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Assessing the Remanufacturability of Office Furiniture: A Multi-Criteria Decision Making Approach

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ASSESSING THE REMANUFACTURABILITY OF OFFICE

FURINITURE: A MULTI-CRITERIA DECISION MAKING APPROACH

by

Po-Hsun Chen

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ABSTRACT

ASSESSING THE REMANUFACTURABILITY OF OFFICE FURINITURE: A MULTI-CRITERIA DECISION MAKING APPROACH
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While the average life cycle of consumer goods is continuously decreasing, the amount of used product at their end-of-life (EOL) is accumulating fast at and at the same pace. Most EOL products end up in landfills, and many of which are not biodegradable. These two challenges have necessitated renewed global interest in product EOL management strategies by manufacturers, third party companies, consumers and governments. Remanufacturing is one of the EOL strategies which is highly environmental-friendly. Additionally, remanufacturing is seen as one of the highly profitable re-use business strategies. The selling price of remanufactured products is usually about 50—80% of a new one, making remanufacturing a win—win solution, saving both money and preserving the environment as well as raising the bottom-line of enterprises.

Through the literature review of remanufacturing, we realize many researchers in this area have focused on a few product categories such as automotive, electrical and electronic equipment as well as ink cartridge, thus accelerating innovations for the remanufacture of these product categories. There is therefore, a need to explore the remanufaturability of other products, especially the ones with high market potential

growth as well as profit margin. Furniture industry is the one that fits the description and is the focus of this thesis.

The goal of this exploratory research is to present the first framework of its kind that aims at assessing the remanufacturability of office furniture. The proposed evaluation model considers three aspects of the assessment problem: economic, social and environmental to obtain a holistic view of remanufacturability of office furniture. We apply the fuzzy TOPSIS methodology to deal with incomplete and often subjective information during the evaluation.

Furthermore, we validate our evaluation model using published research data for a multi-criteria allocation decision making (MCDM) problem. Through the model validation, we show that the proposed evaluation model has the capability to solve MCDM problems. Lastly, a case study which involves three pieces of office furniture is used to illustrate the function of the proposed model.

To
my mother, Yuan-Fen Lin.

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Chapter 1

Introduction

1.1 Background on Remanufacturing

The average life cycle of consumer goods is continuously decreasing, while the amount of used products at their end of life (EOL) is accumulating fast at the same pace. Most EOL products end up in landfills, many of which are not biodegradable. These two challenges have necessitated renewed global interest in product EOL management strategies by manufacturers, consumers and governments. Some of these EOL strategies include reuse, recycling and remanufacturing. Of these strategies, remanufacturing is generally seen as the most environmentally friendly way of handling EOL products.

Remanufacturing is defined as the restoration of a used product to like-new-condition with regards to quality by replacing failed or old components, thereby renewing the value of used products [1]. By eliminating the use of resources and emissions associated with manufacturing new products, an OEM (original equipment manufacturer) could take credit for reducing their negative environmental impact. OEMs that remanufacture their products also improve profit margins through the reduced demand for virgin material. The selling price of remanufactured products is usually about 50—80% of a new one, therefore remanufacturing can be regarded as a win—win solution, saving both money and the environment [2].

Following the global interest in ecologically friendly manufacturing practices, there has been a trend to integrate industrial practice and research initiatives to achieve the optimal goal of making the world more sustainable. For instance, remanufacturing has been integrated with other aspects of manufacturing such as product design; Ijomah et al. (2007) proposed the idea of “Design for Remanufacture (DfRem) guidelines” [3], whereby new product designs are built with the intention to ensure that they are eventually remanufacturable. Sundin and Bras (2005) built up the “RemPro Matrix” strategy that links design considerations with specific stages of the remanufacturing process in order to facilitate the efficiency of functional sales [4].

On the other hand, some researchers proposed a way of adapting the existing design methods or tools to remanufacturing requirements. For example, Yuksel (2010) proposes a method that uses Quality Function Deployment (QFD) to address the “voice of the remanufacturer” when it comes to design requirements [5]. Bashkite et al. (2014) propose a method which integrates the “Theory of Inventive Problem Solving” (TRIZ) in order to generate design alternatives [6].

In addition to product design phase, the channel between remanufacturing and current supply chain is also a recognized subject. Sasikumar et al. proposed a multi-echelon reverse logistic model for product recovery using network design [7]. Ijomah and Chiodo (2014) suggest a way of improving remanufacturing productivity by using Active Disassembly Technology [8]. For the storage phase, Chung and Wee (2011) propose an integrated production inventory model based on the replenishment policy [9]. Some researchers also make an effort toward facilitating the remanufacturing process. For instance, Kurilova-Palisaitiene and Sundin (2014) point out the challenges as well as opportunities of remanufacturing by introducing lean process management techniques [10]; they also suggest the implementation of pull (Kanban) reordering system to fasten information flow with material flows together as a solution to uncertainties for remanufacturing [11].

Typically, remanufacturing involves the following fundamental processes: acquisition of used products, reverse logistics, disassembly, cleaning, storage, rework, assembly and testing [4]. These remanufacturing processes can be broken down further into process attributes such as labor, materials and overheads as shown in Figure 1.

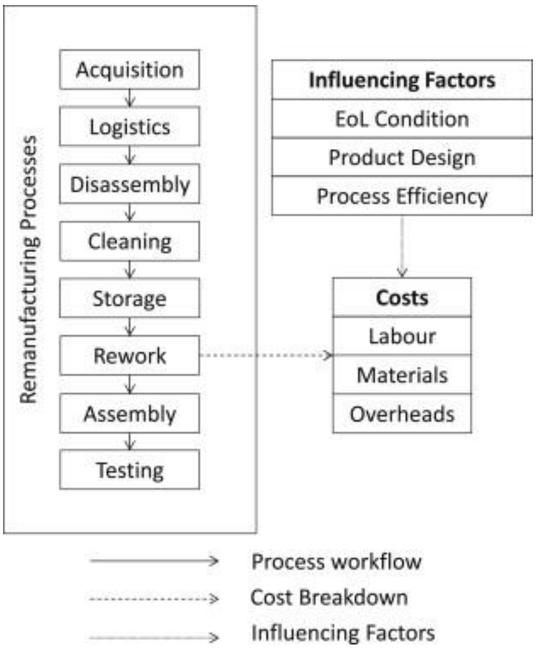

Figure 1. Breakdown of the generic remanufacturing processes with cost and the influencing factors shown for the rework stage [12]

