Chapter 5
Service Design of Rehabilitative Exoskeleton for Sustainable Value Creation: A Case Study of Stroke Rehabilitation in China

Jing Tao and Suiran Yu

Abstract Stroke is characterized by high morbidity and high disability rate. Physical rehabilitation can effectively alleviate functional disability of stroke patients, and thus reduce potential nursing costs and save social resources. Given the prominent conflicts between limited resources provision-especially the qualified rehabilitative personnel-and the huge demands of rehabilitation, China is now actively encouraging R&D as well as popularization and application of rehabilitation robots. Aside from the design of rehabilitative exoskeleton itself, which is the focus of most studies in this era, the service design is also critical if rehabilitative exoskeletons are to realize the declared social-economic benefits. Service design may provide solutions to wider and fairer access to exoskeleton, better affordability and satisfaction of exoskeleton-based treatments, while creates monetary or non-monetary benefits for manufacturers, medical facilitates and other possible stakeholders. This study is focused on rehabilitative exoskeleton value creation. The service design of rehabilitative exoskeleton for stroke patients, which is considered the most promising application era of exoskeleton technology in China, are exploited based on the national conditions. First, sustainable value was conceptualized based on the understanding of value from the sustainable view point that includes economic, social and environmental perspectives. Then, the application scenarios of stroke patients' exoskeleton-based rehabilitation were developed based on China's multi-level rehabilitation service delivery system. In accordance to a modular product architecture, the service design of rehabilitative exoskeleton driven by sustainable value requirements with life cycle considerations was presented. The proposed sustainable value-driven service design may provide insights to rehabilitative exoskeleton developers and manufacturers in servitization of the emerging technology.

Keywords Rehabilitative exoskeleton · Service design · Sustainable value · Life cycle

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5.1 Introduction

With the advent of aging society, China is suffering form the high incidence, mortality and disability rates of stroke. The population over 40 years old in China who have suffered from and have suffered from stroke is estimated to be 12.42 million and 70% of the survivors of stroke have different degrees of disability (Wang et al. 2019). Stroke and disability caused by stroke are the major contributors to "poverty due to illness" in China.

Modern rehabilitation theories and practice have proved that rehabilitation training can alleviate functional disability of patients, accelerate the rehabilitation process of stroke, reduce potential nursing costs, and save social resources (Ostwald et al. 2008). Despite of the government's efforts on developing the nation-wide rehabilitation delivery system, China is still struggling with the conflicts between limited resource provision and the huge demands of rehabilitation. According to the National Survey on Resources of Rehabilitative Medicine in 2009, there was a personnel gap of 15,000 rehabilitative specialists and 28,000 therapists based on the requirements of personnel quota listed in the Guide on Establishing and Managing Rehabilitative Units in General Hospitals (Chinese Association of Rehabilitation Medicine 2009). In terms of treatment method, therapists carry out most rehabilitation treatments manually. Therefore, therapists are often overworking and it is difficult to ensure the recommended amount and consistent quality of rehabilitation training.

Exoskeletons are basically wearable machines providing power and/or structural supports to human body. Given the nature of rehabilitation exoskeleton being a kind of advanced robotic technology, it has the advantages of automation, programmability, controllability and accuracy. Studies showed that the exoskeleton-based rehabilitation is a promising alternative to conventional manual therapy for improving motor function of stroke patients (Norouzi-Gheidari et al. 2012), because the device is designed to have multi-DOF to mimic various limb movements to accommodate all types of exercises (Rahman et al. 2015). It is also suggested that exoskeletons can be a potential solution to high quality rehabilitation training and a possible replacement (or supplement) of therapists. Given the huge patient population and the increasing desire for better life quality, there is huge potential for rehabilitative exoskeleton to prevail in China. However, currently there are very few rehabilitative exoskeletons certified for medical use and most of them are too expensive to popularize in China.

Given the encouraging policy of domestication of advanced medical devices and technologies as well as the emergence of a Blue Sea market, rehabilitative exoskeleton has been drawing attentions and interests of Chinese high-tech companies, universities, and research institutions [e.g. Chen et al. (2019, 2018), Zhang et al. (2019)]. However, aside from the design of rehabilitative exoskeleton hardware and software, which is the focus of most studies in this era, the service design is also critical if rehabilitative exoskeletons are to realize the declared social-economic benefits. Service design may provide solutions to wider and fairer access to exoskeleton, better affordability and satisfaction of exoskeleton-based treatments, while create

monetary or non-monetary profits for manufacturers, medical facilitates and other possible stakeholder in the business.

