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Hierarchical analysis of factors influencing acceptance of remanufactured medical devices

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ABSTRACT

The growth of remanufacturing has seen its application in different industrial sectors including automotive, electronics and medical devices. In medical and healthcare sector, remanufacturing presents an opportunity to equip facilities with functional, safe, affordable and sustainable medical systems. However, there is a lack of understanding of the key factors that influence customers' acceptance of remanufactured medical devices. This study addresses this gap by analysing and ranking key factors that impact customers' decisions to purchase and use remanufactured medical systems using pairwise comparisons obtained from the analytical hierarchical process (AHP) model. The structural decision hierarchy was developed followed by a description of the adopted scale of importance. Thereafter, pairwise comparisons were performed by the expert panel constituted by six medical equipment experts with a total of 194 years' experience between them. The responses were tested for rationality and consistency, the analysis of the comparisons was performed, and factor weights obtained for each factor. Results obtained ranked product quality as the most critical factor affecting acceptance of remanufactured devices followed by price, warranty, brand equity, available information, added value services and environmental friendliness. Findings from this study highlight the peculiarity of medical devices remanufacturing which gives more attention to product quality in terms of performance and safety. Taken together, these results provide a basis on which medical devices remanufacturers can improve customer acceptance. Before this study, discussions on customer acceptance of remanufactured medical devices were purely anecdotal and this is the first comprehensive investigation of customer factors in medical devices remanufacturing.

1. Introduction

Ongoing discussions about sustainability issues caused by resource depletion, population blowout and climate emergencies have resulted in direct and indirect actions of businesses to reduce material and energy consumption, waste generation and landfill impacts (Lahrour and Brissaud, 2018; Subramoniam et al., 2009). Concerns about the unsustainable interactions of humans with non-renewable resources are championing a drive towards circularity and sustainable development. Sustainable development strategies ensure that the ability of future generations to provide for themselves is not negatively impacted by efforts to meet present needs (Gehin et al., 2008).

Different end of life recovery strategy such as reuse, repair, reconditioning, refurbishment, remanufacturing and recycling have been discussed in literature (Ijomah et al., 2007a; Paterson et al., 2017; Yang et al., 2015). Particularly, remanufacturing has been preferred due to its environmental, economic and social benefits (Butzer et al., 2016; Golinska et al., 2015; Subramoniam et al., 2013) and it has been described as good for business, environment and the consumers. Also, "remanufacturing results in conservation of inherent product value, protection of intellectual property and creation of new market opportunities" (Subramoniam et al., 2009). Remanufacturing has been described as an industrial operation that returns a used device to "as new" condition in terms of performance and warranty (Ijomah et al., 2007a) through a series of activities which include core collection, disassembly, cleaning, inspection, sorting, part recovery or replacement, reassembly and testing (Ijomah et al., 2007a; Lund, 1985; Nasr and Thurston, 2006) as shown in Fig. 1. Table 1 shows the description of end-of-life product recovery options.

Remanufacturing achieves a significant reduction in environmental footprint (Bras and Hammond, 1996) which favourably places it as a key facilitator of sustainable development (Gehin et al., 2008; Nasr and

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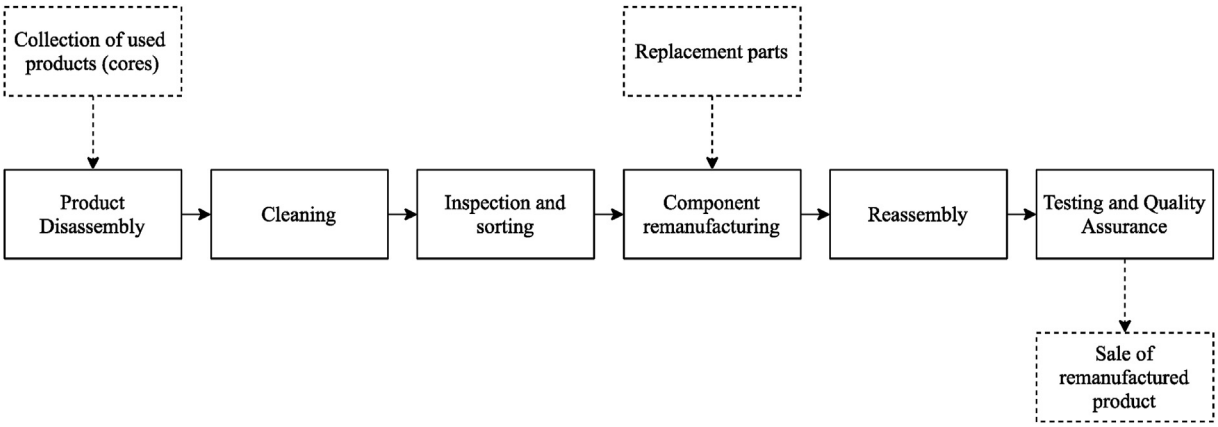

Fig. 1. Remanufacturing process.

Thurston, 2006). As a result, remanufacturing has received much attention across many industrial sectors such as automotive, aerospace, electrical and electronic equipment, furniture marine and offshore, rail, heavy duty and off road equipment and medical devices (ERN, 2015; Steinhilper and Weiland, 2015). However, there is need for greater traction in the utilisation of remanufacturing in medical devices industry, especially in the UK. In Europe, for instance, medical devices remanufacturing (MDR) account for 3.4% of the overall market turnover and only 0.83% of total remanufacturing firms engage in MDR in 2015 (ERN, 2015).

Although discussions on the recovery of end of life medical devices have been going on for the past 2 decades, it is only recently that researchers began to suggest ways to reduce the complexity of medical devices remanufacturing (Eze et al., 2019; Foley, 2006; Jensen et al., 2019; Leung, 2019). Widera and Seliger (2015) highlighted key barriers in core acquisition, steps in the remanufacturing process and selling of remanufactured devices (Widera and Seliger, 2015). Jensen et al. (2019) assessed sustainable values created through the end of life recovery programs of 3 manufacturers (Jensen et al., 2019). Although these studies (Jensen et al., 2019; Widera and Seliger, 2015) offer solutions to specific problems for OEMs, they do not assess the critical factors that impact the acceptance of remanufactured medical devices (Akano et al., 2021). As original manufacturers consider end of life recovery option for their products, there is a need to present a comprehensive assessment of factors that influence customer acceptance (Widera and Seliger, 2015). Thus, this study presents a brief review of MDR followed by a comprehensive assessment and ranking of key consumer factors using numerical weights obtained from AHP. This study aims to rank the relative importance of factors considered by medical equipment experts in the UK when deciding whether or not to use, recommend, repair or perform any related activities on remanufactured medical devices. The remainder of this report is structured as follows. Brief review of medical devices remanufacturing and consumer acceptance literature is presented in section 2 followed by description of the AHP method in section 3. The results, discussions and conclusion are presented in section 4, 5 and 6 respectively.