In addition to the connection between remanufacturing and supply chain management, other researchers provide up-to-date status from the industries. For example, Tan et al. (2014) [13] and Zhang et al. (2011) [14] show us the current policies, regulations and the developing patterns with regards to government incentives. Furthermore, when it comes to decision making towards remanufacturing, the need for multi criteria decision making (MCDM) techniques are essential. In order to address various aspects efficiently, scholars use MCDM techniques to evaluate the economic and environmental indicators. For instance, Jiang et al. (2011) use the MCDM technique to evaluate six different criteria when selecting technology portfolio to optimize enterprise benefits [15]. Subramoniam et al. (2013) use MCDM to validate the Remanufacturing Decision Making Framework (RDMF) [16].

1.2 Remanufactured Product Sectors

Remanufactured products are normally seen to be good for business, customers and the environment, since they require fewer raw materials and consume less energy during the process. Remanufactured products also help manufacturers to avoid waste-related penalties by integrating waste back into the manufacturing cycle [17]. Typically, the remanufacturing sector was dominated by small, independent manufacturers [18]. However, in recent years, this sector has seen a growth in the number of original equipment manufacturers (OEMs). One of the OEMs, Caterpillar, a leading global manufacturer of earth-moving equipment, provides various types of remanufactured products and even came up with a slogan “Remanufacturing — A new era of profitability” in 2011 [16]. As estimated, the global annual turnover of the remanufacturing industry is about $85–$100 Billion [19]. Just U.S. alone, it accounts for $53 Billion per year and creates direct employments of around 480,000 in over 73,000 firms [18].

For enterprises, remanufacturing can be seen as a profitable business venture. With the appropriate selection of a target market, companies have the opportunity to expand across international markets by offering remanufactured quality goods at competitive prices. According to Steinhilper and Weiland (2015), the remanufacturing market is mostly divided into three sectors, namely, automotive, consumer products and investment goods, as shown in Figure 2. Within each sector, there are products with great potential to become a solid remanufacturing market [20].

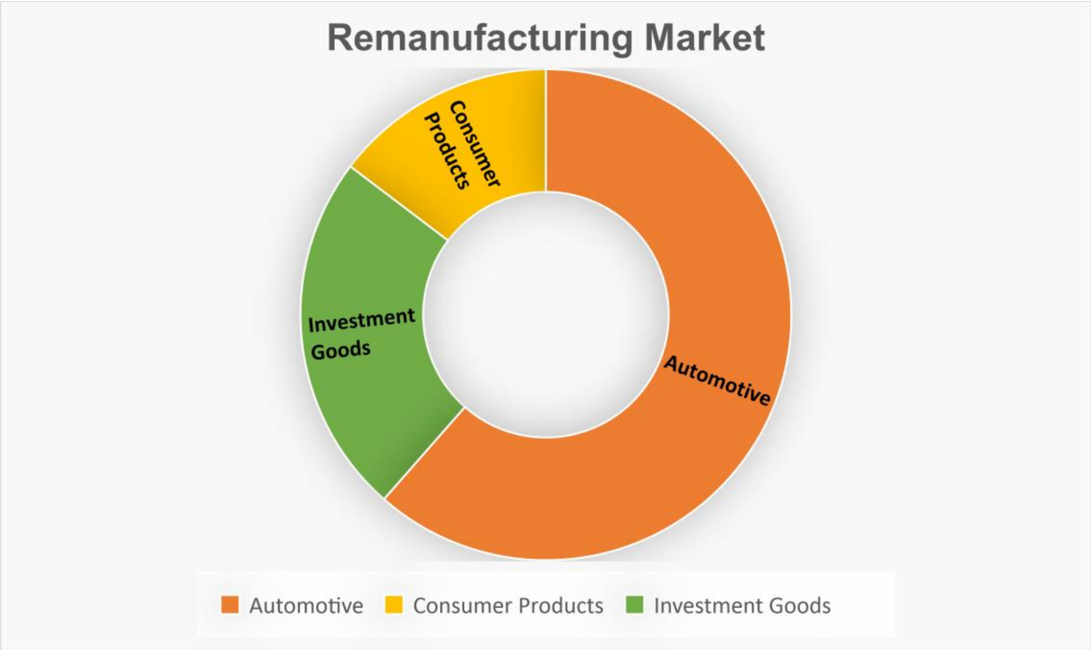

Figure 2. Three market sectors for remanufacturing [20]

As illustrated in Figure 2, the automotive industry accounts for approximately two-thirds of the global remanufacturing volume and is estimated to be $85-100 Billion industry worldwide. Based on the estimation of the Automotive Parts Remanufacturers Association (APRA), remanufactured automotive parts alone grossed $40 Billion in sales in the United States in 2010 [19]. Figure 3 illustrates the idea of reachable markets as well as market players in the automotive spare parts business, where remanufactured parts play a significant and growing role [20].