To design effective service, a number of approaches such as product and service system (PSS) (Tukker and Tischner 2006), customer-oriented design (Kimita et al. 2009), are suggested. However, service design is still challenging with the increasing environmental pressure and demand of customization. With growing demands for sustainable products, there are clear implications for developing engineering capabilities of holistic application of sustainability concepts to products, processes and services design. Tao et al. (2018) proposed a QFD-based approach of life cycle scheming driven by sustainable value requirements. The proposed approach help bring experts in fields of product and process engineering, industrial management and ecological assessments to a common vision, and therefore accelerate design convergence for more sustainable products, processes and business. There are also evident needs of the systematic methodical support for the entire design process from requirements identification to concept configuration for product and service customization. To address the needs, Song et al. (2016) proposed a customization-oriented framework for design of sustainable product/service system, while Fargnoli et al. (2019) proposed a product/service design process with synergic use of QFD for PSS, Axiomatic Design (AD) and the service blueprint tools.

Rehabilitative exoskeleton is considered advanced medical instrument in China. According to the authors knowledge, service design of such exoskeleton is still new in practice. The purpose of this study is to exploit service design of rehabilitative exoskeleton for stroke patients based on the Chinese national conditions. Taking advantages of some existing methods, in this study, sustainable value is conceptualized from engineering perspectives and introduced as the anchor of stakeholder interests and motive power to drive the service design process. This study may shed lights on servitization of the emerging technology.

5.2 Conceptualization of Sustainable Value

With the three pillars of sustainability in mind, “sustainable value”, in this study, is conceptualized as the total satisfaction of value requirements from perspectives of economic, social and environment. Also, under the umbrella of life engineering, the total sustainable value of a product and/or service include values delivered to customers and businesses partner throughout the life cycle. Thus, sustainable value requirements (SVRs) answer to the critical question of WHAT is valuable to different shareholders from sustainable perspectives. Without loss of generality, the system of SVRs is proposed as shown in Fig. 5.1. Therefore, the ultimate goal of sustainable value engineering is to maximize the overall value perceived by different stakeholders by increasing level of satisfaction of value demands.

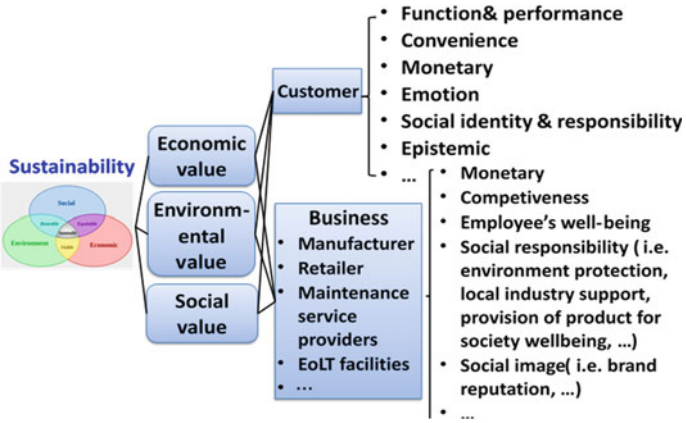

Fig. 5.1 General sustainable value requirements (Tao and Yu 2018)

5.3 Simplified QFD for Sustainable Value Driven Service Design

In this study, the service design is carried out as the structured and strategized process of translation of sustainable value requirements into product and service design solutions (see Fig. 5.2). The concept of "domain" from Axiomatic Design is employed to characterize stages of the translation, while the simplified QFD is employed for organized mapping between design semantics in different domains.

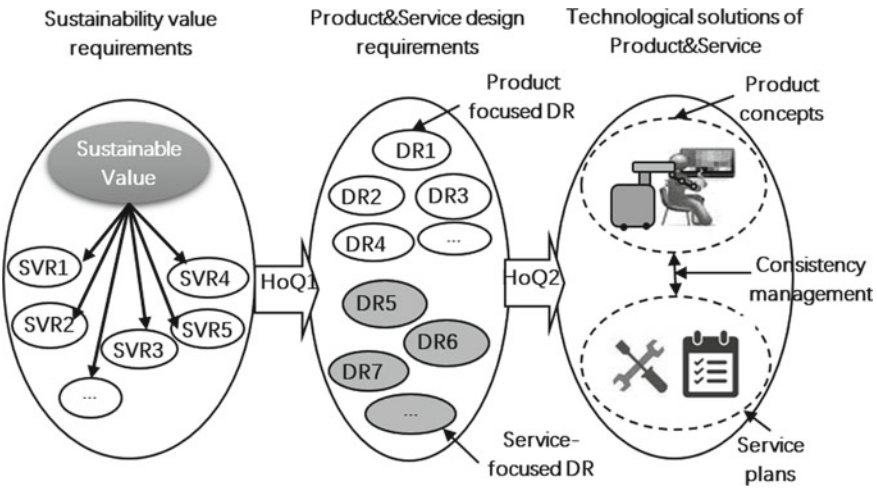

Fig. 5.2 Domain mapping for sustainable value-driven product and service design. Adapted from Tao and Yu (2018)