2. Literature review

2.1. Medical devices remanufacturing

The increasing waste generation in the healthcare sector (Leunget al., 2019; Kwakye et al., 2010) coupled with reducing funding for healthcare expenditure and growing pressure to keep down cost of healthcare equipment (Sloan, 2007) is driving the growth of sustainable practices in the medical devices industry. Also, original manufacturers have realised the leverage that reprocessing medical systems give them over competitors in the industry (Hede et al., 2013). However, awareness and acceptance of such sustainable practices is abysmal, especially in the U.K. with remanufacturing intensity in the medical devices industry being as low as 0.5% (Widera and Seliger, 2015). Eze et al. (2019) defined medical devices remanufacturing (MDR) as a process that returns used medical devices to the initial specifications of the OEM in terms of performance, safety, intended use, warranty and post-sales technical services (Eze et al., 2019). Although this definition provides a basis to better understand remanufacturing, other recovery options like refurbishment, servicing and recycling are more commonly used in the medical devices industry (Centre for Remanufacturin, 2008; R et al., 2009).

Despite the extensive benefits of remanufacturing medical devices (Kwakye et al., 2010), critics continue to misunderstand the process and raise issues surrounding the safety of the patient. Some have argued that patient consent should be sought before reprocessed equipment can be used on them (MacPherson, 2010). These, coupled with the biases of OEMs, who fear reduced revenue and market share (Widera and Seliger, 2015; Sloan, 2007), continue to stifle the growth of reprocessing in the medical field.

Conversely, proponents of MDR have claimed that there are no known evidences associating the use of remanufactured medical devices to increased risk to patients (Kwakye et al., 2010). Coincidentally, Amadi et al. (2011) recorded a decline in neonatal mortality in healthcare centres where digitally recycled incubators were used (Amadiet al., 2011). Remanufactured circular mapping catheters by Leung et al. (2019) had good mechanical performance when tested against the specifications of the OEM and its use did not put patient safety at risk (Leunget al., 2019). Also, MacPherson (2010) emphasized that safety of patients is a mandatory consideration in procurement frameworks used by healthcare boards and that obtaining patient consent may not be necessary as equipment that put patient at risk would not be purchased in the first place (MacPherson, 2010). However, the lack of data and research on MDR continues to play part in its slow growth.

Although remanufacturing of hospital beds is routine in the US (Heese et al., 2005), consumer acceptance of remanufactured medical devices in the UK is low (Leunget al., 2019). Kwakye et al. (2010) reported that about 25% of healthcare centres in the United States use at least one type of reprocessed single use medical devices in 2002 (Kwakye et al., 2010). Leung et al. (2019) estimated an annual potential cost saving of £17 million from reprocessing single use medical devices in the UK (Leunget al., 2019). Kwakye et al. (2010) also forecasted the 2017 cost savings from remanufacturing single use devices in the US at $326 million (Kwakye et al., 2010). Amadi et al. (2011) reported on the economic advantages of digitally recycled neonatal incubators in low-resourced settings (Amadiet al., 2011). Heese et al. (2005) discussed significant cost savings associated with refurbished hospital beds in the US (Heese et al., 2005). Sloan, 2007 highlighted that up to 4.6 million

Table 1
Description of end-of-life product recovery strategies.

Operation	Description	References
Direct Reuse	Reusing a product directly means an end of use or returned product is put into the forward goods flow for the next customer without any mechanical work done. In some cases, minor inspection and cleaning may be performed but the overall aim of reuse is to make the product available for the next customer as quickly as possible.	(Agrawal et al., 2016; Charter and Gray, 2008; Ijomah, 2002; Paterson et al., 2017)
Repairing	Repair operations involve the fixing of specified faults or defects in a product with the aim of extending the useful life of the product. The consequence of this is that only components specified as faulty would be corrected or in some cases replaced, which will require spare parts. This is a higher alternative to direct reuse in terms of the performance, but repaired products have lower quality and warranty when compared to refurbished or remanufactured products.	(Brunoe et al., 2019; Camilleri, 2019; Gharfalkar et al., 2016; Ijomah, 2002; Ijomah et al., 2007a; King et al., 2006; Parker and Butler, 2008)
Refurbishment	Refurbishing involves mechanical operations that fix or replace failed parts or components very nearly failed to take the product to a physical and performance characteristic that is acceptable to the customer. In most cases, refurbished product quality is higher than repaired or directly reused product, but it is less than that of a remanufactured product.	(Paterson et al., 2017; Brunoe et al., 2019; Ijomah et al., 2004; Östlin et al., 2009; Ziout et al., 2014)
Remanufacturing	Remanufacturing is described as the process of returning a used (or preowned) product to a physical and performance condition that is similar or better than that of an equivalent new product. The quality and warranty of remanufactured product is highest of product recovery operations.	(Paterson et al., 2017; Ijomah, 2002; King et al., 2006; Center for Remanufacturin, 2009)
Recycling	Recycling recovers the inherent raw materials associated with a product at its end of life. As such, the product is broken down into the basic raw materials which can be used in other manufacturing activities.	(Paterson et al., 2017; Nasr and Thurston, 2006; Camilleri, 2019; Charter and Gray, 2008; Ijomah, 2002)

medical devices were refurbished globally in 2004 (Sloan, 2007).

Perception, acceptance and use of remanufactured medical device is complex. For example, Sloan (2007) used examples of orthopaedic blades, cardiac catheter, compression sleeves and trocar to validate a model with which medical experts can compare the costs, probability of failure and cost of failure for new and reprocessed equipment and then decide whether or not to use a remanufactured equipment in their facility (Sloan, 2007). While this model gave useful insights into the key concerns of prospective users and help them decide whether or not to use a remanufactured medical equipment, it failed to examine the importance of factors considered during the cost-failure decision trade-off. This is achieved in this study by ranking the critical decision factors based on their relative important to decision-makers.

Research effort on the decision-making of 'whether or not' to remanufacture a medical equipment is currently lacking. Taghipour et al. (2011) developed a multi-criteria decision model (MCDM) to rank the criticality of medical devices and prioritize their maintenance or reprocessing (Taghipour et al., 2011). Also, Hede et al. (2013) presented a multicriteria hierarchical model (MCHM) to incorporate the triple bottom line of sustainability (environment, economic, social) into the development of medical devices (Hede et al., 2013). These models provide an understanding of the nature of decision-making in medical devices industry, stating the key players, boundaries and considerations. However, they fail to assess the considerations of medical experts when deciding to use remanufactured medical devices. Since remanufacturing decisions depend on customers accepting, purchasing and using remanufactured medical systems, medical professionals and devices experts have massive impact on the decision process. Therefore, this study which aims to understand the relative importance of key factors that influence acceptance and use of remanufactured medical systems lead the way in this area of medical equipment remanufacturing research.