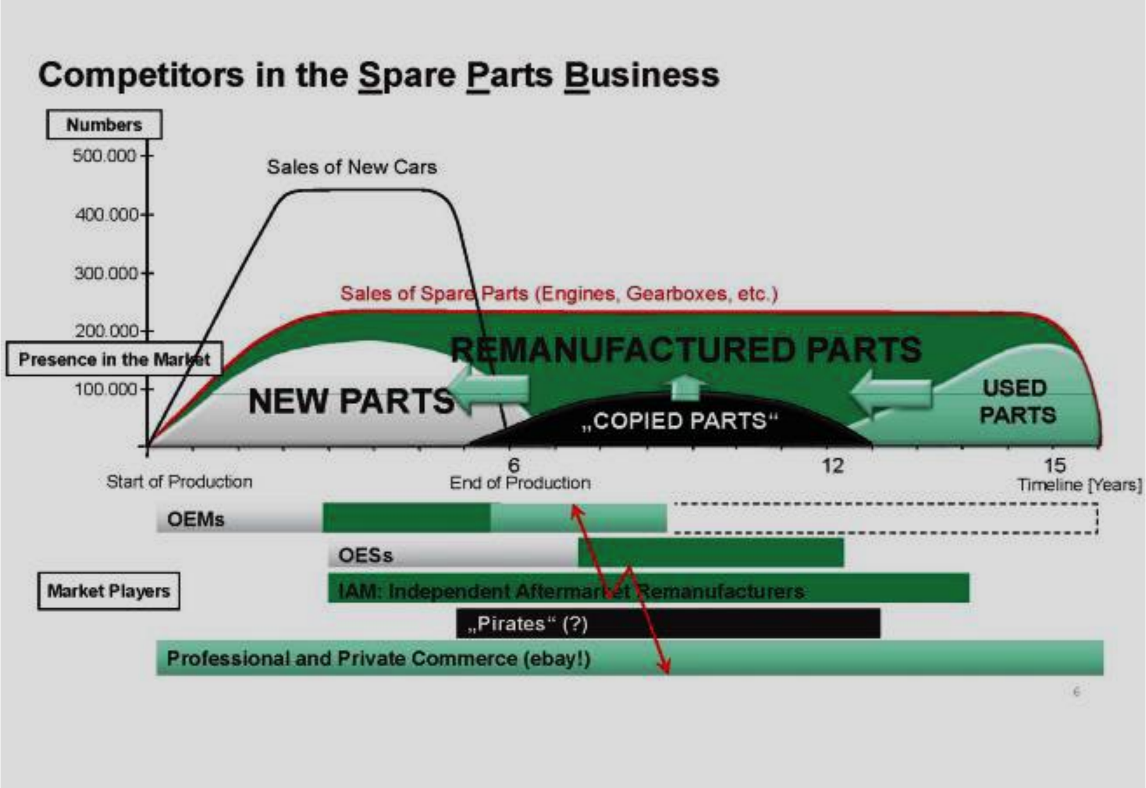

Figure 3. Market and market players for automotive spare parts [20]

Automotive remanufacturing market not only takes place in the U.S., but also in the European market. One example is heavy duty tires for trucks, off road vehicles and construction machinery. The European market for replacement of heavy duty tires is approximately 10 million units out of which remanufactured or retreaded tires share is 3.8 million of the business [20].

Another example of the high-value remanufacturing market is the aerospace industry. The remanufacturing market of the aerospace industry is growing steadily. Components like engines, hydraulics, landing gears and tires are widely remanufactured. Nevertheless, many of the components are remanufactured by the airline themselves instead of manufacturers, which is an interesting scenario in remanufacturing activities; because none of the other sectors are like the aerospace industry in which the user performs the remanufacturing [20].

For consumer goods, Information and Communication Technology (ICT) equipment is growing fast in the remanufacturing market these days. Adherence to policies like Waste Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substance (RoHS) are matters of current concern. These policies drive the companies to implement better use of material on hand as well as the development of the remanufacturing market. In addition, the fast accumulation of end-of-life ICT products fulfills the supply of parts inventory for the remanufacturing processes, therefore attracting companies to take part in this profitable business. For instance, products like computers, mobile phones and printers are commonly remanufactured. Most importantly, increasing demand for ink and toner cartridges—consumables for printers, makes them a promising products for the remanufacturing market. The difference between ICT products and other remanufacturing sectors shows on the market hierarchy, in that, there is a stratified market composed of high level consumers (who prefer new products) and lower level consumers who prefer to buy refurbished and remanufactured products [20].

For overall performance of different remanufacturing sectors, Chapman et al. (2010) have made some evaluations showing the value of each sector as illustrated in Figure 4. The evaluation also demonstrates refurbishment as well as other reuse status of each sector.

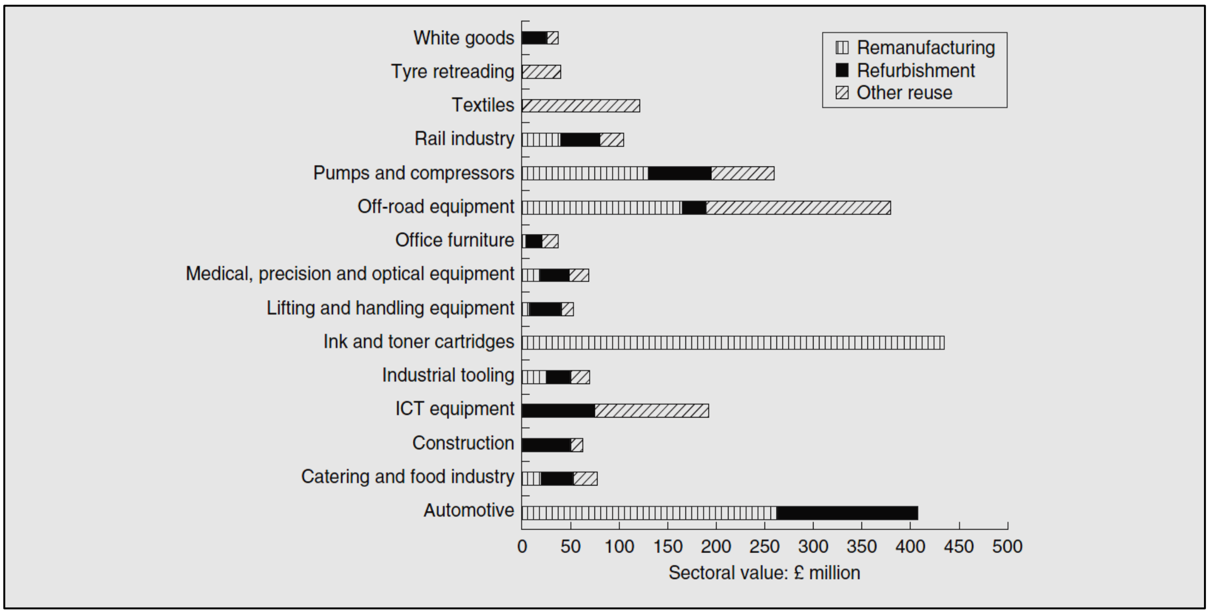

Figure 4. Remanufacturing and reuse value by sector (2010) [21]

In addition to the increasing market for remanufactured for the sectors mentioned in Figure 4, there are other sectors/products with potentially high growth markets that need to be discovered. The study done by Chapman et al. (2010) shows a matrix of overall potential growth versus the level of the remanufacturing value for some sectors as illustrated in Table 1.

