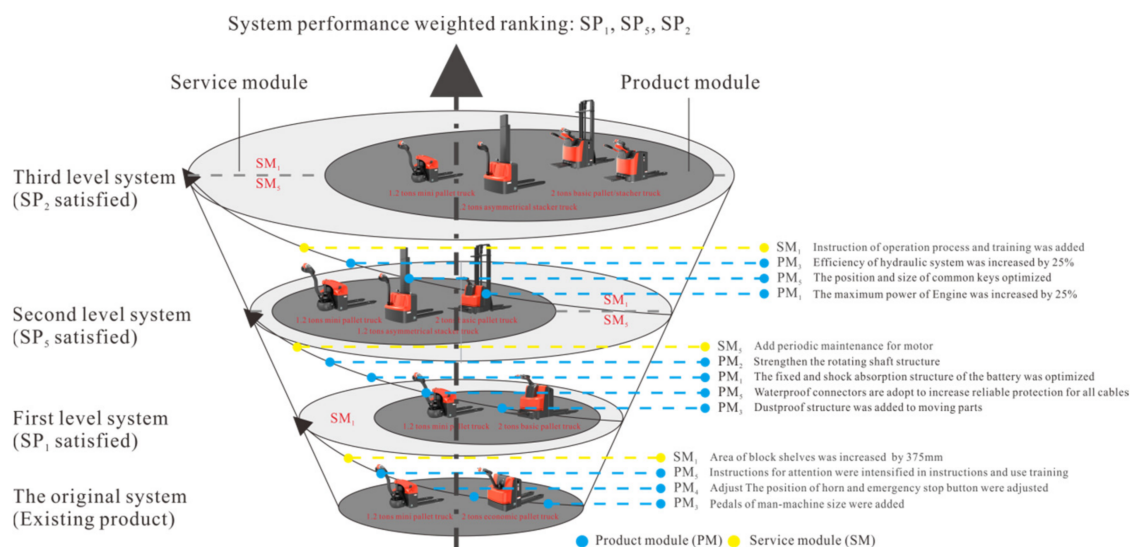


Figure 9. Iterative design result of the warehousing system.

5. Discussion

Expanding product functionality through services to meet customer needs and to reduce the use of tangible materials is a sustainable and innovative approach to manufacturers SMEs [64]. From the point of sustainability, manufacturing SMEs can reduce the loss of physical resources through PSSs. Although PSSs can greatly improve enterprise environmental friendliness, for many manufacturing SMEs, the transition from product-oriented manufacturing to the PSS model is very challenging. The existing design method of PSS lacks the consideration of combining sustainability and acceptability for manufacturing

SMEs. The PSS solutions proposed only from the point of view of satisfying customer needs often require the integration of a large number of new product and service resources. That means huge investments and disruptive adjustments and no opportunity for trial and error for manufacturing SMEs. As a result, it is difficult to accept PSSs as a method to improve their sustainability for many manufacturing SMEs.

To address the above problems, this study proposes a new PSS design method from the perspective of improving the acceptability of PSSs in enterprises and the utilization of existing resources. Firstly, AHP is used to map customer needs to system performance requirements. In this way, the design goals can match the customer needs. Secondly, the whole design process is carried out by spiral iteration. Compared with the design method from “0” to “1”, this way is more in line with the law of gradual development of manufacturing SMEs. The initial PSS solution can be upgraded after it has been applied and after feedback. Thirdly, the LDfX method is used to modularize the existing product components, and the DSM method is used for service components. The approach of building PSSs based on existing product and service resources greatly increases the utilization of existing resources. Fourthly, the correlation between the system performance demand and each module is calculated quantitatively based on PCC. AHP and PCC are combined to build a complete model from customer requirements and system performance to a modular solution. In the case study described in Section 4, a warehousing equipment manufacturing enterprise (Company H) build a warehousing system iteratively in order to satisfy the top three most important customer needs based on its own product and service resources. Compared to the existing parallel PSS design process, this iterative design method is more helpful for manufacturing SMEs to adjust the design solution in time with the development of technology and the changing demand. As manufacturing firms improve their service capabilities, they can continue to upgrade their existing PSS solutions to meet additional customer needs.