2.2. Customer acceptance of remanufactured products: identifying key decision factors

Evaluating customer acceptance and market demand for remanufactured devices is a critical step when assessing the viability of remanufacturing (Akano et al., 2021). Also, the success of remanufacturing endeavour hinges on customers purchasing, using and/or recommending remanufactured products. However, customer acceptance of remanufactured products is determined by the trade-off between their perceived risks and perceived benefits (Milios and Matsumoto, 2019). Research issues relating to customers purchase intentions of remanufactured items has been discussed extensively in literature (Duan and Aloysius, 2019; Shu et al., 2017; Singhal et al., 2019).

Abbey et al. (2019) described risk as consumers' judgement of the probability of failure of remanufactured items and the relative impact of such defect on the user (Abbey et al., 2019), which would include both the hospital and patient in the case of medical devices remanufacturing. Consumer risk perceptions relates to the quality, performance, appearance and financing (Singhal et al., 2019), safety and disposal (Van Weelden et al., 2016; Baron, 2017), and serviceability (Milios and Matsumoto, 2019) of remanufactured devices. Perceived risks may also include breakdown risks, technology/obsolescence risks, financial risks and safety risks (especially in high-risk industries such as medical devices). These risks are associated with fear of frequent servicing, increased operating costs, higher safety concerns, and sudden breakdown (Singhal et al., 2019). Benefits of remanufacturing have been extensively discussed in literature (Ijomah et al., 2007a; Nasr and Thurston, 2006; Li et al., 2017; Hanson and Hitchcock, 2009). The financial benefit of remanufactured medical devices as a cheaper alternative to new product without compromising its quality, safety and warranty is considered to be the far-reaching motivation for customers.

Some customer decision factors that were identified in literature include functional performance or product quality (Hosseini-Motlagh et al., 2018; Vafadarnikjoo et al., 2018; Abbey et al., 2017), environmental friendliness (Duan and Aloysius, 2019; Wang et al., 2018), brand equity (Singhal et al., 2019; Li et al., 2017; Govindan et al., 2019), warranty (Alqahtani and Gupta, 2017, 2018; Gan and Chen, 2019), available product information (Milios and Matsumoto, 2019; Duan and Aloysius, 2019), services (Gaur et al., 2015; Van Weelden et al., 2016) and price (Govindan et al., 2019; Jiménez-Parra et al., 2014; Bittar, 2018), as shown in Fig. 2.

2.2.1. Quality of product (in terms of performance and safety) (F_1)

As a product-related factor, quality is critical to customers and has

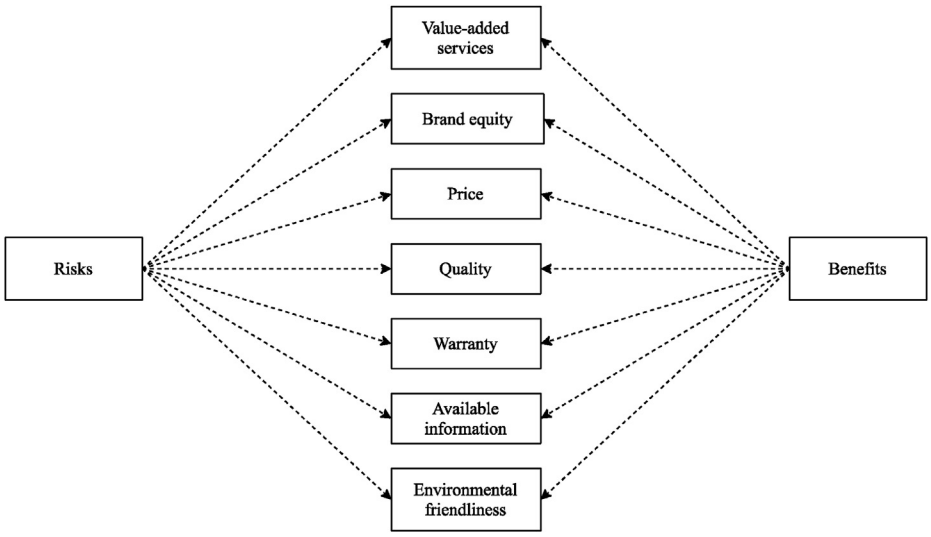

Fig. 2. Factors influencing the trade-off between risks and benefits (Van Weelden et al., 2016).

significant impact on the decision to procure and use a remanufactured device. It has been discussed in existing literature (Duan and Aloysius, 2019; Van Weelden et al., 2016; Hosseini-Motlagh et al., 2018; Vafadarnikjoo et al., 2018; Abbey et al., 2017; Gan and Chen, 2019). When compared to other reprocessing strategies, remanufacturing offer devices with higher functionality, safety, technology and appearance similar to that of an equivalent new product (Paterson et al., 2017; Ijomah, 2009). The quality factor assessed in this study covers performance and accuracy of measurements (Q_p), physical appearance (Q_{py}), safety (Q_s) and technology (Q_t) of the remanufactured medical devices. The quality factor also cover other issues (Q_o) such as the risk of infection, failure probability, limitations on use, decontamination and disposal procedure (Leunget al., 2018).

$$F_1 = \begin{cases} Q_p \\ Q_{py} \\ Q_s \\ Q_t \\ Q_o \end{cases}$$

2.2.2. Available information (e.g., previous use, expected life, quality certification) (F_2)

Information available to customers about a remanufactured product plays an influential role in helping customers form their opinions of the risks and benefits associated with using such product. Information provision through product quality certification and eco-labelling plays an important role in consumers' decision making (Milios and Matsumoto, 2019; Duan and Aloysius, 2019). Milios and Matsumoto (2019) reported that Swedish consumers targeted in their study were more likely to accept remanufactured parts that are quality certified than uncertified parts. Meanwhile, Eze et al. (2019) implied that disclosing information about the remanufacturing process, adjustments performed, parts replaced and tests performed on remanufactured medical systems could have a beneficial impact on customer acceptance (Eze et al., 2019). This factor covers information about the remanufactured product such as its use history, reason for remanufacturing, number of remanufactured or replaced components, age in lifecycle, results of tests performed as part of the remanufacturing process and quality certification (Van Weelden et al., 2016), (Vafadarnikjoo et al., 2018).