Table 1. Evaluation of remanufacturing value with potential for growth [21]

Overall potential growth	***Current remanufacturing value***		
	Low	Medium	High
High	Medical, precision and optical equipment, Office furniture		Off-road equipment
Medium	Catering and food industry Industrial tooling Tire retreading White goods	Rail industry ICT equipment Textiles	Aerospace Pumps and compressors
Low	Lifting and handling equipment	Construction	Automotive Ink and toner cartridges

One of the high potential growing sectors is medical, precision and optical equipment whose products range from therapy equipment to imaging devices. For medical services, complicated equipment like MRIs, CT scanners and X-ray systems are mostly manufactured by a third party or a similar division within a larger OEM [20]. Due to its requirement of high-tech and large investment in product processing, the remanufactured products are also provided by the OEM themselves. Companies like Siemens, GE Healthcare and Philips offer remanufactured systems with warranties and service back-up as part of their business. As for optical equipment, such as microscopy products which are built to last for long periods, the usage phase for optical equipment ends when they become obsolete, either by being replaced by advanced technology or due to function degradation [21].

Office furniture, which is the key sector that we wilI base this thesis upon, has great potential to obtain high value remanufacturing market in the near future. This sector includes products such as seats, desks, storage units and small items, such as office partitions. Additionally, the service life of office furniture can last for upwards of 9 to 12 years. Despite their relative long service, office furniture is often replaced for reasons aside from damage or loss of function. Usually, the entire office suite is replaced rather than an individual piece unless severe damage occurs. The replacement is generally driven by office re-location, the need to change the corporate image among other reasons, thereby sending well-functioning furniture into landfills.

The remanufacturing market for office furniture is still at its initial stage. However, it has so far already held a market share of 9% of the total office furniture sale [21]. There are some examples showing that the practice can become a successful business model for a corporation. For instance, Kenwood Office Furniture provides remanufactured or reused furniture to the market as one of their profitable business strategies [22]. According to a report done by the Business and Institutional Furniture Manufacturers Association (BIFMA) in 2015, the value of U.S. office furniture market has continuously grown in recent years [23]. The need for better reclamation of end-of-life office furniture is obvious as well as the potential growth in the market, making the remanufacturing of office furniture a next frontier for the remanufacturing business.

Figure 5. Value of U.S. office furniture market value from 1994 to 2015 [23]

1.3 Furniture Industry

Furniture is a broad product group that encompasses various types of products such as chairs, tables, closets, shelves and others. Typically, the furniture industry is a labor-intensive industry with a predominance of small and medium-sized enterprises (SMEs). Based on an estimation done by the Center for Industrial Studies (CSIL), the global production of furniture was worth €361 Billion in 2012 (see Table 2). Their estimation data were collected from official sources, including both national and international covering the 70 countries which collectively account for 92% of the world's traded goods and most of the global furniture production.

Table 2. World furniture production [24]

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
€billion	233	230	248	268	279	278	264	299	321	361
Growth rates	-	3.0%	8.2%	7.9%	4.0%	-0.1%	-5.3%	13.6%	7.2%	12.4%

*Table 3. World furniture production, high vs. middle/low income countries** [24]

	2006	2007	2008	2009	2010	2011	2012
High-income countries, %	66%	62%	57%	51%	47%	45%	41%
Middle/low income countries, %	34%	38%	43%	49%	53%	55%	59%

Note: *High-income countries (e.g. United States, Italy, Japan…etc.)
Middle/low income countries (e.g. China, Poland, Vietnam…etc.)

Over the past decade, total world furniture production has increased annually except for the recent economic recession years of 2008 and 2009. In 2012, world furniture production volume was 60% greater than it was ten years prior in 2002. More specific analysis (see Table 3) shows that while volume increased in that period, the total share of the production volume from high-income countries has dropped from 66% to 41%. For the first time in 2010, the production shares of the middle/low income countries generated over half of the total world furniture production at 53%. There are two reasons behind this change:

- Emerging economies, such as Brazil and India, have a rapidly growing number of local suppliers in order to fulfill their increasing demand from their domestic markets, result in the increased share of the world furniture production.
- Outsourcing: When advanced economies seek for lower production cost, they tend to make productive investments in other growing economies. In fact, there are three countries that benefit from this kind of investment greatly, namely China, Poland and Vietnam, where production is growing rapidly because of the investments in new plants.

In recent years, there is an impressive growth of the Chinese furniture market rendering China to be the current leader of the global furniture production ($93.4 Billion as of 2016). At the present, 80% of the world’s furniture production is contributed to by ten countries, with China alone providing 40% of global production (see Table 4). United States ranks second and followed by Germany and Italy.

Table 4. World furniture production, top 10 producing countries, 2003 and 2012 [24]

	2003		2012	
Country	€billion	%share	€billion	%share
China	22,555	10%	145,318	40%
USA	60,677	27%	51,642	14%
Germany	15,492	7%	17,738	5%
Italy	19,388	9%	15,950	4%
India	5,386	2%	11,624	3%
Japan	11,925	5%	10,743	3%
Poland	4,393	2%	8,323	2%
Canada	8,385	4%	8,262	2%
Brazil	3,168	1%	7,970	2%
France	7,817	4%	7,929	2%
Top 10	159,137	71%	285,499	79%
Others	63,877	29%	75,363	21%
World	**223,014**	**100%**	**360,862**	**100%**

In addition to the change of the leading role of China in global furniture production, a growing degree of market openness is observed in the past decade in the country, resulting in the rapidly increasing international trade of furniture (see Table 5). The fast increasing is due to several factors such as: trade agreements among nations, expansion of retail chain at international level and improvements in logistic [24][25]. Figure 6 shows the international furniture trade carried out within each economic region.

