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Sustainable Product-Service Systems Customization: A Case Study Research in the Medical Equipment Sector

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Abstract: The paper proposes a Product-Service System (PSS) methodology for customizing solutions to different patterns of use while achieving a better environmental performance than a stand-alone product. The approach is based on combining the Quality Function Deployment for Product-Service Systems (QFDforPSS) and the Screening Life Cycle Modeling (SLCM) tools. QFDforPSS is augmented by the Fuzzy Analytical Hierarchy Process (FAHP) to reduce service-related ambiguities and uncertainties on the one hand and better define the product and service characteristics of the solution on the other. The SLCM evaluates the possible outcomes by determining the environmental impact and comparing it with the manufacturer's current solution. A case study at a manufacturer of medical diagnostic equipment illustrates the use of the approach depicting the possible benefits that can arise: the PSS solution can be customized to fit customers who intensively use the product and consumers with a more moderate use. This offers flexibility and an optimized life cycle through easier maintenance, upgrades, and end-of-life schemes. Concretely, it shows how the PSS approach can enhance the development of sustainable solutions that can be adapted to varying and future customer needs, such as adjusting current solutions to new requirements, i.e., adapting existing products to COVID-19 detection and different levels of use.

Keywords: product-service system (PSS); quality function deployment for product service system (QFDforPSS); medical devices; fuzzy analytic hierarchy process (FAHP); screening life cycle modeling (SLCM); customization; life cycle assessment (LCA); circular economy (CE)

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Citation: Haber, N.; Fargnoli, M. Sustainable Product-Service Systems Customization: A Case Study Research in the Medical Equipment Sector. *Sustainability* **2021**, *13*, 6624. https://doi.org/10.3390/su13126624

Academic Editor: Yuri Borgianni

Received: 4 May 2021
Accepted: 8 June 2021
Published: 10 June 2021

1. Introduction

In recent years, research into Product Service Systems (PSSs) has seized the attention of many researchers and practitioners who have highlighted the effectiveness of such an approach in the development of integrated solutions that can practically accomplish the Circular Economy (CE) principles [1].

The PSS approach is founded on the simultaneous development of both tangible characteristics of the product and intangible ones related to the services surrounding the product, e.g., maintenance services and end-of-life recovery schemes, aiming to provide an integrated offering capable of taking into account all the life cycle phases of a product and the related services efficiently [2–4]. Commonly, PSS can be classified into three main categories based on the offering types and delivery channels: product-oriented, use-oriented, and result-oriented services [5]. Furthermore, other PSS classification types exist in literature depending on the target of the analysis [6–8]. In such a context, the one proposed by Gao et al. [9] is worth mentioning, which is based on the competitive advantages and value creation PSSs can provide manufacturers with. Differently, Kjaer et al. [10] proposed a differentiation of PSS approaches based on the circular economy resource decoupling strategy, while Doni et al. [11] contributed to expanding PSS knowledge by highlighting the effectiveness of the servitization processes, i.e., the shift from putting on the market physical goods only to the proposal of integrated offerings, which are the core of PSS solutions. Hence, focusing more on the PSSs' practical implications, it is deemed that on the one hand, the PSSs can enable manufacturers to improve their environmental performance by optimizing their product's lifecycle, fostering remanufacturing, reuse, and recycling activities [12,13]; on the other hand, they can augment the product's value, which leads to a higher customer satisfaction and hence enables the manufacturer to have an advantage over other competitors [14,15].

Such a twofold perspective of PSS solutions brings to light their complex nature and the difficulties in their practical use. Indeed, Zhang et al. [16] emphasized the need for further research on how to merge sustainable PSS models that allow customization and also improve customer satisfaction.

By meeting their customers' requirements, manufacturers have the chance to expand their business generating higher value and reducing unnecessary costs, as pointed out by Ulaga and Reinartz [17]. To achieve such a goal, it is essential to identify the intended customers properly, to understand their requirements and expectations, and to effectively translate them into PSS characteristics [18], minimizing possible conflicts between the material and immaterial components of a PSS, i.e., the product and the services [19].

From an environmental point of view, an ineffective PSS solution may lead to additional resource consumption and reduced life cycle performances: as suggested by Catulli et al. [20], PSSs are potentially more resource efficient than conventional products since they extend the suppliers' responsibility beyond the end of the usual product life cycle, fostering the recovery of resources and reuse of products and components. However, as noted by Salazar et al. [21], the development of acceptable PSS offerings requires that environmental aspects and knowledge of customers are combined, as successful solutions can be achieved when taking into account the performances of the offer during its whole life cycle. Accordingly, they pointed out the need to analyze the PSS users' expectations and perceptions more deeply.

Exploring these two main issues more in detail, i.e., PSS's sustainability and customer satisfaction features, Blüher et al. [7] argued that a key factor in PSS implementation is represented by the need to consider environmental concerns as early as possible in the development and creation of PSS. However, they claim that there is a lack of procedures to support engineers in achieving such a goal. In particular, the research field of use case-based assessment of sustainability effects of PSS should be developed further, where aside from environmental aspects of sustainability, societal ones such as stakeholders' involvement and customer satisfaction must also be considered. Moreover, when ownership remains with the manufacturer and revenue depends on product utilization, availability becomes critical, requiring advanced service design to provide conceptual scenarios to optimize decision making [22]. In such a context, Pirayesh et al. [23] underlined the lack of tools and reference methods capable of depicting the PSS requirements in implementing sustainable PSS solutions. In addition, due to the complexity of a PSS and its stakeholders' needs, methods to elicit PSS requirements properly are requested, as suggested by Song and Sakao [24]. These authors underlined that an insufficient systematic methodical support for the customization process may cause implementation difficulty at a practical level.

Accordingly, the lack of studies addressing the assessment and prioritization of the expected PSS characteristics emerges from these studies. This supports the research gap recently outlined by Rondini et al. [25], according to which a major concern in literature is represented by the scarcity of studies proposing methodologies aimed at systematically assessing early-stage PSS concepts. Similarly, Mourtzis et al. [26] pointed out that the literature on the customization of PSS is very limited, especially when considering the PSS evaluation throughout the entire PSS lifecycle, fostering the development of a methodical support for the strategic-level decisions. Similarly, Bertoni [27] argued that in the early stages of the PSS development process, decisions are dominated by ambiguity and uncertainty, which makes it difficult to combine sustainability implications with customer value.

Based on the above considerations, it is clear that additional research is needed to successfully deal with the challenges facing customization in sustainable PSS development. The goal of this research can be summarized by the following research question (RQ):

How can customer needs elicitation and feasibility analysis be integrated in the development of sustainable PSSs?

In other words, the problem raised by the current study is twofold. On the one hand, it addresses the difficulties that manufacturers deal with when they have to transform customer requirements into accurate PSS characteristics while grasping both product and service perspectives; on the other hand, it investigates a possible approach for practically supporting decision making when PSS concept solutions need to be analyzed to provide successful PSS offerings while benefiting the environment.