2.2.3. Pricing (in terms of acquiring, operating and maintaining remanufactured devices) (F_3)

Bittar (2018) discussed the concept of remanufactured product 'price ratio' which is defined as the ratio of the price of remanufactured product to that of an equivalent new product, expressed as a percentage (Bittar, 2018). Weelden et al. (2016) illustrated in his study that although lower pricing was a major motivation for customers' decision to purchase a remanufactured product, adjusting the price beyond a specific threshold will flip the balance between customers risk and benefit perceptions (Van Weelden et al., 2016). For example, customers may perceive remanufactured item as having mediocre characteristic and performance if priced significantly lower than new. On the other hand, a higher price of remanufactured product does not imply superior product quality but may increase customers' perceived financial risks (Van Weelden et al., 2016). This factor covers the cost of procuring remanufactured device (P_a), day-to-day operating cost (P_o), maintenance and repair costs (P_m), and disposal costs (P_d). The price factor may also include failure and training costs.

$$F_3 = \begin{cases} P_a \\ P_o \\ P_m \\ P_d \end{cases}$$

2.2.4. Warranty provided on the remanufactured device (F_4)

Alqahtani and Gupta (2018) defined warranty as a contract between the seller (or the remanufacturer) and the buyer of the remanufactured device regarding the liabilities and expectations from both parties in the event that the purchased remanufactured device breaks down or does not function as expected (Alqahtani and Gupta, 2018). For remanufactured medical devices, the warranty is expected to be similar to (or better than) that of new systems (Eze et al., 2019) The warranty factor assessed in this study covers the length of warranty (W_l), the cost of warranty (W_c), trade-in value of remanufactured device (W_v), and repair and other services as a warranty (W_r).

$$F_4 = \begin{cases} W_l \\ W_c \\ W_v \\ W_r \end{cases}$$

2.2.5. Added value services (including post-sales technical services) (F_5)

To support its provision of warranty, remanufacturers may offer value-added services such as scheduled preventive maintenance and repairs to improve product performance and prevent unexpected failure of components (Alqahtani and Gupta, 2017). This is a common practice in medical devices industry especially with new and remanufactured medical systems by original manufacturers. These post-sales technical services may include provision of replacement parts, software updates,

servicing and maintenance, advice and help, and user training. This factor is important as a means of getting feedback from the users, collecting diagnostic information about the remanufactured medical device and reliability assessment (Eze et al., 2019).

2.2.6. Brand equity (in terms of who performs the remanufacturing operation) (F_6)

Bittar (2018) described brand equity as the extra value that a remanufactured device attracts based on who performed the remanufacturing (Bittar, 2018). However, Weelden et al. (2016) argued that consumer's perceived risks of using a remanufactured device depends on the seller's reputation rather than the identity of the remanufacturer (Van Weelden et al., 2016). Thus, the term 'brand' in remanufacturing may refer to the seller, manufacturer or remanufacturer, what matters is the specific name(s) under which the remanufactured device is offered to buyers (Govindan et al., 2019).

2.2.7. Environmental friendliness (in terms of waste generated, material and energy consumption) (F_7)

Environmental issues relating to the scarcity of finite resources, population growth and climate breakdown has increased awareness of sustainability and ensured a focus on waste generation, material and energy consumption (Lahrour and Brissaud, 2018). Although there is lack of data to back this up, remanufacturing literature have emphasized the significance of environmental friendliness of remanufactured products (Ijomah et al., 2007a; Bras and Hammond, 1996). In contrast, Gutowski et al. (2011) argued that although remanufactured devices have a history of saving energy, current product design and manufacturing trends ensure that new products are more energy efficient and that remanufacturing old devices with lesser energy efficiency is not environmentally friendly (Gutowski et al., 2011). The environmental friendliness factor assessed in this study covers waste generated (E_w), material consumption (E_m) and energy consumption savings (E_e).

$$F_e = \begin{cases} E_w \\ E_m \\ E_e \end{cases}$$

3. Method

3.1. Analytical hierarchy process (AHP) in remanufacturing

The AHP technique, proposed by Saaty (Saaty and Kearns, 1985), is not new in remanufacturing research. Subramoniam et al. (2013) ranked strategic decision factors in the automotive industry using AHP and proposed a remanufacturing decision-making framework (RDMF) based on the results of the AHP (Subramoniam et al., 2013). Also, using the AHP technique, Gaur et al. (2017) proposed a pragmatic decision framework based on the results obtained from a pair-wise comparison of consumer-related factors that affect core acquisition and supply in the remanufacturing industry (Gaur et al., 2017). While these two studies proposed decision frameworks based on the factor ranks, some other studies have used factor weights obtained from AHP to develop models and methods for remanufacturing decision-making. For example, Jiang et al. (2011) proposed a planning method for selecting remanufacturing technology portfolio in the power plants and process industry (Jiang et al., 2011). Du et al. (2012) proposed a remanufacturability assessment method for used machine tool to calculate technological feasibility, economic feasibility and environmental benefits of remanufacturing (Du et al., 2012). Both (Jiang et al., 2011; Du et al. (2012)) used factor weights from AHP. However, application of AHP in medical devices remanufacturing is non-existent.

This study follows a five-step guideline set out by Saaty (Saaty and Kearns, 1985; Saaty, 2002), in line with guidelines in existing remanufacturing literature (Subramoniam et al., 2013; Ahmed et al., 2016; Chakraborty et al., 2017): 1) Developing structural hierarchy for decision problem, 2) Understanding the scale of importance, 3) Pairwise comparison, 4) Hierarchic analysis and rank, and 5) Testing for rationality and consistency.

3.2. Developing structural hierarchy for decision problem

The model developed in this study (refer to Fig. 3) shows the decision hierarchy for assessing acceptance of remanufactured medical devices. At the higher level, the goal of the study is to understand the relative importance of different factors that influence consumer acceptance. At the criteria level, seven (7) consumer-related decision factors, identified from the remanufacturing literature and from experience of the authors as academic researchers, are adapted to medical devices. At the lower level, the alternatives are consumer decisions to or not to accept remanufactured medical devices, which would inform the decision to remanufacture medical device.

3.3. Decision factors

The seven (7) decision factors used in this study include product quality, available information, price, warranty, added value services, brand equity and environmental friendliness. Although each of these 7 factors have sub-factors described in section 2, they were not directly used in this study. That is, pairwise comparison of the sub-factors was not performed. However, these sub-factors were presented to the participant to improve their understanding of the seven (7) factors in the pairwise comparison matrix. By considering the seven (7) high-level decision factors, this study follows the suggestions in (Saaty and Vargas, 2012) to yield a better consistency, reduce confusion and make it easier for participants to accurately complete the pairwise comparison (Vafadarnikjoo et al., 2018).

3.4. Scale of importance

This study adopted the fundamental scale recommended by Saaty (Saaty and Kearns, 1985; Saaty, 2002), shown in Table 2. Numerical values (1–9) are used to represent linguistic terms that best describe the relative importance of each factor with respect to others. For example, when assessing the relative importance of the factor i over factor j, a number x_{ij} is used. x_{ij} can be any number between 1 and 9 from Table 2. Also, even numbers (2, 4, 6, 8) are intermediate values between the odd numbers and can also be used in the pairwise comparison. Consequently, the relative importance of j over i, x_{ji} is the reciprocal of x_{ij} as shown in the equation below. Further discussions on the AHP method and pairwise comparison can be found in literature (Saaty and Kearns, 1985; Saaty and Vargas, 2012; Korhonen and Voutilainen, 2006).

$$x_{ij} = \frac{1}{x_{ji}}$$

3.5. Pairwise comparison

3.5.1. Developing pairwise comparison questionnaire

The number of pairwise comparisons performed in AHP depends on the number of factors (n). In this study, 7 factors were considered, therefore 21 pairwise comparisons are performed by each participant.