Table 5. World furniture trade [24]

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
€billion	59.0	63.7	69.2	75.9	81.8	81.6	70.0	82.8	86.8	98.1
Growth rates	-	8%	9%	10%	8%	0%	-14%	18%	5%	13%

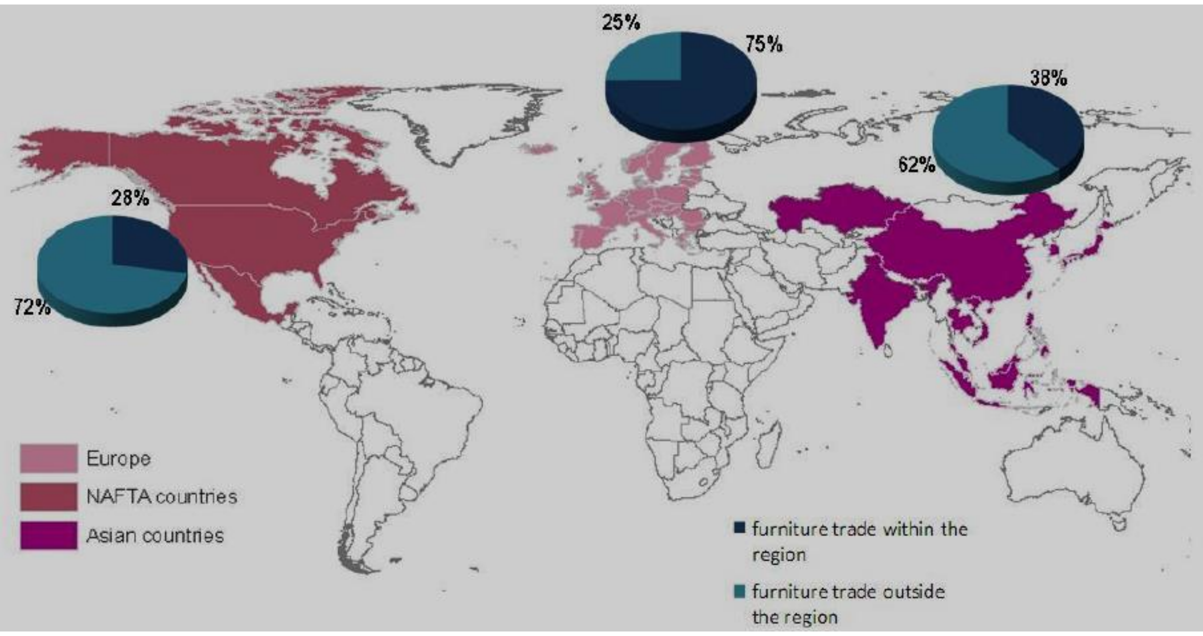

Figure 6. Percentage of global furniture trade carried out within each economic region [24]
*Note: *North American Free Trade Agreement (NAFTA)*

As illustrated in Figure 6, there is a great portion of the U.S. furniture trade that is outside of its own reign due to the profound impact of the global market openness. According to the United States International Trade Commission (USITC), total U.S. furniture imports grew dramatically from $1,115.3 million in 1997 to $ 5,7075.4 million in 2007 [26]. As a result, the production value of the U.S. furniture industry has dropped in the past decade because of the accumulating dependency on imports from low labor cost suppliers, particularly from East Asia [24]. At the present, the U.S. furniture industry is mainly concentrated in two geographic locations: Great Lakes region encompassing Michigan, Indiana, Ohio, Wisconsin and Illinois and the Southeast region that includes North Carolina, Mississippi and Virginia [24].

Irrefutably, the economy recession had a negative impact toward U.S. furniture industry when consumers lessen their spending on non-essentials. Nevertheless, recent statistics has shown upticks on both production value and furniture sales as shown in Figures 7 and 8 [27][28].

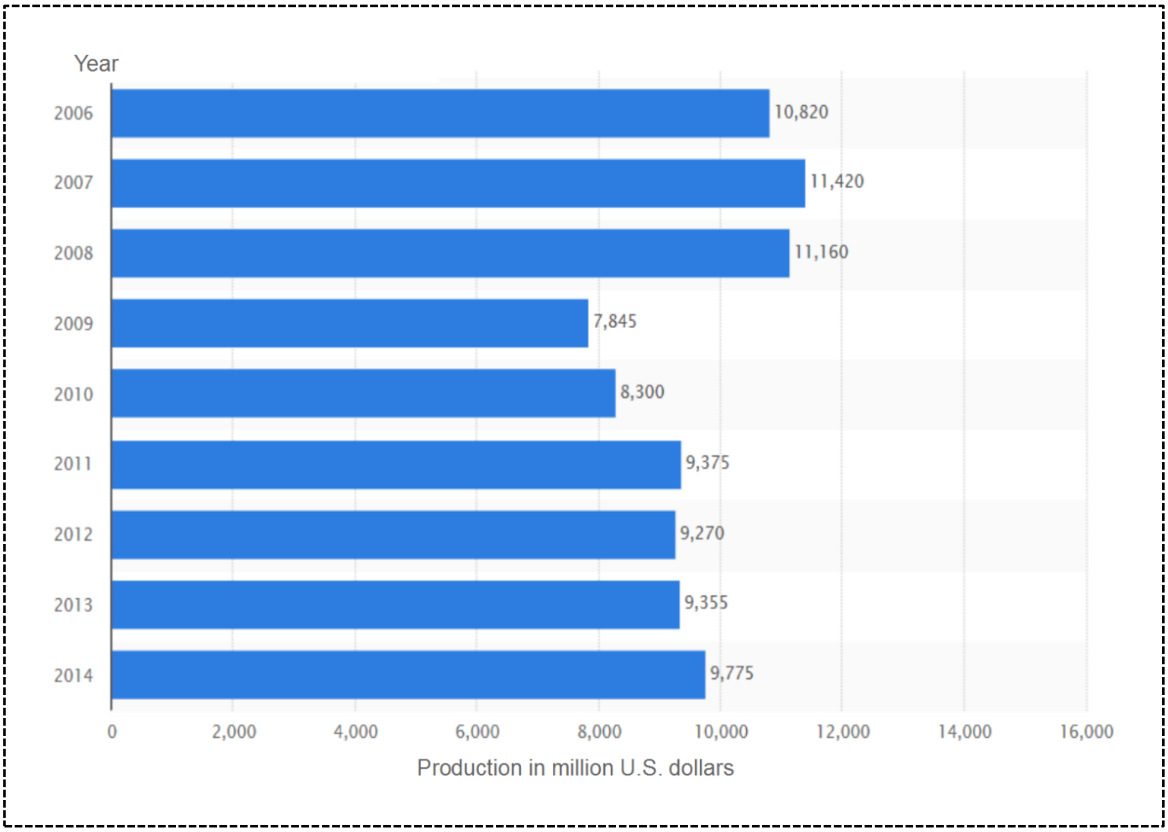

Figure 7. Production value of office furniture manufacturers in the United States in recent year (in million U.S. dollars) [27]