With this goal in mind, the present study seeks to propose an approach founded on the Quality Function Deployment for Product-Service Systems (QFDforPSS) [28] integrating the Fuzzy Analytical Hierarchy Process (FAHP) [29] as a means of addressing the intangibilities of services and potential conflicts with the product. The feasibility analysis is handled by means of the Screening Life Cycle Modeling (SLCM) tool [30], where environmental issues are dealt with using the life cycle assessment (LCA) method [31]. Such an approach was developed by means of a practical case study in the medical sector, where effective service strategies are crucial for success [32,33].

More in detail, the remainder of the article consists of the following: Section 2 presents the research approach in detail. Section 3 describes the application at a medical device manufacturer and the results are discussed in Section 4. Section 5 concludes the paper addressing further research areas.

2. Materials and Methods

2.1. Quality Function Deployment for Product Service Systems

The Quality Function Deployment (QFD) method is deemed one of the most effective tools to understand the customers' requirements (CRs) and to convert them into design information for engineers. A plethora of studies can be found in literature documenting its use in various conditions and contexts [34–36]. Accordingly, numerous examples of QFD augmentations highlight its integration with other supporting tools, reflecting on the advantages, disadvantages, and limitations [37–42].

QFDforPSS is founded on the conventional quality function deployment method and adapts it to the design and development of product-service systems. In fact, its objective is to support engineers in identifying customers' requirements and assessing them to conceive an optimal PSS solution [43,44]. Differently from the conventional method consisting of four phases, QFDforPSS requires the development of two phases only, each characterized by a House of Quality (HoQ) as shown in Figure 1. In the first phase, the input is represented by the "Receiver State Parameters" (RSPs), consisting of any feature that may be judged positively or negatively by the customer. According to Sakao et al. [45], the positive features are classified as "value" whereas the negative ones are classified as "cost". Hence, RSPs are more beneficial than conventional Customers' Requirements (CRs) because they enable PSS designers to assess the mutual comparability among multiple RSPs more coherently. Moreover, they can support engineers in integrating the needs of different and numerous stakeholders. The product and service characteristics of the PSS are derived from the first phase. These outputs are the counterpart of the "Engineering Characteristics" (ECs) encountered in a conventional QFD.

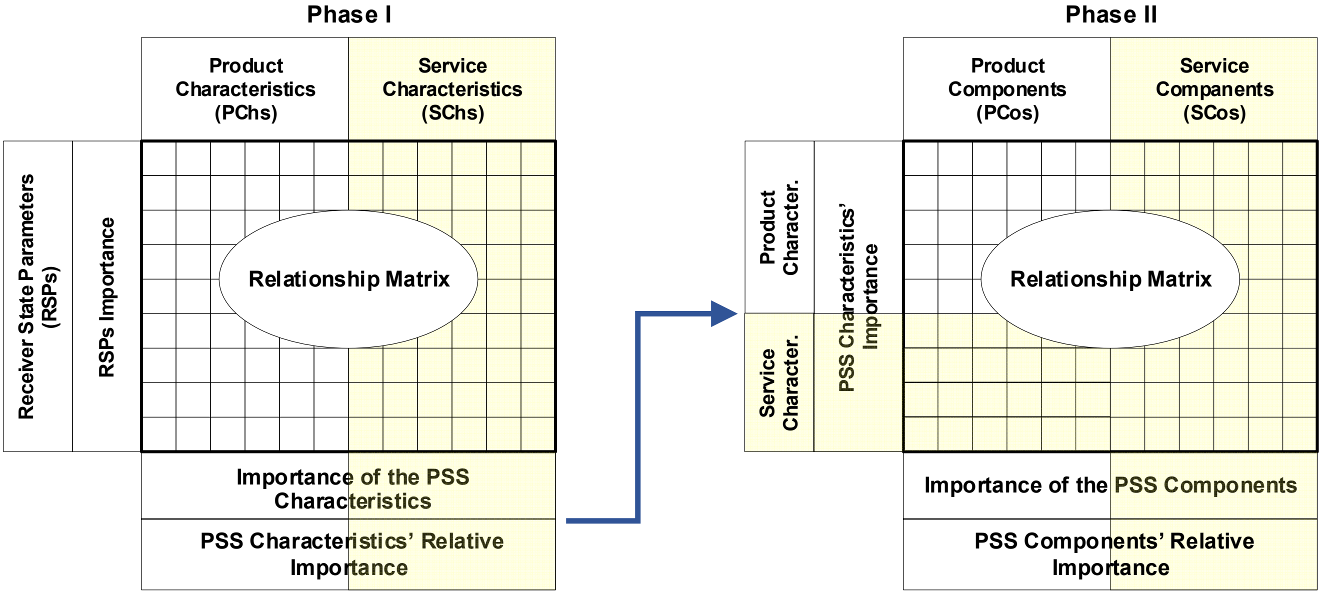

Figure 1. Representation of the scheme of Quality Function Deployment for Product Service Systems (based on the scheme by Haber et al. [44]).

The second phase of the method (Phase II in Figure 1) goes deeper and defines the product and service components required to fulfil the PSS characteristics and achieve customer value. In a PSS development context, the first phase of the method can be applied to translate customer needs and expectations into PSS main characteristics addressing the planning phase of the development process, while the second phase (i.e., the PSS components' definition) can be used fruitfully in the conceptual stage of the process when the PSS features are decided, and the detailed development has to be addressed [28]. As far as the scoring method is concerned, the evaluation metrics of QFDforPSS are the same as the QFD relationship matrices [46]. Hence, the tools to augment the effectiveness of conventional QFD can also be used to improve the QFDforPSS outputs.

2.2. QFDforPSS Supporting Tools

As stated earlier, an important number of studies propose ways to enhance the QFD output by incorporating additional tools, especially those aimed at better defining and assessing customer information in the first phase of the method, reducing its drawbacks [40]. Among them, the most common tools are the Kano model [47] and fuzzy logic [48], as well as the Analytic Hierarchy Process (AHP) [49] or the Analytic Network Process (ANP) [50]. These augmentations are aimed at fostering the analysis of the relationships between the different parameters of the House of Quality to reduce the ambiguity and vagueness that characterize conventional QFD metrics [51]. In the case of this paper, we limited our scope to the two following tools to be applied to the first phase of QFDforPSS:

- The AHP method, developed by Saaty [52], and
- Fuzzy logic sets [48,53].