To clearly prove the better acceptability of the method proposed in this study, the existing PSS design methods and the iterative design method to build modular PSSs was evaluated from the perspective of manufacturing SMEs. Firstly, in-depth interviews were conducted with 35 entrepreneurs, whose enterprises produce an annual output value of approximately 100 million RMB. Moreover, they all want to transform their businesses from products manufacturing to PSSs. Secondly, the interview records were collected for collation and analysis to determine the influencing factors and their weights from the perspective of acceptability. Four main influencing factors were determined: (1) customer satisfaction, which contains satisfaction of customer value needs and acceptable expenditure, refers to the value satisfaction and expenditure of money, time, and energy obtained by customers; (2) resource utilization, which contains product utilization rate and service utilization rate, refers to the existing product and service components being utilized as much as possible in the new PSS solution; (3) solution iteration, which contains stage implementation and stage optimization, refers to the stage scheme in the design process that can be directly applied by enterprises and can be modified and optimized at any stage; (4) design efficiency, which contains design difficulty and design duration, refers to the difficulty of the design and the time required. Thirdly, entrepreneurs were invited to rate these factors and subfactors. An evaluation system was established for enterprise feasibility of PSS methodologies, as shown in Table 5. Finally, seven PSS design methods were explained to the above entrepreneurs and rated according to the main influencing factors, as shown in Table 6.

Table 5. Evaluation system of PSS design methods for acceptability of manufacturing SMEs.

Factors	Weight	Sub Factors	Sub Weight
Customer satisfaction	0.38	Satisfaction of customer value needs	0.58
		Acceptable expenditure	0.42
Resource utilization	0.25	Product utilization rate	0.61
		Service utilization rate	0.39
Solution iteration	0.22	Stage implementation	0.6
		Stage optimization	0.4
Design efficiency	0.15	Design difficulty	0.57
		Design duration	0.43

Table 6. Acceptability survey result of PSS design methods.

PSS Design Methods	Customer Satisfaction	Resource Utilization	Design Iteration	Design Efficiency	Acceptability
A method for evaluating customer needs [19]	0.90	0.45	0.24	0.61	0.52
Study of customer experiences [20]	0.85	0.78	0.35	0.25	0.63
A mode of PSS cost quantification [21]	0.52	0.51	0.57	0.72	0.56
A PSS design framework for an integrated PSS design [22]	0.72	0.64	0.34	0.45	0.58
A collaborative PSS design system [23]	0.75	0.56	0.65	0.55	0.65
A new approach for PSS design through functional activity mapping [24]	0.62	0.52	0.78	0.78	0.64
An iterative design method to build modular PSS based on existing resources	0.82	0.93	0.83	0.8	0.85

From the perspective of sustainability, the method proposed in this paper mainly has the above four advantages, as shown in Table 7. The first advantage is better acceptability of PSSs. Manufacturing SMEs are more willing to attempt the transformation from manufacturing to PSS provider in the method proposed in this paper as seen in the results of the entrepreneurial survey. This transformation contributes to improving their sustainability. The second advantage is the reuse of resources. PSS solutions are built by stage implementation and stage modification. This approach reduces the waste of existing resources and upfront cost input. The third advantage is resource savings. PSS solutions are built to satisfy the primary customer needs with as few existing resources as possible, which support manufacturing SMEs to carry out the initial PSS transformation in the most cost-effective way. The fourth advantage is flexible iteration. An iterative approach enables enterprises to upgrade from existing solutions in time with the development of technology and changing demand. The PSS solutions generated by iteration have the ability of sustainable development in this approach, which support manufacturing SMEs to constantly improve their sustainability based on the previous PSS solutions.

Table 7. Sustainability comparisons of these design methods.

PSS design methods	Acceptability	Reuse of Resources	Resource Saving	Flexible Iteration
A method for evaluating customer needs [19]				
Study of customer experiences [20]		✓		
A mode of PSS cost quantification [21]	✓		✓	
A PSS design framework for an integrated PSS design [22]				✓
A collaborative PSS design system [23]	✓			
A new approach for PSS design through functional activity mapping [24]				✓
An iterative design method to build modular PSS based on existing resources	✓	✓	✓	✓

6. Conclusions

Although PSS is a method conducive to sustainable development, there are two difficulties for manufacturing SMEs to adopt PSSs: the large number of resources involved in PSS and the seldom consideration for combining acceptability and sustainability in an existing theory. This study proposes a design method to iteratively build modular PSS solutions based on existing product and service components to meet the major customer needs. AHP, LDfX, DSM, and PCC are combined to build a complete design method from customer needs and system performances to PSS solutions. It is easier to accept this method for manufacturing SMEs which has four advantages in the following aspects: customer satisfaction, resource utilization, solution iteration, and design efficiency. This method also has great advantages in sustainability.

Helping manufacturing SMEs establish PSSs with as few resources as possible is complicated. The current research progress is to propose a new design method to build a modular PSS solution that meets the major customer needs for manufacturing SMEs based on existing product and service components. The implementation of this method and the corresponding changes need to be further studied in the organizational structure of enterprises. In addition, manufacturing SMEs that lack sufficient technical capacity might encounter some difficulties in the practical application of some models and algorithms involved in this study, e.g., inconvenience in implementing the design, the large number of calculations, and the low level of automation. Based on the design method proposed in this paper, an auxiliary design system from products to PSSs will be developed in the future so as to improve the acceptability and efficiency for manufacturing SMEs.

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