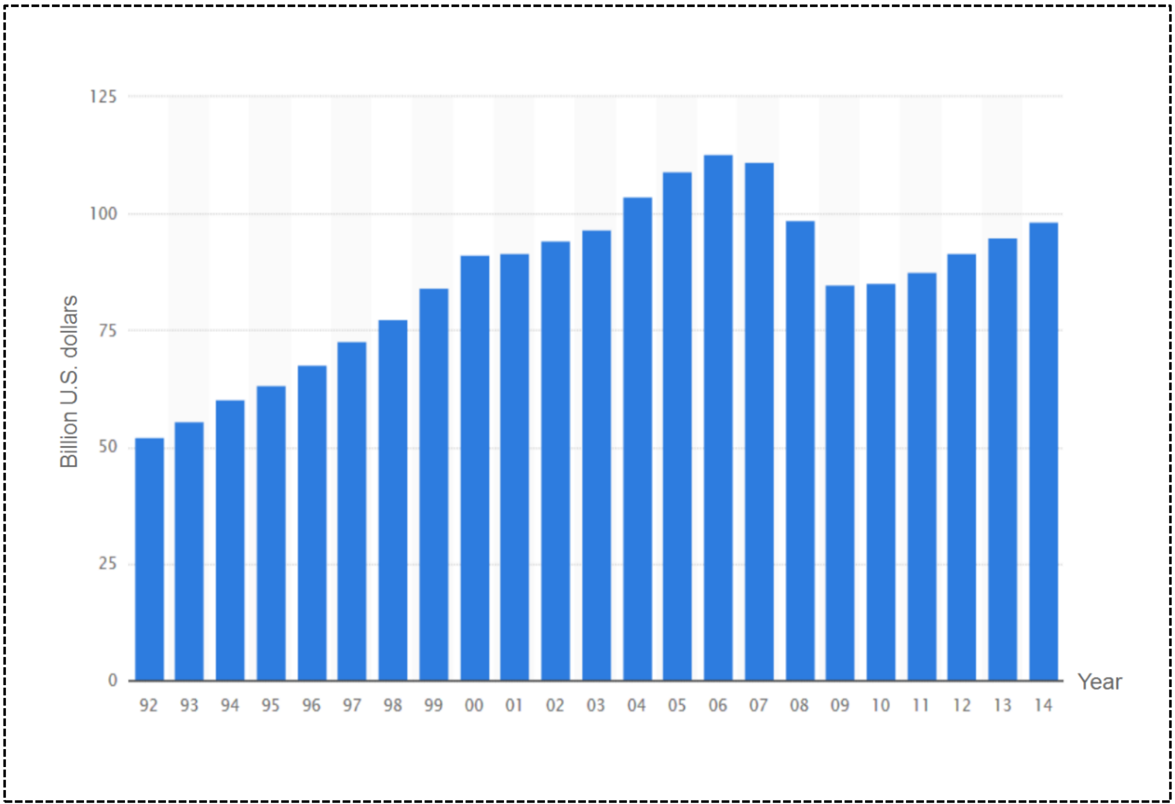

Figure 8. Furniture and home furnishings store sales in the United States from 1992 to 2014 (in Billion U.S. dollars) [28]

The demand for furniture has also increased because of the shifting consumer preference and new innovation. Followed by the uptick in recent years, there are several essential trends emerging from the furniture industry [29].

1. *Demand for home office furniture is rising*: The need for home offices has been on an increase following the financial crisis years of in 2007 and 2008, as well as the subsequent European debt crisis of 2009.
2. *Multi-functional, versatile furniture becomes popular in the market*: Following the increased number of small households, small and portable furniture has been obtaining popularity among the middle class. Consumers have increased preference towards furniture with multi-purpose, foldable and technology-driven, especially when considering living in the smaller spaces.
3. *The fast-growing online purchasing channel*: Online purchasing has become a shopping pattern and the fastest-growing channel in developing markets. Companies are putting efforts on their online retail stores, by offering incentives like easy to assemble, free delivery or two-day shipping.
4. *Demand for luxury furniture is increasing*: As the economy has improved, the willingness for consumers to buy luxury items for work and living environments has increased at the same time.
5. *Furniture vendors are choosing to go green*: More and more venders are developing eco-friendly furniture in order to satisfy consumer preference which driven by environmental concerns such as deforestation. Even with the relative expensive price of eco-friendly furniture, the demand for

such product is still rising, motivating the manufactures and companies to provide these products.

As the global furniture markets have become more complex and demanding, the purchasing criteria for consumers have also changed. Traditional factors like price, quality, branding and uniqueness still exist [30]; however, non-traditional factors like environmental impact, sustainable products and ergonomics are consumers' new concerns [31]. In order to catch up with the changing preferences on the markets, companies have to make their products distinguishable from other competitors. Therefore, innovative concepts have been applied to address various aspects.

Particularly, the implementation of eco-design has been considered as an opportunity for differentiating their products [25]. Eco-design or design for environment (DfE) is a concept that integrates multifaceted aspects of design and environmental considerations. Based on the concept, companies examine the life cycle of a product and try to find a way that makes the product greener thus environmentally benign. Chaves (2008) proposes a design guideline for furniture sustainability which applies Life Cycle Assessment (LCA) and environmental indicators when addressing environmental concerns [32]. Costa et al. (2015) develop a sustainable Product Service System (PSS) design for furniture manufacturer. The methodology applied LCA to analyze environmental impact at each product life cycle stage and share the information between product take-back phase and the design phase in order to obtain the sustainable system for furniture manufacturing [33]. With the change of consumer preference, future furniture designs will be different from todays; but one thing can be sure, as long as the environmental issues still attract people's attention, the environmental concerns in furniture design will need to be addressed.