3.5.2. Selection of participants

The medical equipment industry is classified as high risk, thus maintenance, repair and other activities in healthcare facilities are performed by multi-skilled and highly experienced engineers. This category of experts, who have worked within the healthcare system for several years while maintaining and offering technical services on medical devices, were targeted in this study. Their experience puts them in a good position to answer questions relating to the safety, functionality and warranty requirements for remanufactured medical devices. Therefore, it

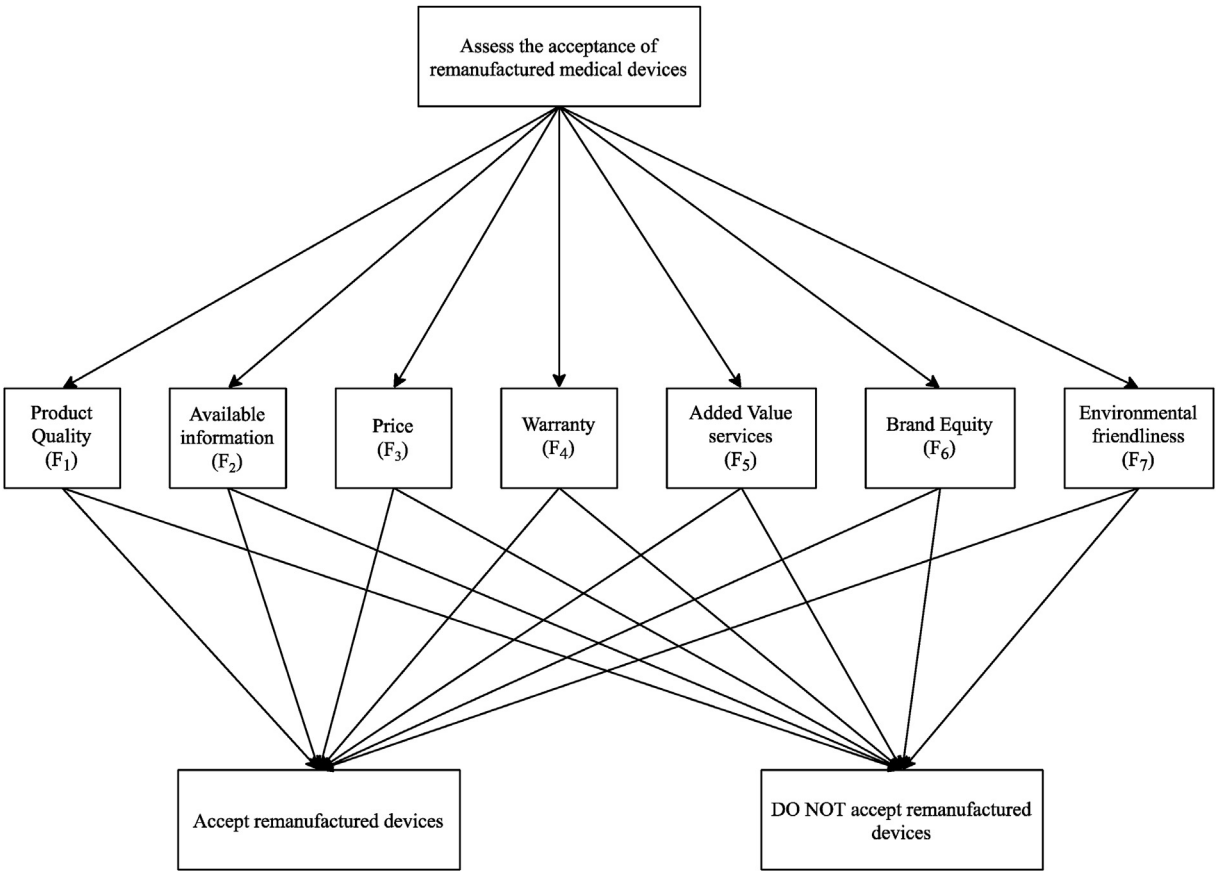

Fig. 3. Structural hierarchy of the decision problem.

Table 2
Scale of relative importance (Saaty and Vargas, 2012).

Level of importance	Linguistic terms	What this means
1	Equal Importance	The two factors contribute equally to the objectives
3	Moderate Importance	Your experience and judgement slightly favour one factor over the other
5	Strong Importance	Experience and judgement strongly favour one factor over the other
7	Very strong or demonstrated importance	One factor is favoured very strongly over the other factor and this has been demonstrated in practice
9	Extreme importance	The evidence that favours one factor over the other has the highest possible level of affirmation

Table 3
Title, Area of specialisation, location and years of experience of participants.

Title	Area of specialisation	Location	Number of years of experience
Head of Service, Medical Equipment Management	Medical Equipment Asset Management	Scotland, UK	37
Acting Head of Medical Equipment Management	Anaesthetics and ventilation	Scotland, UK	28
Head of Electromedical Equipment Services	Equipment management	Scotland, UK	30
Head of Medical Physics & Clinical Engineering	Diagnostic Imaging	England, UK	30
Chairman	Asset management and policy	England, UK	30+
Independent Medical Devices Professional	Medical Equipment Management	England, UK	39

is imperative that this assessment be performed by a small group of highly experienced professionals (Korhonen and Voutilainen, 2006). Fifteen (15) potential participants were contacted by email (mostly based on referral) and invited to participate in the study. The potential participants were followed up two weeks later by email, clearly highlighting the importance of their response and the impact of such serving as a basis on which to improve medical devices remanufacturing. Six (6) completed pairwise comparison were obtained from six (6) medical equipment professionals forming an expert panel with a total of 194 years of experience and an average of 32.33 years' experience making decisions related to medical devices as shown in Table 3.

3.5.3. Survey process

The survey was delivered to participants in the form of a questionnaire. Beforehand, participants were not familiar with the AHP method, therefore a comprehensive explanation of the method was given and three (3) examples of the AHP pairwise comparison process were presented to the participants. The pairwise comparison table was presented as matrix and participants were asked to complete the upper diagonal half of the matrix in line with (Escobar and Moreno-Jiménez, 2000; Shiraishi et al., 1998) and as shown in the examples provided to them.