With the proposed method, three domains are defined, which are the sustainable value requirement domain, the product and service design requirement domain, and product service solution domain. Design requirements (DRs) also known as HOWs of engineering capabilities to fulfil the 'value' requirements. In this study, DRs are categorized into product-focused and service-focused DRs. Product-focused DRs are those on product itself including function and performance, quality, structure, appearance, material, etc., while service-focused DRs are those on various service activities throughout product life cycle, such as efficiency and effectiveness, availability and affordability, technicality of service. Capability of value delivery is enhanced by translation of sustainable value requirements into product and/or service focused DRs.

The total design solution is characterized by the combination of product concepts and service plans. The product concept (PC) and service plan (SP) tell the major engineering characteristics of the physical product entity and service activities. In this study, the service options for technology-intensive products (i.e. rehabilitative exoskeleton) include pre-sale services such as information revealing and (or) inquiry, pre-sale consultation, customization, after sale and in-use services such as delivery and installation, training and qualification of operators, in-use consultation and supervisions, maintenance and upgrade, and end-of-life services such as collection, refurbishment and circulate, recycling and safe disposal of retired product and components. It should be notice the product concept should always be consistent with the service plan. For instance, if upgrade service is provided on certain component of the product, the component should be designed to be easy to assemble and dissemble and functionally upgradable. As shown in Fig. 5.3, the simplified QFD creates two interlinked mappings. The correlation matrix in the second HoQ is divided into three matrices: two self-correlation matrices of PCs and SPs, and one matrix of correlation between each PC and SP. The PC-SP matrix is used for product-service consistency management which produce the detailed service plans on module and component levels.

5.4 Sustainable Value Driven Service Design of Exoskeleton for Stroke Rehabilitation in China

As shown in Fig. 5.4, The Chinese rehabilitation delivery network is characterized by a "3+3" architecture (Tao and Yu 2019 ; Xiao et al. 2017). The three level network is consistent with stroke rehabilitation progress, including the acute stroke patient stage, the mild stroke patients or midway in recovery process stage and the full recovery stage (Zhang 2011).

In this study, the exoskeleton use scenario is characterized by 'who the patient is', 'training with whom', 'where the training taking place' and 'what training delivered'. Thus, the considered customers include stroke patients who are the end user of the exoskeleton, the therapist and healthcare personnel who are the operators and in