The goal of this study is to present a framework that assesses the remanufacturability of furniture, using office chairs and desks as case illustrations. To accomplish this goal, we use Fuzzy TOPSIS, which helps to deal with imprecise subjective information when evaluating the potential of office furniture for remanufacture. In Chapter 2, we present a review of literature regarding the remanufacturing process as well as decision support systems and tools in remanufacturing. In Chapter 3, a detailed description and steps of our proposed evaluation model are presented. We use previously published data in Chapter 4 to validate our model, hence prove its capability for solving multi-criteria decision making problems. Additionally, a case study is presented in the same chapter. Finally, results discussion and concluding remarks are presented in Chapter 5.

Chapter 2

Literature Review

2.1 Environmentally Conscious Manufacturing and Product Recovery

The concept of Environmentally Conscious Manufacturing and Product Recovery (ECMPRO) had been brought up in the 1900s. The idea hadn't gained popularity until the growing awareness in preventing negative impact towards the environment [34]. Driven by the environmental concerns and regulations, manufacturers and consumers begin to produce and dispose products in an environmentally responsible manner. As a result, the need for developing studies of reducing environmental impacts towards product life cycle is increasing. Concepts like product life cycle can provide a holistic view of the material flow and information flow within each stage as illustrated in Figure 9 [35].

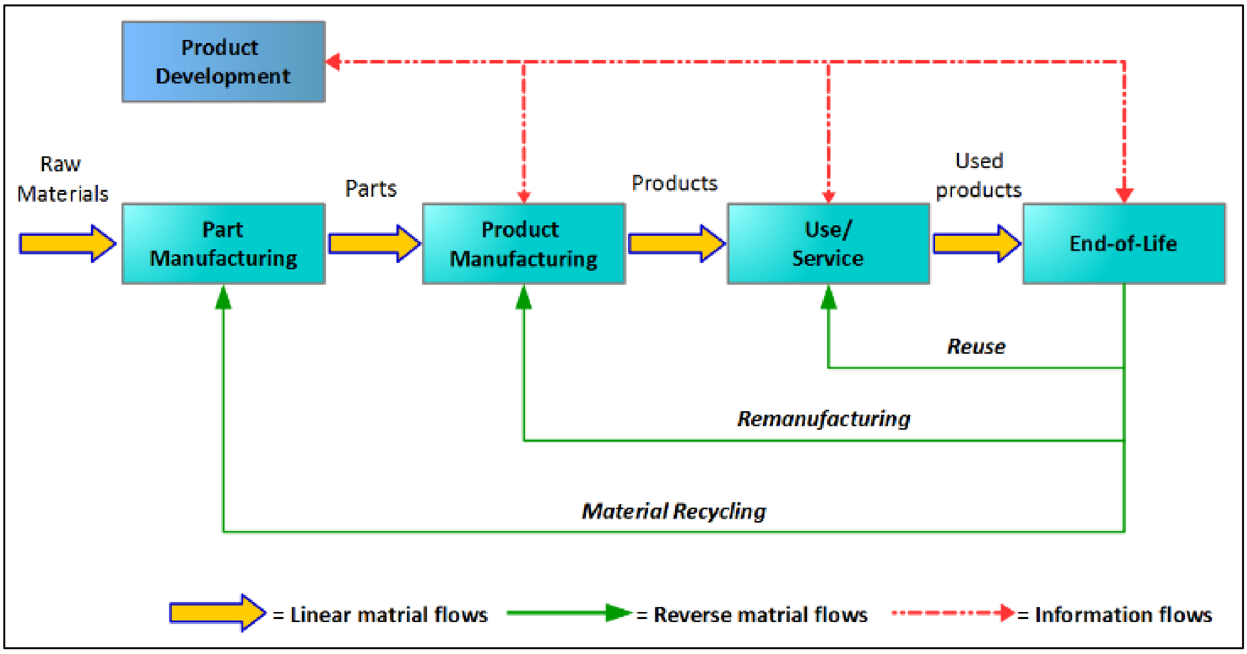

Figure 9. Product life cycle [35]

2.2 Remanufacturing

Remanufacturing, as parts of the ECMPRO has been considered the most environmental friendly EOL treatment for the retired products. Generally, remanufacturing is an industrial process that involves converting worn-out products to like-new conditions [1]. In remanufacturing, retired products (cores) are first collected and then disassembled, parts are repaired and ultimately reassemble to like-new condition. Different from the traditional manufacturing, remanufacturing benefits the environment by lessening the consumption of energy as well as virgin material. However, the high variability of the remanufacturing operations makes it difficult to apply the traditional operation management techniques [34]. As a result, researchers have made efforts developing new methodologies to improve the practice of remanufacturing.

2.2.1. Design for remanufacturing

The concept of design for remanufacturing (DfRem) resulted from the recognition that many of the technical barriers to remanufacturing practice can be related back to how the product was designed [3]. Remanufacturing processes like disassembly cannot be carried out efficiently and effectively if they are not accommodated at the first place when designing the products. Generally, the goal of DfRem is to improve the remanufacturability of the products. In order to do that, a designer needs to consider each step in remanufacturing, and address the concerns from various aspects to design the product appropriately for ease of remanufacture. As a result, many research initiatives have involved the analysis of remanufacturing issues with respect to product design and further developed the design aids such as tools, methods and approaches to help improve DfRem. For instance, DfRem metrics were developed by Bras and Hammond (1996) which focus on finding technical as well as quantitative solution for DfRem [36]. However, other researchers appear to focus on suggesting familiar design methods with improved qualitative guidance to designers. The advantage of utilizing widely-known methods such as QFD (Quality Function Deployment) and modularization is that the designer may already familiar with them because of past experience or related knowledge. Table 6 shows the summary of DfRem research methodologies [37].

Based on the study done by Ijomah et al. (2011), both the industrial practitioners and literature by academics mostly focus on the automotive, electronic product or ink cartridge, as illustrated in Figure 10. None of the existing literature focuses on the remanufacture of office furniture, and this thesis is produced in a bid to fill this research gap.