The integrated use of Fuzzy-AHP and QFD is a well-recognized approach to reduce the shortcomings of the House of Quality (HoQ) [35,37,54]. The use of such tools is not a novelty in the PSS context, since some examples of integrated QFD models can be found. For instance, Song et al. [55] integrated the QFD and FAHP methods in a procedure aimed at selecting and assessing the PSS requirements from a life cycle point of view. Similarly, Sousa-Zomer and Cauchick-Miguel [56,57] proposed a FAHP-QFD procedure to prioritize the stakeholders' requirements in the sustainability dimensions, and the fuzzy set theory is considered capable of reducing the vagueness and uncertainty during the PSS development process. Differently, Liu et al. [58] developed two HoQ models for a product and service, respectively, integrating them with the Kano model to evaluate customer requirements more precisely and using the FAHP to obtain a more accurate index weight and importance ranking of engineering characteristics. However, these investigations do not address the risks related to a possible lack of customer satisfaction when handling PSS development nor do they provide suggestions to transition from customer requirements to the elicitation of PSS characteristics that can hold a positive (or negative) impact on the PSS receivers. To reduce such drawbacks, a few studies have proposed QFDforPSS augmented models. For example, Haber et al. [44] integrated it with FAHP and the Kano model to improve the RSPSs' elicitation, while Fargnoli and Haber [59] used the ANP approach to better estimate mutual interactions among PSS elements. A more comprehensive approach was proposed by Yin et al. [60], who used a three-stage fuzzy ANP-QFDforPSS approach to investigate the relationship between PSS offerings and stakeholders. In particular, this study was aimed at supporting the decision-making of the stakeholders' selection in PSS development from the quality management perspective. Despite such differences, these studies show that in a PSS context, customer requirements involve imprecise estimations and vagueness, which the PSS provider has to address to avoid negative consequences. In addition, Ulaga and Loveland [61] outlined that unlike a product-reliant context, in PSSs, manufacturers and designers alike have to deal with a "fuzzy front end" to really understand what customers desire and how to fuse products and services to meet such objectives. Such an issue is relevant especially in the case of PSSs in regulated markets, where some services are normally provided as part of the procurement rules in the calls for tender [62,63]. Hence, to augment customer value, the selection of the customers' needs has to go beyond mandatory requirements [64,65], providing an effective list of characteristics capable of augmenting customer satisfaction along with the whole PSS lifecycle [66].

2.3. The Screening Life Cycle Modeling Method

In PSS development, a clear perspective of the lifecycle impacts of the solution represents a key factor to implement effective circular economy strategies for improved environmental impacts [67]. Indeed, the proper calibration of the product's lifespan should take into account not only remanufacturing and refurbishing opportunities, but also the rebound effects due to the technological obsolescence, both in terms of customer value and energy consumption during the use stages [68,69]. It is worth noting that the product's life cycle (i.e., the durability of the physical part of the PSS) has to be distinguished from the PSS life cycle that is related to the durability of the PSS offering, which is usually characterized by multiple product life cycles. Therefore, the development of different scenarios should be considered to find the right balance to reduce material flow and maximize resources [70]. In such a context, the use of the Screening Life Cycle Modeling (SLCM) method [30] has demonstrated the effectiveness of scenarios' modeling in performing a feasibility analysis when developing PSS [8]. More in detail, SLCM consists of a streamlined life cycle simulation aimed at investigating the impact a system (i.e., a product, a service, or their combination) can have on the environment during its expected life cycle, where environmental performances can be evaluated by means of Life Cycle Assessment (LCA) tools [10,71]. In practice, SLCM allows engineers to estimate the main environmental impacts related to the PSS lifecycle, providing options for its improvement by means of the development of a series of alternative life cycle scenarios. The starting point of the application consists in defining a PSS base model, which is usually represented by the existing model adopted by the manufacturer/provider. Accordingly, the development of different life cycle scenarios brings to light the environmental behavior of the PSS under different conditions. In this way, it is possible to collect "dynamic" information related to the use of the product and the related services.

2.4. Research Approach

The current study relies on a case study research where the above-mentioned tools were implemented in a coordinated manner as schematized in Figure 2. This approach is based on the application of the first phase of the QFDforPSS method, augmented by the integration of the FAHP approach to derive PSS characteristics, which are used to implement the SLCM method for the feasibility analysis. The case study concerns a manufacturer of medical equipment based in France, which provides different types of molecular diagnostic instruments. More in detail, the following features characterize the proposed procedure:

1. Identification of customers' needs: market survey and experts' involvement constitute the basis for the definition of customers' needs and expectations, providing a list of customers' requirements (CRs), which goes beyond the mandatory requisites that characterize this type of market where the main features of the offerings are subjected to the rules of public procurement on the one hand, and specific safety issues on the other.
2. Elicitation of Receiver State Parameters: a translation process is carried out by a group of experts to transform the customers' requirements into RSPs, which allows a more coherent integration of the stakeholders' requirements and hence a more reliable evaluation of their comparability. This is necessary because CRs are sometimes expressed vaguely and in such a way that they are difficult to be compared. Then, a survey among potential and current customers allows their involvement in the PSS development process.
3. Application of the Fuzzy Analytical Hierarchy Process: based on the output of a specific survey among customers, the prioritization of the Receiver State Parameters is performed by means of the FAHP, determining the importance level of each RSP by pairwise comparisons [52] and refining it through the fuzzy logic approach [72]. More precisely, the "crisp" results of the pairwise comparisons are transformed into Triangular Fuzzy Numbers (TFNs) and then de-fuzzified as per the transformations described by Kamvysi et al. [29].
4. Definition of PSS Characteristics: in collaboration with the group of experts the definition of the characteristics of the product (PChs) and the characteristics of the service (SChs) is performed.
5. Application of the QFDforPSS (Phase I): the first phase of the method allows engineers to assess the relative importance of each PCh and SCh, and to define the level of the product-service integration.
6. PSS conceptual solutions: in this phase, possible conceptual solutions are defined in collaboration with experts.
7. Feasibility analysis: the SLCM method is applied to identify possible offerings' scenarios and evaluate them by means of the LCA method. Accordingly, this stage allows the definition of feasible PSS offerings from both the technical and environmental standpoint, which represent the input for the implementation of practical PSS detailed design.

Phase	Tools
1. CUSTOMER NEEDS IDENTIFICATION	Market analysis, Experts' consultation
2. RECEIVER STATE PARAMETERS ELICITATION	Survey 1
3. RECEIVER STATE PARAMETERS PRIORITIZATION	Survey 2, FAHP
4. PRODUCT/SERVICE CHARACTERISTICS DEFINITION	Experts' consultation
5. PRODUCT/SERVICE CHARACTERISTICS PRIORITIZATION	QFDforPSS (phase I)
6. PSS SOLUTIONS DEFINITION	Experts' consultation
7. SOLUTIONS' FEASIBILITY EVALUATION	SLCM

Figure 2. Scheme of the proposed procedure.

3. Case Study

The case study takes place at a medical equipment manufacturer producing molecular diagnostic equipment. In detail, this equipment aids medical professionals in identifying multi-resistant bacteria and viruses (e.g., salmonella, meningitis, COVID-19, etc.). The manufacturer provides the equipment, the consumables, and all the services required for its use. It also has remote service centers scattered across the nation and it intends to improve the product-related services to augment its value offering, maintain customer loyalty, reduce its costs, and enhance its environmental impact.