3.6. Testing for rationality and consistency

Saaty recommended the use of the consistency ratio (CR) and the consistency index (CI) to measure the consistency of the pairwise comparison since the AHP methodology depends on a consistent and logical response of the participant. Different thresholds of acceptable CR (τ) are

recommended by Saaty (Saaty and Kearns, 1985; Saaty, 2002) depending on the number of factors considered in the study. When three factors (n = 3) are considered, CR must not exceed 5% (τ = 0.05), a 9% (τ = 0.09) threshold when the number of factors does not exceed four (n = 4) and 10% (τ = 0.1) when more than four factors ($n > 4$) are considered. When these thresholds are exceeded (i.e. CR > τ), the comparison is considered inconsistent and unreliable, the pairwise comparison must be repeated, and CR recalculated until CR < τ (Saaty and Vargas, 2012).

3.6.1. Estimating CR

In this study, CR was computed for pairwise comparisons by each participant in line with (Saaty and Vargas, 2012; Korhonen and Voutilainen, 2006). The procedure for calculating the consistency ratio is outlined below. Once the pairwise comparison matrix *X* is completed, the CI is calculated using the equation below:

$$CI = \frac{\lambda_{max} - n}{(n-1)}$$

n is the number of factors considered in the study, λ_{max} is the result of the product of the row column sum and the eigenvector matrix, W.

$$\lambda_{max} = [C_{1s}C_{2s}C_{3s}.....C_{ns}] \begin{bmatrix} W_1 \\ W_2 \\ W_3 \\ \vdots \\ W_n \end{bmatrix}$$

C_{1s}, C_{2s}, C_{3s} are the sum of column 1, 2, 3 up to the sum of the nth column C_{ns}

$$CR = \frac{CI}{RI}$$

where RI is the random index which depends on the number of factors considered in a study. The RI table given by Saaty (Saaty and Kearns, 1985) is shown in Table 4.

3.6.2. Dealing with inconsistencies (i.e., when CR > 0.10)

The results of the consistency ratio (CR) for each participant are shown in Table 5. Two (2) out of 6 responses had CR > 0.1, the participants were contacted and asked to redo the pairwise comparison clearly stating the importance of consistency in the AHP method. The revised pairwise comparisons were consistent with CR < 0.10. Subsequently, the consistency ratio of the aggregated matrix is estimated as 0.05 which is less than the threshold 0.10.

4. Results

The participants in the majority (67%) agreed that the 7 factors used in this study cover their major considerations when deciding whether or not to accept a remanufactured medical device. One of the participants highlighted the importance of human factors such as ease of use or likelihood of user making an error while operating the remanufactured device. Another participant commented on the availability of replacement parts to serve remanufactured devices. However, it can be argued that both human factors and availability of spare parts have been taken care of in the study using factor F_5 (added value services) which include user training and supply of replacement parts as discussed in section 3.5.

To aggregate the individual pairwise comparisons into one, the geometric mean approach, which was proposed by (Saaty and Kearns, 1985; Saaty, 1987) and generalised by (Dong et al., 2010; Krejčí and Stoklasa, 2018), is used. The geometric mean comparison matrix is presented in Table 6. To calculate the relative weights of each factors, this matrix is normalised to produce Table 7.

Table 8 shows the ranking of the factors based on the relative weights (or factor scores) obtained from the AHP process and the cumulative factor weights represented in Fig. 4. The cumulative weights of the factors show that the first 4 factors (quality, price, warranty and brand equity) account for 78.74% in line with the pareto principle (Backhaus, 2016; Sher, 2020). Also, the weight of product quality factor exceeds a third (1/3) of the total weights. This further shows the importance of quality of remanufactured devices especially in the medical devices industry where safety of device is paramount.

Furthermore, analysis of the pairwise comparison of individual participant shows some similarity. Five out of six (5/6) participants ranked quality as the most critical factor and environmental friendliness as the least influential factor on their purchase or use decisions. A summary of this finding is presented in Table 9 and further discussions is presented in the next section.

Table 5
Estimated consistency ratio (CR).

Participants	Estimated consistency ratio (CR)	
	First Attempt	Second Attempt
Participant 1	0.08	0.08
Participant 2	0.08	0.08
Participant 3	0.09	0.09
Participant 4	0.14	0.09
Participant 5	0.09	0.09
Participant 6	0.27	0.06
Aggregated Matrix	**0.05**	

5. Discussions

Results from the AHP ranked seven factors that influence acceptance of remanufactured medical devices. These factors (listed in order) are *quality*, *price*, *warranty*, *brand equity*, *available information, added value service* and *environmental friendliness*. *Quality* was ranked as the most critical factor that influences acceptance of remanufactured medical devices. The overall factor weight of product quality (32.38%) underscores the underlying cause of a low acceptance of remanufactured medical devices because experts are wary of sudden failure, safety issues, accuracy of measurements, contamination, and the impact of the remanufactured product on the patients. Four out of the six participants ranked quality first with factor weights more than 30% with the other two participants sharing the significant weights between quality and pricing. This is likely influenced by the perception of reprocessed devices in other industries such as electronic devices (Van Weelden et al., 2016) and the automotive industry (Vafadarnikjoo et al., 2018). This finding is backed up by existing research (Duan and Aloysius, 2019; Van Weelden et al., 2016; Hosseini-Motlagh et al., 2018; Vafadarnikjoo et al., 2018; Abbey et al., 2017; Gan and Chen, 2019). A focus on ensuring that medical systems are remanufactured to a quality standard that is as good as new may increase customer acceptance.

Customers expect that the price of remanufactured items will be lower than that of new. *Pricing* and quality of remanufactured devices are two cardinal factors that influence customer acceptance in medical devices industry (Starret al., 2020). This is validated in our study with both factors accruing more than half of the overall factor weights (51.38%). Also, analysis of each participants' pairwise comparison showed the sum

Table 4
RI for number of factors considered (Saaty and Kearns, 1985).

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 6
Geometric mean pairwise comparison matrix.

Factors	Quality	Available information	Price	Warranty	Added value services	Brand equity	Environmental friendliness
i. *Quality* of product in terms of performance and safety	1.00	4.74	2.22	2.29	3.89	2.57	5.97
j. *Available information* (e.g., previous use, expected life, quality certification)	0.21	1.00	0.44	0.91	2.44	0.82	3.13
k. *Price* in terms of acquiring, operating and maintaining medical devices	0.45	2.28	1.00	1.05	2.99	2.14	5.38
l. *Warranty* provided on the medical device	0.44	1.10	0.95	1.00	2.67	1.22	4.97
m. *Added value services* including post-sales technical services	0.26	0.41	0.33	0.37	1.00	0.53	2.80
n. *Brand equity* in terms of who performs the remanufacturing operation.	0.39	1.22	0.47	0.82	1.87	1.00	4.82
o. *Environmental friendliness* in terms of waste generated, material and energy consumption	0.32	0.32	0.19	0.20	0.36	0.21	1.00
SUM	**3.06**	**11.07**	**5.60**	**6.64**	**15.21**	**8.49**	**28.07**

Table 7
Normalised pairwise comparison matrix (X^N).