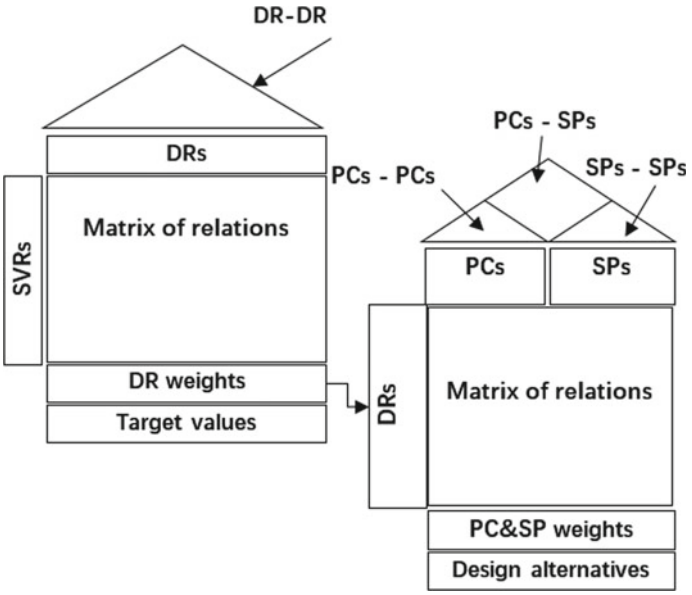

Fig. 5.3 Simplified QFD for sustainable value-driven product and service design

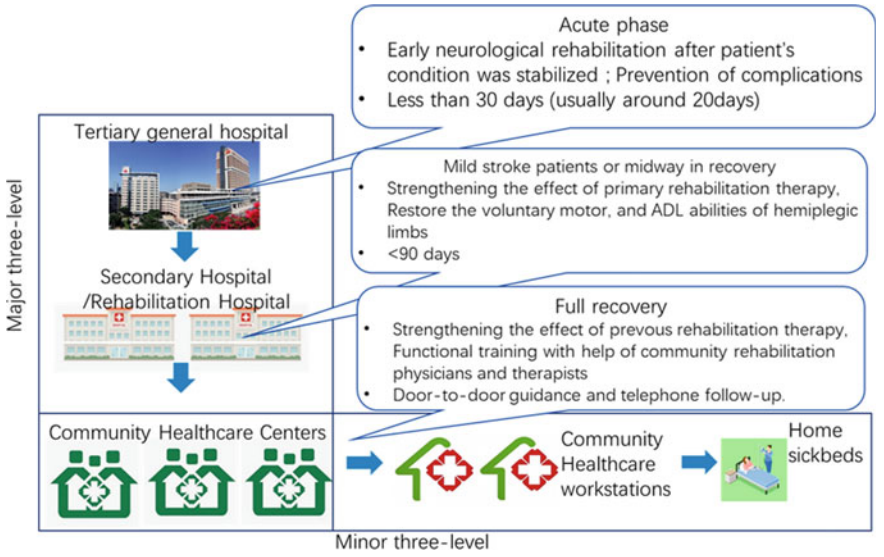

Fig. 5.4 Stroke rehabilitation in China

Table 5.1 Critical sustainable value requirements of customers and business

General customers	*Sustainable value requirements*
Patients; Therapist&Health care personnel; Medical facilities	• Function&Performance: Adaptivity to different patients; Multi-functional; Long useful lifetime & few malfunction • Convenience: Ease to put-up&off; Compact&Space-saving; Easy to operate; Visualization&Digitalization • Emotion: Safety&Security; Fun&Encouraging; Assitance&Care • Availability: Availability of treatment to patients; Availability of exoskeleton to healthcare facilities • Monetary: Affordability of treatment; Affordability of exoskeleton • Social Identity&Responsibility: Creditability of technology; Domestication; Warranty
Business	*Sustainable value requirements*
Manufacturing; Distribution; Maintenance; End-of-Life Treatment	• Monetary: Business profitability • Competitiveness: IP&Patents; Creditability of Technology; Brand awareness & Market share • Social responsibility: Qualification & Certification; Standardization; Legitimacy

charge of management of the exoskeleton, and the healthcare facilities who are decision maker of exoskeleton purchase. The critical sustainable value requirements of general customers and the business are presented in Table 5.1.

It is found that the functional requirements of exoskeleton vary in different stages of stroke rehabilitation. According to the training principles, the exoskeleton is required of fully powered and controlled movements of patient's affected joints for acute rehabilitation, while 'assist-as-needed' and resistive movements, respectively, for mid-way and full recovery phases. Thus, the proposed exoskeleton and services should be able to adapt different training needs of different patients in different rehabilitation stages.

According to the interview with patients and therapists, as the period of rehabilitation gets longer, the patients usually become more worried about treatment costs, as the medical insurance coverage on rehabilitation is still limited. Patients value availability of rehabilitation. This is typically due to the insufficient medical devices and healthcare personnel to carry out treatment, especially in base level facilities.

Also, it is found that the healthcare personnel's specialty in rehabilitation may decrease as patients are transferred from top to base of the rehabilitation network, and so does healthcare facilities' the affordability of expensive medical devices. Thus, demands for easy-to-operate, automated and intelligent, cost-effective exoskeletons and just-in-time technology support from the manufacturers or service providers may increase.