Recent market surveys and analysis revealed a decrease in sales despite the general growth of this market. Customer service representatives highlighted the customers' dissatisfaction with the reliability of the equipment, the current maintenance service, and the lack of a proper End-of-Life (EoL) strategy. Furthermore, these data showed an average lifespan of 26 months instead of its intended 48 months mainly due to electro-mechanical issues regarding the motors related to diagnostic activity (the syringe motor for biological sampling, the pressing motor for specimen immobilization, and the tray motor for opening and closing the insertion doors), gears that regulate the opening and closing of the lids, and thermo-sensors that deteriorate over time. When a breakdown occurs, the equipment is most frequently replaced by another piece. Moreover, when diagnostic needs change during the contract period (e.g., become pressing, such as the current case of COVID-19), existing equipment may require upgrades to adapt for such screening and its operators find themselves using it more often which adds more stress on the components and increases the risks of failure if maintenance is belittled or neglected.

Hence, an adequate service strategy is essential for customer satisfaction and eco-friendly results [73]. Whereas service offerings in this manufacturing sector are recognized, strict regulations surround their provision [62]. Consequently, PSS implementation is faced by a more challenging task [74].

3.1. Customer Requirements Identification and Prioritization

Firstly, we conducted a market survey in collaboration with the manufacturer's marketing team and the instrument development manager. For confidentiality purposes, the identities of the manufacturer and the personnel will not be disclosed, and the data collected will be kept anonymous due to ethical and privacy reasons on the one hand, and to avoid any possible biases on the other. The information collected from the customers was through semi-structured questionnaires sent to professionals working mainly in public clinics, hospitals, and laboratories situated in five European countries. The company's experts were consulted when technical support was needed and where a multi-disciplinary judgment was required.

Given that many of the customers are in the public sector and the procurement system relies on open calls for tender in most European countries [75,76], we examined the calls launched during a 36-month period and selected 28 that were a close match to the manufacturer's environment. At a closer level, we examined the technical product as well as the service characteristics mentioned in the calls and we analyzed the acceptance criteria used for their evaluation. A further investigation led to separating requirements that are essential for the correct functioning of the product (i.e., presence of a barcode scanner, presence of a colored monitor, etc.) from innovative ones whose implementation can contribute to better customer value, profit generation, and cost reduction [44,77]. In other words, the definition of the Receiver State Parameters (RSPs) is any aspect that can provide a positive or a negative effect on a PSS receiver [43]. Based on this, to evaluate the RSPs' importance, questionnaires were sent to 200 customers of which 137 provided full responses. Each product and service requirement was assessed using a 1-to-5 scale where 1 depicted a very low importance and 5 referred to a very high importance (Table 1). To complete the data, we submitted a questionnaire to the same respondents where they were asked to evaluate the RSPs in a pairwise comparison manner and using a 1-to-9 scale (Figure 3) [52].

Table 1. List of the receiver state parameters (RSPs).

Receiver State Parameter	Importance	Relative Importance
RSP1. Easiness to use	3.8	12.5%
RSP2. Availability of the equipment (mean time before failure)	4.6	15.1%
RSP3. Quality of maintenance service	4.3	14.1%
RSP4. Reactivity of technical support	4.4	14.4%
RSP5. Supply of consumables (kits, cartridges, etc.)	3.9	12.8%
RSP6. Data storage options	3.1	10.2%
RSP7. Takeback facilitations	3.6	11.8%
RSP8. Environmental and safety assistance	2.8	9.2%

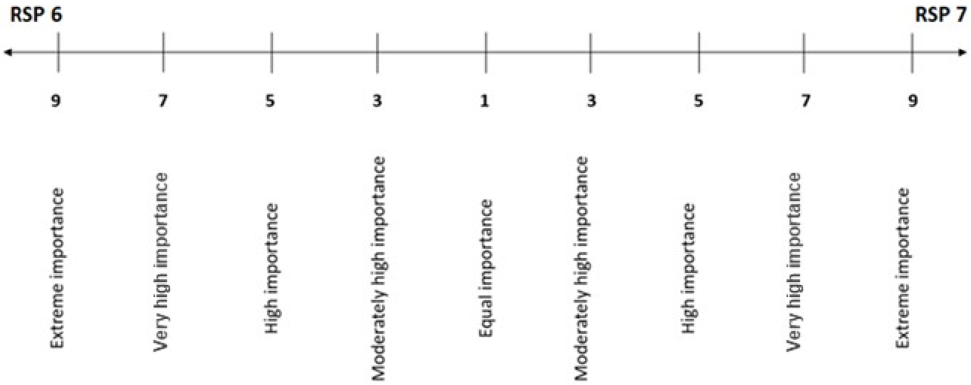

Figure 3. Example of a pairwise comparison between two RSPs.

The RSPs defined were then assessed according to the pairwise comparison questionnaires to have a better understanding of which RSPs have the highest impact. The analysis of these questionnaires served as the input of the comparison matrix ("i" rows and "j" columns) when a row RSP_i is prioritized over a column RSP_j via Equation (1) (in Table 2 an excerpt is illustrated):

$$RSP_i = \frac{1}{RSP_j} \tag{1}$$

Table 2. Example of the pairwise comparison assessment from one correspondent (excerpt of three RSPs).

	RSP1	**RSP2**	**RSP3**	**RSP4**	**RSP5**	**RSP6**	**RSP7**	**RSP8**
RSP1	1	1/7	1/5	1/3	3	3	5	3
RSP2	7	1	3	5	7	7	5	9
RSP3	5	1/3	1	1	5	3	7	5

The following steps consisted of transforming the RSP crisp numbers into triangular fuzzy numbers. The transformation is described by Kamyvsi et al. [29], where each consisted of three values: the lowest possible value "l", the highest possible value "u", and the most promising one "m". The latter is portrayed in Table 3 based on Zaim et al. [50].

Table 3. The scale for defining the importance of the RSPs.

Importance Level (Crisp).	**TFN**	**Reciprocal TFN**	**Definition**	**Explanation**
1	(1, 1, 1)	(1, 1, 1)	Equal importance	The two RSPs are of equal importance
2	(1, 2, 3)	(1/3, 1/2, 1)		
3	(2, 3, 4)	(1/4, 1/3, 1/2)	Moderately high importance	A RSP is moderately preferred over another
4	(3, 4, 5)	(1/5, 1/4, 1/3)		
5	(4, 5, 6)	(1/6, 1/5, 1/4)	High importance	A RSP is highly preferred over another
6	(5, 6, 7)	(1/7, 1/6, 1/5)		
7	(6, 7, 8)	(1/8, 1/7, 1/6)	Very high importance	A RSP is heavily preferred over another
8	(7, 8, 9)	(1/9, 1/8, 1/7)		
9	(8, 9, 10)	(1/10, 1/9, 1/8)	Extreme importance	A RSP is dominant over another

The TFNs were then defuzzified via Equation (2) and the resulting crisp values were checked for consistency, as per Kwong and Bai [78]:

$$RSP\ importance_{crisp} = \frac{(4m + l + u)}{6} \tag{2}$$

The RSPs final importance values (RSPcrisp) are depicted in Table 4.

Table 4. Evaluation of the RSPs through the FAHP.