Factors	Quality	Available information	Price	Warranty	Added value services	Brand equity	Environmental friendliness
i. *Quality*	0.3264	0.4283	0.3966	0.3446	0.2556	0.3026	0.2127
j. *Available information*	0.0689	0.0904	0.0784	0.1371	0.1602	0.0963	0.1116
k. *Price*	0.1470	0.2059	0.1786	0.1579	0.1968	0.2520	0.1916
l. *Warranty*	0.1426	0.0992	0.1702	0.1505	0.1753	0.1439	0.1769
m. *Added value services*	0.0839	0.0371	0.0596	0.0564	0.0657	0.0630	0.0997
n. *Brand equity*	0.1270	0.1104	0.0834	0.1231	0.1229	0.1178	0.1718
o. *Environmental friendliness*	0.1042	0.0288	0.0332	0.0303	0.0235	0.0244	0.0356

Table 8
Ranking of user-related factors using weights obtained from AHP.

Rank	Factor	Relative Weight	Cumulative Weight
1	Quality of product in terms of performance and safety	0.3238	32.38%
2	Price in terms of acquiring, operating and maintaining medical devices	0.1900	51.38%
3	Warranty provided on the medical device	0.1512	66.50%
4	Brand equity in terms of who performs the remanufacturing operation.	0.1224	78.74%
5	Available information (e.g. previous use, expected life, quality certification)	0.1061	89.35%
6	Added value services including post-sales technical services	0.0665	96.00%
7	Environmental friendliness in terms of waste generated, material and energy consumption	0.0400	100.00%

of factor weights for quality and pricing as 49.99%, 64.98%, 43.98%, 39.42%, 48.09% and 48.26%, which further reiterates the importance of these two factors combined. Price is a key factor that drives customers towards remanufactured systems (Jiménez-Parra et al., 2014) and it was ranked as the second most critical in this study, with an overall weight of 19.00%. A similar finding was reported by (Abbey et al., 2015) and the importance of pricing as it relates to acceptance of remanufactured products has been discussed by (Gaur et al., 2015; Vafadarnikjoo et al., 2018; Phantratanamongkol et al., 2018). Developing an effective pricing strategy is necessary for firms venturing into remanufacturing operation (Gaur et al., 2015). This study also supports evidence from (Callea et al., 2017) which highlights the importance of pricing on the procurement and selection of medical devices.

In line with the definition of remanufacturing, customers expect warranty similar to what is obtainable in a new device, or even better (Ijomah et al., 2007b). The extent to which customer acceptance of remanufactured medical devices is influenced by *warranty* provision is reflected in the factor weight obtained in this study (15.12%) which ranks warranty as the third most critical consideration. This result reflects those of Vafadarnikjoo et al. (2018) and Weelden et al. (2016) which also described warranty as a critical motivation to purchase a remanufactured device (Van Weelden et al., 2016; Vafadarnikjoo et al., 2018). Provision of warranty may reduce customers' perceived risk associated with using remanufactured devices, especially in high-risk industries such as the medical devices industry (Docters et al., 2010). A 'like-new' warranty may include scheduled preventive maintenance and repairs to improve product performance and prevent unexpected failure of components (De Santana et al., 2018).

Brand equity was ranked fourth with a relative weight of 12.24%. This finding is consistent with data obtained in a study by Vafadarnikjoo et al. (2018) which ranked remanufacturer and retailer's reputation as fifth and seventh respectively (Vafadarnikjoo et al., 2018), and Gan and Chen (2019) which ranked remanufacturer's and retailer's reputation as fourth and fifth, respectively (Gan and Chen, 2019). In healthcare, branding is assumed to be an important consideration especially when the users have little or no knowledge of, or experience with remanufactured medical systems as is the case in the UK healthcare sector (Lee, 2010; Torney et al., 2018). However, this research indicates a lower relative weight when compared to other factors i.e., quality, price, certification and warranty have a greater influence on the customers decision than branding of the remanufactured medical systems.

Available information about the remanufactured device is ranked as the fifth most critical factor that influence acceptance of remanufactured device with a factor weight of 10.61%. Knowledge of remanufacturing operation remains low in many industries, more so in medical equipment industry (Basile and Quarngesser, 1997). Wang et al. (2019)'s result reflect a low mean value of product knowledge of remanufactured products whereas Milios and Matsumoto (2019) reported that up to two-third (60%) of its participants were not aware of auto parts remanufacturing and a whooping 76.4% have not ever used remanufactured auto parts (Milios and Matsumoto, 2019; Wang et al., 2019). Customers' negative perception about the quality level of remanufactured products (Singhal et al., 2019) may be improved by issuing quality certification to gain user confidence. Abbey et al. (2017) refers to this as 'functional quality labelling or certification' (Abbey et al., 2017). Weelden et al. (2016) concluded by suggesting that consumers are likely to accept associated risks with refurbished products if comprehensive and accessible information is provided (Van Weelden et al., 2016).