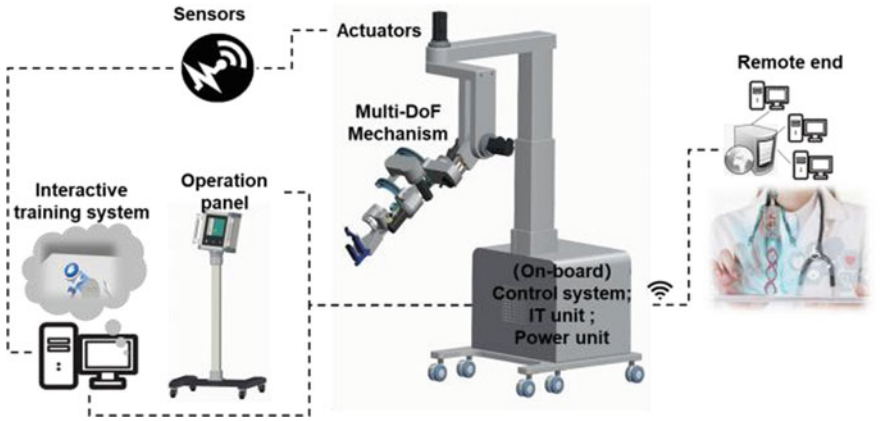

Fig. 5.5 Modular product concept

Technology creditability is identified as the major influencer on purchase decision, as it is closely related to the value of social responsibility and reputation of healthcare facilities. Technology credibility is also important to business, as it is directly linked to the competiveness of the exoskeleton in the market, and therefore the profitability of the business.

The simplified QFD process is carried out for generation of product and service solutions. The full QFD matrix is not be presented in this paper due to length limit. The product concepts are generated based on reference product, such as Armeo and Lokomat of Hocoma (see Fig. 5.5). Given the emphasis of this study being service design, more explanation of the service plan generation is presented as followed (Fig. 5.6).

The pre-sale, after-sale/in-use, and end-of-life service solutions are proposed to maximize the value delivery to stakeholders. The certification inquiry and pre-sale consultation services are propose to address customers' concerns on rehabilitative exoskeleton technology. Such services are also beneficial to brand building and marketing. The customized configuration service is proposed for better adaptability to exercise needs in different stages, as well as expansion of device price range. The financial leasing service is proposed to address the economic concerns of base level healthcare facilities (see Fig. 5.4) of owning an exoskeleton. In that case, the manufacturer or an exoskeleton service provider, rather than the healthcare facility, owns the device and is responsible for the maintenance of it, while the healthcare facility pays for functionality of the exoskeleton. Therefore, instead of a one-off payment for ownership, there will be a much smaller cost for the healthcare facilities.

With the development of telecom and internet technologies (e.g. IoT), it is also possible to provide in-use tele-monitoring and supervision services, which in combination with intelligent exoskeleton, may enable self-rehabilitation at community or by home sickbeds. In that case, fairer access to exoskeleton-based rehabilitation technology, which contributes to social well-being, may be realized. Cloud-based