RSPs	**RSP_{Crisp}**	**RSP Rel.Imp.**	**Rank**
RSP1. Easiness to use	0.73	5.81%	8
RSP2. Availability of the equipment (mean time before failure)	2.79	22.20%	1
RSP3. Quality of maintenance service	1.98	15.75%	3
RSP4. Responsiveness of technical support	2.24	17.82%	2
RSP5. Supply of consumables (kits, cartridges, etc.)	1.41	11.22%	5
RSP6. Data storage options	0.8	6.36%	7
RSP7. Takeback facilitations	1.52	12.09%	4
RSP8. Environmental and safety assistance	1.1	8.75%	6

3.2. *Definition of the PSS Characteristics*

Collaborating with the manufacturer's team of experts, the PSS characteristics that would fulfil the Receiver State Parameters are defined in Table 5. They were classified into two sets: Product Characteristics (PChs) and Service Characteristics (SChs) [45].

Table 5. The PSS characteristics.

Product Characteristics (PChs)	**Service Characteristics (SChs)**
PCh1. Product dimensions	SCh1. Intervention information requests
PCh2. Product connectivity	SCh2. Intervention response time
PCh3. Number of setup operations	SCh3. Periodic consumables provision
PCh4. Alarm features	SCh4. Product recovery scheme
PCh5. Easy-to-use software	SCh5. Quality of technical support
PCh6. Eco-consumables	SCh6. Operational hours of technical support
PCh7. Equipment manual quality	

3.3. *QFDforPSS: Phase I*

Having defined and prioritized the Receiver State Parameters on the one hand and having defined the PSS characteristics on the other, the first phase of the QFDforPSS could then be applied: the relationship matrix utilized a 1-3-9 scale to combine the RSPs, the PChs, and the SChs; 1 depicted a weak relationship, 3 a medium relationship, and 9 a strong relationship. If a relationship does not exist, the cell was kept empty. The results of this matrix are the absolute and relative importance ratings of each PSS characteristic (Table 6). It should be noted that the assessment of the relationships between the RSPs, PChs, and SChs was done in collaboration with the manufacturer's engineers and technical experts.

Table 6. Results of the QFDforPSS phase I.

RSP	**RSP crisp**	**RSP rel.imp.**	**PCh1**	**PCh2**	**PCh3**	**PCh4**	**PCh5**	**PCh6**	**PCh7**	**SCh1**	**SCh2**	**SCh3**	**SCh4**	**SCh5**	**SCh6**
RSP1	0.7	5.8%	9	3	3		9		3						
RSP2	2.8	22.2%			1	3			3	3	9	3		3	
RSP3	2.0	15.8%		3	3				3	9	3		3	9	3
RSP4	2.2	17.8%				3				9	9		3	3	9
RSP5	1.4	11.2%						9				9			
RSP6	0.8	6.4%		9			1								
RSP7	1.5	12.1%	3								1		9	1	1
RSP8	1.1	8.8%		1		3		9	3	3		1	3	3	1
Ch Absolute Importance			11.1	16.4	10.9	18.4	7.4	22.6	19.8	49.7	52.7	22.2	29.6	37.7	28.7
Ch Relative Importance			3.4%	5.0%	3.3%	5.6%	2.3%	6.9%	6.1%	15.2%	16.1%	6.8%	9.1%	11.5%	8.8%
Ch Rank			11	10	12	9	13	6	8	2	1	7	4	3	5

The results show that the service characteristics are of higher importance than most of their product counterparts. Hence, the need for an effective service strategy arose from the collected information. This would enable the manufacturer to be more responsive to its customers' current needs and extend the lifecycle of its equipment while having enough flexibility to quickly adapt to changes without incurring unwanted economic and environmental costs. Additionally, a business model with life cycle considerations can improve the product's reliability, reduce its environmental impact, and increase customer satisfaction [79,80]. In such a context, maintaining ownership of the product aids in ensuring its correct maintenance, implementing smarter intervention schemes, and improving its end-of-life treatment [8,10,71].

3.4. PSS Solution Feasibility Evaluation

Given the information above, a shift from a sales-based model to a use-oriented PSS is an adequate choice since it enables the manufacturer to improve its performance in all aspects. Moreover, PSSs can allow more flexibility for the manufacturer to adapt to changing requirements, different customer segments, and use patterns (e.g., medical centers, specialized laboratories, general practitioners) while achieving better environmental results [66,81].

In this context, the PSS solution comprises of a leasing agreement between the manufacturer and the customers. Customer-related information is obtained by the sales team, and according to the demanded quantity and delays a suitable PSS is proposed to the customer. Upon acceptance, an instrument is prepared and delivered to his address. The field service team installs the instrument and accessories, validates its correct operation, and provides the user with sufficient training for its daily setup and use. Ordinary maintenance interventions are planned and coordinated with the customer to ensure their occurrence at the right time. This allows the manufacturer to keep control of the instrument and observe its state evolution over time—deterioration is monitored and pieces subject to wear and tear (i.e., tray gears, movement motors, etc.) are replaced with qualified parts and by a dedicated team. If left to the customer, the manufacturer will encounter difficulties gathering such information, the replacement parts may not be qualified, and third-party maintenance crews may not have sufficient competencies for correct maintenance execution. This would significantly jeopardize the instrument's life cycle, leading to customer complaints and dissatisfaction.

Therefore, a leasing plan appears as a suitable solution to address these matters. In addition, it would be a concrete response to fulfil the characteristics resulting from the QFDforPSS phase I. For example: obtaining accurate information regarding the intervention requests (SCh1) and hence facilitating a better response time (SCh2) for an overall service quality enhancement (SCh5). Furthermore, the leasing model can be diversified and tailored for each customer, hence offering better market potential and possibilities [82]. The leasing plan will follow one of the two following directions:

- Intensive use-oriented: intended for large analysis laboratories and hospitals. The leasing consists of a three-year renewable duration during which the manufacturer provides the users with the needed training for the right use of the product to prevent unwanted failures or reduced performance (opening the lid while a test is running, forcing the movement of the tray, etc.). When ordinary maintenance activities need to occur, a field service engineer goes to the client according to a predefined schedule. Once the three years have passed, the manufacturer recovers the instrument and provides the client with a substitute, generally a refurbished instrument. It should be noted that the ideal period for the exchange is in the summer period where sicknesses are less frequent than in winter.
- Moderate use-oriented: intended for small clinics and cabinets. In this case, the leasing consists of a "5 + 5" and provides the same training, maintenance, and recovery services as the three-year plan.

To evaluate and assess the viability of the two proposed PSSs, the SLCM was implemented. The cornerstone of the method was the definition of the current scenario, known as the Base Scenario (BS). With feedback from the manufacturer's team of experts, the following was assumed:

- Lifespan of the instrument: 4 years.
- Production rate: 160 instruments/year.
- Operational duration:
  - Intensive use: 254 days/year at an average of 8.5 h/day.
  - Moderate use: 216 days/year at an average of 7 h/day.
- Shipment and distribution: the manufacturer delivers the instrument to the customer employing a transport truck for an average distance of 250 km.