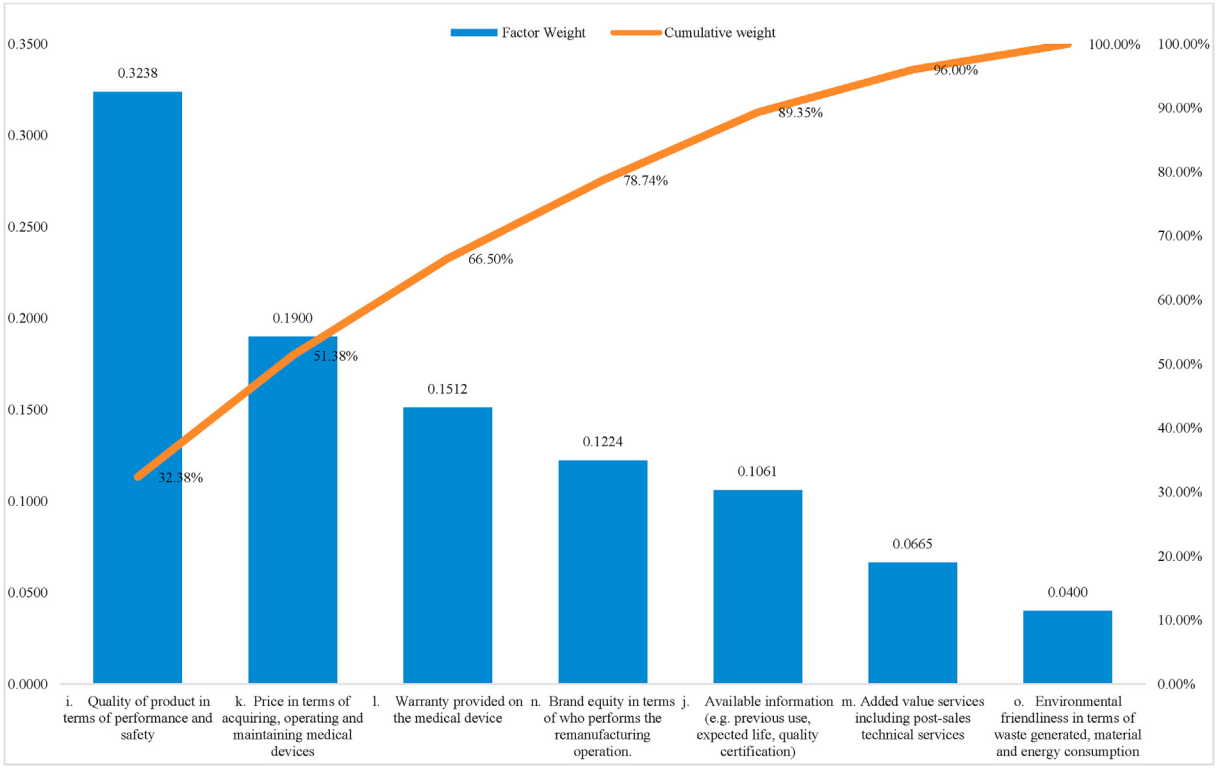

Fig. 4. Cumulative sum of factor weights obtained from AHP.

Table 9
Factor weights and ranking by each participant.

Factors	Factor Weight *(Ranking)*					
	Participant 1	Participant 2	Participant 3	Participant 4	Participant 5	Participant 6
i. Quality of product *in terms of performance and safety*	30.15% ***(1)***	38.10% ***(1)***	21.78% ***(2)***	30.56% ***(1)***	33.37% ***(1)***	27.21% ***(1)***
j. Available information *(e.g., previous use, expected life, quality certification)*	3.82% ***(6)***	12.02% ***(4)***	8.69% ***(5)***	19.66% ***(2)***	7.19% ***(5)***	19.17% ***(3)***
k. Price *in terms of acquiring, operating and maintaining medical devices*	19.84% ***(3)***	26.88% ***(2)***	22.20% ***(1)***	8.86% ***(6)***	14.72% ***(3)***	21.05% ***(2)***
l. Warranty provided on the medical device	15.33% ***(4)***	12.82% **(3)**	13.10% ***(4)***	16.65% ***(3)***	21.07% ***(2)***	12.22% ***(5)***
m. Added value services *including post-sales technical services*	8.03% ***(5)***	3.24% ***(7)***	7.74% ***(6)***	10.92% ***(4)***	6.82% ***(6)***	4.99% ***(6)***
n. Brand equity *in terms of who performs the remanufacturing operation.*	20.72% ***(2)***	3.36% ***(6)***	21.62% ***(3)***	10.38% ***(5)***	13.32% ***(4)***	12.80% ***(4)***
o. Environmental friendliness *in terms of waste generated, material and energy consumption*	2.11% ***(7)***	3.57% ***(5)***	4.86% ***(7)***	2.97% ***(7)***	3.51% ***(7)***	2.56% ***(7)***

Customers consider warranty policy and *added value services* such as the availability of spare parts, repair and maintenance services only after assessing the price, quality and warranty of the remanufactured product. In most cases, service agreements are embedded with the warranty policy at least for the duration of the warranty. This is reflected in the relatively low ranking of added value services as sixth with a weight of 6.65% only ahead of environmental friendliness. Added value services such as user training and replacement part availability were suggested by participants in this study. This shows the slight importance attached to the provision of technical services in the medical devices industry. Weelden et al. (2016) described warranty and service as a major 'risk reliever', 'builder of consumer trust' and a source of added value to the consumers (Van Weelden et al., 2016).

Environmental friendliness is the least ranked factor with a weight of 4.00% despite increasing discussions on sustainability in the medical and healthcare sector. This is another factor with the same ranking (7th) by five of six participants. Duan and Aloysius (2019) suggested that industries with high environmental consciousness perceive remanufactured products to be of good and acceptable quality and vice versa (Duan and Aloysius, 2019). The low relative environmental consciousness in the medical and healthcare sector partly explains the low acceptance of remanufactured devices. This finding supports previous arguments on the impact of environmental benefits on customer acceptance in the medical devices industry (Compton, 2018; Kadamus, 2008; Cheong et al., 2020).

6. Conclusion

Increasing awareness of the need to reduce waste equipment going to landfills has provided a unique market opportunity. As manufacturers jostle to make impact in the remanufacturing business, there is a lack of understanding of consumer requirements from the perspectives of the OEM. Also, a clear knowledge gap was identified on understanding the importance of factors that influence consumer acceptance of remanufactured medical devices. Thus, this present study was designed to present a background of medical devices remanufacturing followed by the ranking of the relative importance of consumer factors. To achieve this, pairwise comparison of seven factors identified in literature was performed using the AHP method. Six highly experienced medical equipment experts form the expert panel. Results show that the responses from the participants were consistent and rational with consistency ratio less than 0.1 for all completed pairwise comparisons. This study ranked

product *quality* in terms of performance, appearance and safety as the single most critical factor that influence customer acceptance of remanufactured medical devices followed by pricing, warranty, available information, brand equity, added value services and environmental friendliness. This finding echoes the importance of quality factors in medical devices industry, where reliability and safety of devices are important requirements. The findings in this study will be of interest to researchers, remanufacturers and OEMs.

This study contributes to existing knowledge in the following ways. First, it builds on Vafadarnikjoo et al. (2018) which highlighted a lack of understanding of consumer requirements from the viewpoint of the remanufacturer. Second, this study performed a ranking of customer factors using feedback from highly experienced medical device experts (32.33 years' experience on the average) from the consumers side and presented in such a way that it is easy and clear for remanufacturers to identify the key factors on which to focus on to improve acceptance of remanufactured medical devices. Third, each of the seven critical factors may be assessed individually with the aim of improving customer acceptance, assessing viability of remanufacturing and improving growth of medical devices remanufacturing. Also, a quantitative evaluation of the interactions between two or more factors and the impact on remanufacturing decisions may be considered in future research. Future research may also build on this research by assessing technologies and methods to ensure that products are remanufactured to acceptable consumer standard.

A limitation of this study is the relatively small size of participants. However, this limitation is managed by using feedback from highly experienced medical equipment experts with a total of 194 years of experience, and consistent pairwise comparisons (CR < 0.10). In spite of the limitation, the study adds to understanding of the customer acceptance in medical devices remanufacturing. What is now needed is an ardent effort of researchers to seek out ways and methods of improving acceptance of remanufactured devices in medical and other industrial sectors. OEMs and remanufacturers must remain open-minded about distinct requirements of their customers.

The findings of this study can be used to develop targeted interventions aimed at improving remanufacturing decision-making, remanufacturing process planning, remanufacturing business assessment and core acquisition and supply with the aim of improving sustainable development. This approach may also be extended to other industries and remanufacturing sectors and more participants recruited to produce better results.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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