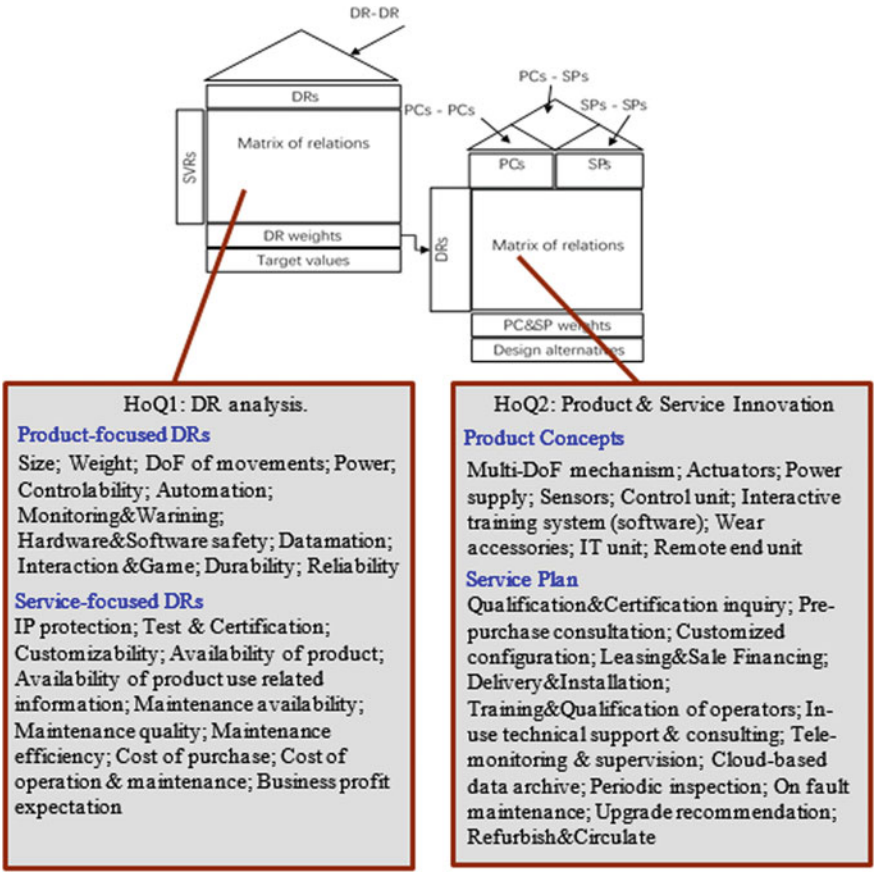

Fig. 5.6 QFD-based product and service design of rehabilitative exoskeleton

data archive service is proposed for value creation for both customers and the business. Exoskeleton can easily adapt to patients' treatment needs based on training profiles and schedule downloaded (with proper authority) from the cloud. Therefore, patients can conveniently go to any nearby healthcare facility with an exoskeleton for training, while healthcare facilities can attract more patients with the flexible and efficient treatment with the exoskeleton. At same time, the business can benefit from the improved utility of their exoskeletons.

Some end-of-life service options are also proposed. As the exoskeletons are expensive and technology-intensive products, the collection of retired devices or parts and return to manufacturer is beneficial to intellectual property protection. The circulation of refurbished exoskeleton (or components) can help reduce manufacturing and ownership costs, and consequently increase the customers' access to exoskeleton and exoskeleton-based treatments. Especially, it is technically feasible to reuse the mechanical parts of the device, as they have much longer useful lifetime than the

valuable lifetime of the device. In addition, reuse strategies may bring forward environmental benefits, such as material and energy saving for manufacturing new parts. To address the legal concerns of circulating exoskeletons, related laws and regulations are then investigated. It is found that companies with "Medical Device Manufacturing Enterprise License" are allowed to recycle spare parts from retired medical device, and sell qualified renovated devices. Also, the newly issued "Regulations on the Supervision and Administration of Medical Devices" liberalizes the transfer of the safety and effectiveness of the transferred medical devices. Thus, it opens channel of exoskeleton cascade reuse in the rehabilitation service system.

Then, the consistency matrix is generated for service plans on module and component levels. As shown in Fig. 5.7, the highlighted lines of the matrix are the configuration of applicable service options for major modules, which are determined based on module engineering characteristics such as functionality, cost, market and technological trends, etc. For instance, the DoFs of the exoskeleton mechanism are configurable to meet training needs of single joint, reduced DoFs of limb or full DoFs of limb, while actuators with the mechanism are configurable to realized fully powered (i.e. for acute phase training), partial powered or unpowered (i.e. for full recovery phase training) exoskeleton.

Service Plan \ Product concept	Multi-DoF mechanism	Actuators	Power supply	Sensors	(on borad) Control	Operation panel	Interactive training system (software)	Wear accessories	IT unit	Remote ends
Qualification& Certification inquiry										
Pre-purchase Consultation										
Customized configuration	√	√	√			√	√	√	√	√
Leasing&Sale Financing										
Delivery&Installation										
Training&Qualification of operators										
In-use technical support & consultation										
Tele-monitoring&supervison				√			√		√	√
Cloud-based data achive									√	√
Periodic inspection	√	√	√	√				√		
On fault maintenance	√	√	√	√	√	√	√	√	√	√
Upgrade recommendation	√			√	√		√		√	√
Refurbish&Circulate	√	√								

Fig. 5.7 Consistency management of product and service

5.5 Conclusion

This paper first presents the methods of service design driven by sustainable value goals. The sustainable value was conceptualized based on the understanding of value from a sustainable point of view that includes economic, social and environmental perspectives and then characterized by general sustainable requirements. Thus, the total sustainable value of product and/or service can be evaluated as the level of total satisfaction of value requirements. The sustainable value driven product and service design is proposed as the strategic process of translating sustainable value requirements into product and service technological solutions. The concept of "domain" from Axiomatic Design is employed to characterize stages of the translation, while the simplified QFD is employed for organized mapping between design semantics among domains.

Then, based on the architecture of the Chinese rehabilitation service delivery system, the three-stage stroke rehabilitation scenario is proposed. The critical sustainable value requirements of general customers and business are identified. By the proposed QFD-based method, service options are generated in consistency with product design concepts. In addition to conventional services such as pre-sale consultation, in-use technical support, maintenance and upgrade, the customized configuration, leasing and sale financing, tele-monitoring and supervision, cloud-based data service are proposed to address requirements from boarder value perspectives. Thus, the proposed sustainable value-driven service design may provide insights to rehabilitative exoskeleton developers and manufacturers in servitization of the emerging technology.

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