- Ordinary Maintenance Activities (OMA) and use: the manufacturer recommends the ordinary maintenance schedule (Table 7).
- Extra-ordinary Maintenance Activities (EMA): they mainly concern gear malfunctions, spring loosening, and motor performance deterioration (Table 7).

Table 7. Details of the ordinary and extraordinary maintenances.

DESCRIPTION	FREQUENCY (Operational Hours)	ACTIVITY
OMA1. Motor gear	2000–2300	Replacement
OMA2. Motor cables	2000–2300	Adjustment
OMA3. Pressure sensors	4300–4500	Replacement
OMA4. Esthetical touch-up	6200–6600	Cleaning and paint
EMA1. Heat sensors	4300–4500	Replacement
EMA2. Electronic board	6200–6600	Replacement
EMA3. Syringe	4300–4500	Lubrification

The next step is the definition of the Alternative Scenarios (ASs). As mentioned earlier, one scenario will target customers related to intensive use of the product (AS1) and another will be aimed at customers representing a less intense, i.e., moderate, use of the product (AS2). Another aspect to take into consideration is that the AS1 is sought as a replacement of the BS whereas the AS2 is for future implementations. Next, comes the life cycle assessment method using the SimaPro 8.5 [83] and the Eco-Indicator 99 evaluation criteria [84]. Table 8 shows an excerpt of the material types, quantities, and related EoL activities.

Table 8. Excerpt of the materials used in the EoL stage.

MATERIAL TYPE	MATERIAL QUANTITY (KG)	ACTIVITY
Stainless steel	11.53	Recycling
Alloy (Nickel-Titanium)	5.43	Recycling
Optical fibers	0.47	Recycling
Aluminum foil	0.29	Incineration
Electronic board	2.3	Reconditioning

The results of the life cycle assessment are shown in Figure 3 and are depicted in damage points (Pt) for both the base and alternative scenarios: over a four-year life cycle, the BS had an impact of 242 Pt and over a six-year lifecycle the AS had an impact of 250 Pt. In detail, the AS showed a lower environmental yearly impact of 41,7 Pt than the BS which stands at 61 Pt. The output of this analysis is shown in Figure 4, where the LCA refers to one life cycle only. Furthermore, a ten-year simulation was performed to assess the environmental performances of each of the three scenarios referred to the potential duration of the offering (Figure 5).

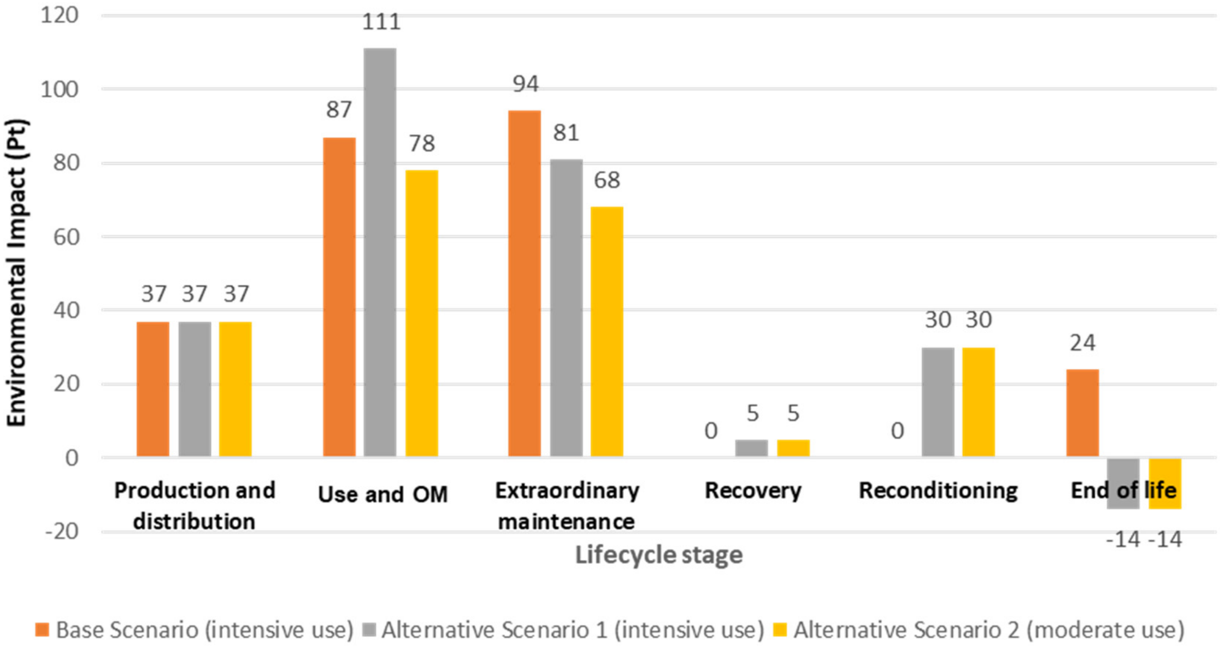

Figure 4. LCA comparison between the BS and AS considering one lifecycle (environmental impact is expressed in Pt as per [83]).

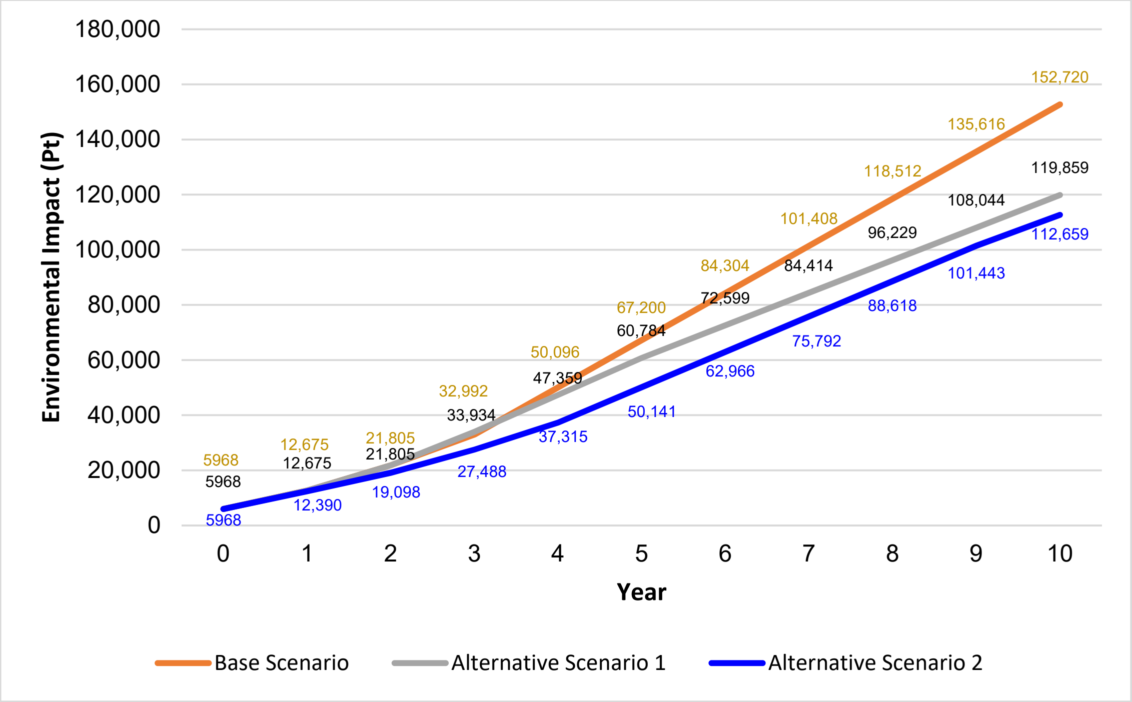

Figure 5. Results of the Screening Life Cycle Modeling method (environmental impact is expressed in Pt as per [83]).

Finally, the effectiveness of the proposed approach in the elicitation of both the receiver state parameters and PSS characteristics has to be pointed out. On the one hand Figure 6 portrays this improvement by comparing the relative importance of the RSPs, while on the other hand, Figure 7 shows the augmentation (in terms of a more granular distinction of relative importance values) related to the PChs and SChs obtained through the QFDforPSS augmented by FAHP compared to their importance achieved by means of a conventional approach.

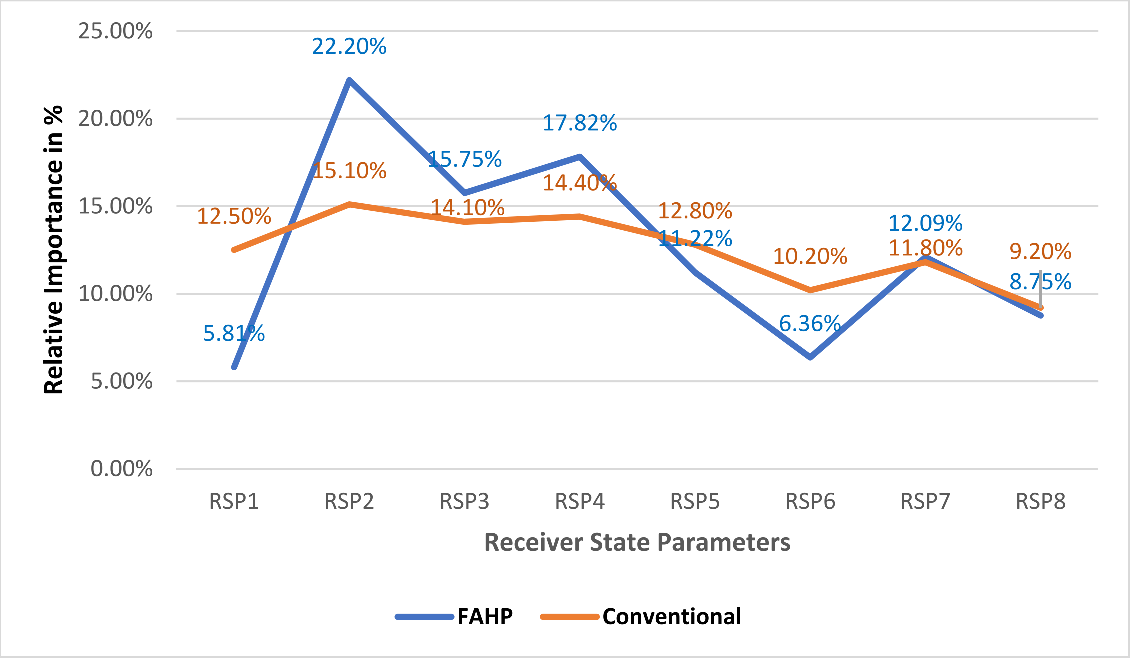

Figure 6. Comparison of the relative importance of the RSPs calculated following the conventional QFDforPSS method and the one augmented by FAHP.

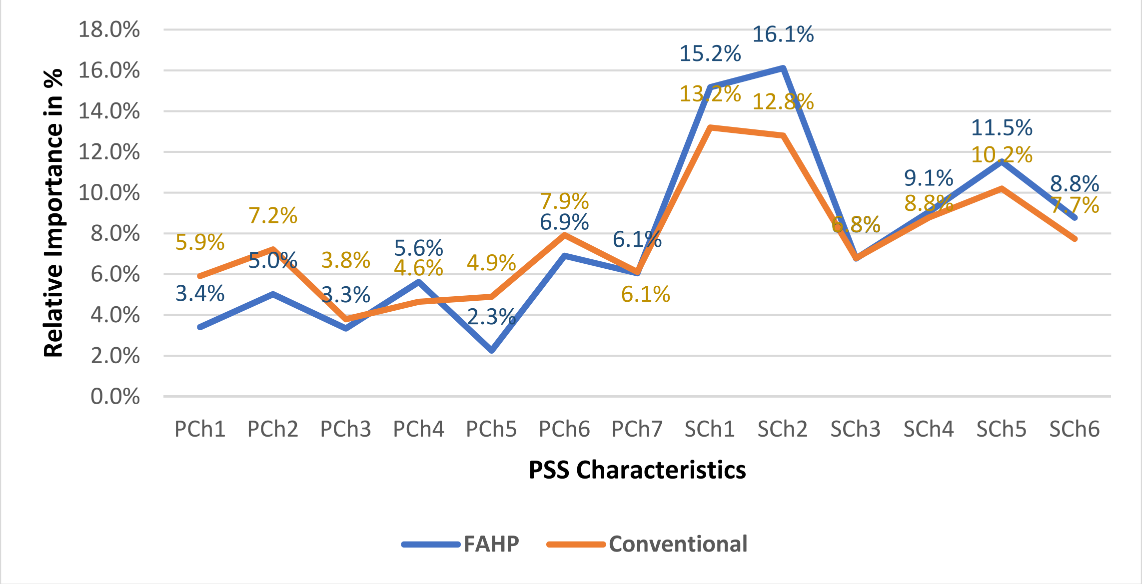

Figure 7. Comparison of the relative importance of PChs and SChs calculated following the conventional QFDforPSS method and the one augmented by FAHP.

It can be noted that while using the FAHP, the RSPs varied within a range of 16% compared to 6% using a conventional approach. In a similar manner, the characteristics varied within a range of 14% via the FAHP compared to 9% using a conventional approach. Hence, a better interpretation of the RSPs led to a better assessment of the PChs and SChs. In other words, the FAHP enhances the understanding of the customers' needs by reducing the imprecisions of the relationships between the CRs and the PSS characteristics and making them more distinguishable.

4. Discussion of Results

Overall, the results achieved show that the proposed approach addressed customer requirements through pairwise comparisons to reduce ambiguities and more notably the intangibilities of services. The FAHP handled the customers' responses and was integrated with the first phase of the QFDforPSS: the more practical evaluation of the requirements allowed a more precise assessment of the PSS characteristics. In the healthcare sector, this is beneficial to customers who will receive a better value offering and the manufacturer who can identify the main aspects of its solution more effectively.

From a more general point of view, the integration of the FAHP with the first phase of the QFDforPSS allows a better representation of the voice of the customer and notably those answered by service characteristics. This meets the needs elicited by Song and Sakao [66] and Sousa-Zomer [57] for the development of methods that better portray the requirements of PSS design since this area has not been investigated deeply.

Considering the deployment of services, the results imply consolidating customer relationships for better management of its service networks to provide more convenient solutions that can augment customer satisfaction. Furthermore, such services can bear improvements on an environmental scale.

Essentially, the LCA and SLCM results consolidate the positive achievable environmental output since the shift from a sales model to a use-oriented PSS enables the extension of the product's life cycle while adapting it to customer needs, i.e., intensive use and moderate use. The proposed leasing models AS1 and AS2 allow better use of the equipment, more efficient and effective maintenance activities, and recycling and reconditioning of the physical components. In fact, they lessen the need for "new" production materials when manufacturing new equipment. For instance, the simulation shows an environmental reduction of 24.9% between the BS and the AS1, which is mainly due to optimized maintenance and end-of-life schemes. Furthermore, the overall customer experience is enhanced since maintenance activities are planned and carried out by the manufacturer, which reduces the probability of breakdowns and ensures the correct functioning of the product for longer stretches of time. Furthermore, the leasing schemes facilitate product updates, notably software plugins that help adapt the equipment to changing needs. For instance, customers who already have an instrument at their disposal and need to integrate COVID-19 detection testing can acquire the feature on the same product via an intervention of the manufacturer's field service team without a replacement and hence the availability is intact. In addition, significant upgrades related to hardware can take place more easily and frequently since the exchange of the product can take place every 3 or 5 years (AS1 or AS2, respectively). Such results provided practical implications for the manufacturer enabling the development of different PSS solutions, which can be dynamically adapted to the future customers' needs. This is in line with the suggestions by Zhang et al. [16], who argued that the provision of a thorough PSS approach can support manufacturers to upgrade their operations and promote sustainable development.

On the whole, the study proposes an original procedure for PSS implementation that integrates customization goals with environmental sustainability. Such an approach allowed a double customization process, at the beginning when customer needs and expectations are elicited, and then in the conceptual phase when a further opportunity of tailoring the PSS solution is provided through the feasibility analysis. In addition, the lifecycle modeling augmented the inner capability of PSS in providing sustainable solutions when supported by life cycle analysis investigations, in line with research cues by Kjaer et al. [10]. Accordingly, it was demonstrated that use-oriented PSS solutions can provide practical environmental benefits achieved by means of better management of maintenance operations, as well as fostering repair, refurbishment, and reuse options. These factors accomplish circular economy targets, expanding research insights outlined in PSS literature [85–87].

From the methodological point of view, this study presented a twofold output. On the one hand, it contributes to augmenting knowledge on PSS conceptual design, which is a critical phase of the PSS development process. At this stage, the effectiveness of potential PSS solutions is determined both in terms of customer value and environmental sustainability, as remarked by Sakao and Neremballi [4]. On the other hand, this study also reduces the research gap outlined by Blüher et al. [7] concerning the scarcity of studies addressing the development and application of a standardized method for the assessment of sustainability effects of PSS. In addition, it has to be noted that the use of tools allowing a practical screen of the PSS lifecycle enables engineers to better tailor both service and product options, proposing solutions that can be upgraded and modified during the contract period. As in the case study context, in fact, the upgrade options related to different types of the instrument's adjustment and use (i.e., the different diagnostic capabilities of the equipment due to the COVID-19 emergency) can be managed in a more effective manner during the contract period, reducing the risks related to improper maintenance services and unexpected interventions [88]. This ensures a better management of the operations, augmenting the balance between customer values and features of the offering [89]. As claimed by Takata et al. [90], a maintenance-centered life cycle approach can allow for advantages from both the environmental's and costs' standpoint.

Finally, the limitations of the study have to be outlined. In particular, the fact that the analysis of the PSS lifecycle did not take into account the risks related to technology improvements, whereas both product's and service's features might change rapidly [91]. Hence, a further expansion of the proposed methodology should include corrective indexes to consider technical and technological advances. Then, although according to company technicians, the proposed solutions should lead to a positive economic effect, a specific cost analysis should be performed to complete the feasibility analysis. Indeed, one might note that in a regulated market, where manufacturers provide both the equipment and maintenance services, financial risks are fewer than in the free market settings [92]. Hence, the implementation of PSS in this type of sector from the manufacturer standpoint can be considered safer than in other contexts [62]. However, when extending service offerings, a cost analysis could reduce the risk of unsatisfactory profitability outcomes as pointed out by Benedettini et al. [93]. Moreover, it has to be observed that the current research is focused on the manufacturer's perspective, while the inclusion of other stakeholders should be foreseen, e.g., expanding the methodology with the inclusion of tools for mapping the whole PSS life cycle considering all stakeholders involved [94,95]. Despite the advantages presented, the case study is limited to the medical device sector and its generalization requires further investigation. For example, more in-depth interviews and statistical testing, as well as a larger pool of customers with a higher response ratio, would represent the state of PSSs more precisely. Furthermore, extending the research to other industrial sectors would better investigate the applicability of the approach and aid in its improvement as indicated by other researchers [96,97]. An example would be the use of the analytical network process which explores the interrelations of not only the receiver state parameters but also the PSS characteristics and the relationships of the entire system as a whole [59].

5. Conclusions

Recent research has demonstrated the benefits of developing sustainable business solutions integrating the tangible and intangible features of their offerings. However, the inclusion of customization issues in PSS development has to be expanded providing models that can be applied to augment the competitiveness of companies. The study represents a practical answer to such a research gap, providing a methodology for PSS development capable of improving customer value and environmental sustainability simultaneously.

In practice, this paper aims to aid practitioners and researchers in better understanding customer requirements by reducing ambiguities and uncertainties through augmenting the QFDforPSS by the FAHP. This allows a better interpretation of the end users' needs. In detail, different customer expectations can be met without significant design changes if the RSPs are properly defined. As the case study showed, heavy and moderate users utilize the same PSS. Another benefit is the environmental improvement that can be achieved without jeopardizing customer value and satisfaction.

In other words, the proposed approach allows engineers to implement customized use-oriented product-service system solutions, achieving circular economy targets by means of both better management of maintenance, as well as optimized end-of-life operations such as repair, refurbishment, and reuse. Accordingly, the study can expand knowledge on methodologies capable of dealing with the varying environmental issues of a product and its related services, as well as their combined value for customers. Lastly, the results are promising but should be handled with caution as their generalization cannot be validated from a single case study. Nevertheless, they can be used as the cornerstone for theoreticians and practitioners to carry out additional research and further refine the presented approach.

Author Contributions: Conceptualization, M.F. and N.H.; methodology, M.F. and N.H.; writing—review and editing, M.F. and N.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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