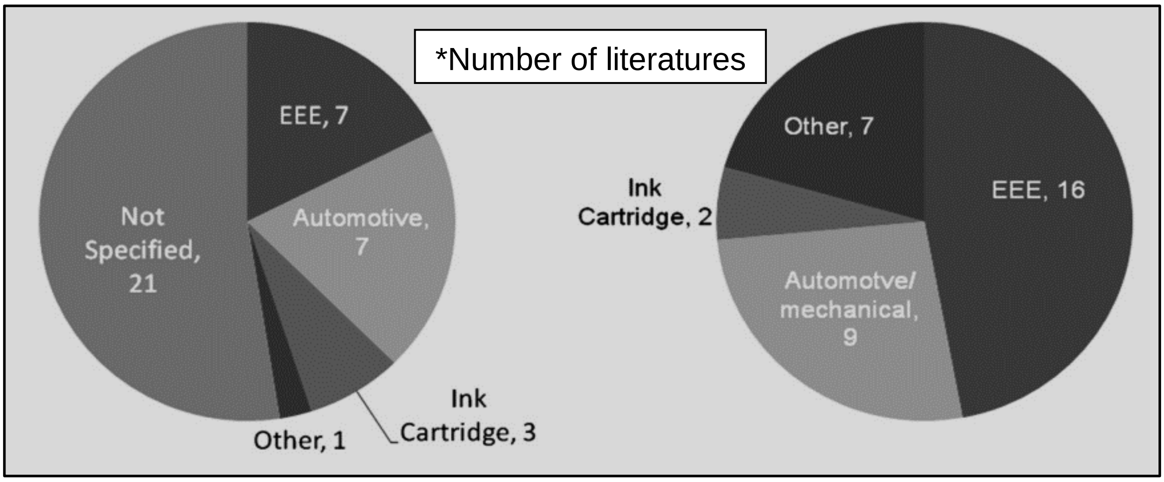

Figure 10. Industry sectors studied in the DfRem literature (left) and case study examples present in DfRem literature (right) [37]

Table 6 Summary of DfRem research methodologies [37]

Approach	Author (s)	Methodology	Industry Sector	Perspective
DfRem metrics	Bras and Hammond (1996); Amezquita et al. (1995)	Survey	Unknown	Remanufacturer
Fastening and joining selection	Shu and Flowers (1999)	Case study	EEE and ink cartridge	Remanufacturer
RemPro matrix	Sundin (2004)	Case study	Unknown	Remanufacturer
REPRO2	Zwolinski et al. (2006); Zwolinski and Brissaud (2008); Gehin et al. (2008)	Analysis/theoretical	Wide range	Designer (theoretical)
DfRem guidelines	Ijomah et al. (2007a,b); Ijomah (2009)	Case study	Various	Remanufacturer
DfRem metrics	Willems et al. (2008)	Unknown	Unknown	Unclear
Hierarchical decision model	Lee et al. (2010)	Unknown	Unknown	Unclear
Energy comparison tool	Sutherland et al. (2008)	Analysis	Automotive	Unclear
Component reliability assessment	Zhang et al. (2010)	Analysis	Automotive	Remanufacturer
Modularisation	Ishii et al. (1994); Kimura et al. (2001)	Theoretical	Unknown	Designer (theoretical)
FMEA	Lam et al. (2000); Sherwood and Shu (2000)	Case study	Automotive	Remanufacturer
Platform design	King and Burgess (2005)	Unknown/theoretical	Unknown	Unclear
Active disassembly	Chiodo and Ijomah (2009)	Various	EEE	Remanufacturer
Design for environment tools	Pigosso et al. (2009)	Literature review	Unknown	Unclear
QFD	Yuksel (2010)	Interviews	Automotive	Remanufacturer

2.2.2. Reverse logistic

Reverse logistics refers to practices related to the collection, recovery or disposal of used products, the goal is to make aftermarket activities more efficient and eventually save money as well as natural resources [38]. Typically, forward logistics deal with events that bring the product to the customer. Reverse logistics, on the other hand, moves backwards in the supply chain by delivering the used goods from the customer to the distributor or manufacturer. Driven by the demanding environmental regulations and diminishing natural resources, the essence of reverse logistics has intensified. Additionally, practices of reverse logistics have a strong impact on the operations of forward logistics like inventory management, labor capacity allocation and transportation. Because of this interdependence, the closed-loop supply chain which considers both forward and reverse supply chain has gained interest with people as an alternative of cost-efficient reverse logistic management [34].

In the remanufacturing processes, product acquisition management is one important issue since the input of the remanufacturing are the retired products (cores). The uncertain nature (quantity, quality, and supply and demand timings) of remanufactured products makes it difficult to manage and requires effective policies and strategies. Furthermore, an uncontrolled acquisition of used products may result in excessive inventory levels or low customer satisfaction. Generally, there are two ways to deal with product acquisition problems: waste stream system and the market-driven system [39]. In waste stream system, the government legislation drives firms to accept retired products from the waste stream. On the other hand, market-driven system utilizes financial incentives as a trigger, motivating users to return their products to the firm.

At present, there are various financial incentives been employed by firms including deposit systems, i.e. cash paid for a specified level of quality and credits toward a new unit [40]. Therefore, the implementation of these incentives becomes the main research issue in product acquisition management. Wojanowski et al. (2007) came up with a deposit refund system which requires payment of a certain deposit at the time of purchase, then refund the deposit when it is returned [41]. For quality oriented incentives, Guide and Van Wassenhove (2001) propose an implementation of a quality-dependent incentive policy in which pre-determined prices are offered for products with a specific quality level [40]. Kaya (2010) propose an optimal incentive value by considering stochastic demand and partial substitution between original and remanufactured products [42].

Overall, the core acquisition of the remanufacturing deal with various types of incentives as well as different categories. How to obtain the optimal acquisition management is still on going. However, it is important to address core acquisition when practicing remanufacturing.

2.2.3. Disassembly

Disassembly is another key operation in remanufacturing which is defined as the systemic separation of products' components, subassemblies or other groupings [43]. There are two major phases of disassembly namely, scheduling and sequencing.

For scheduling in disassembly, timing and cost of the process is of greatest concern. Gupta and Taleb (1994) propose a scheduling algorithm used for disassembling a discrete, well-defined product structure. The algorithm helps to decide the quantity as well as timing of disassembly operation for a single product in order to fulfill the demand for its various parts [44]. Lee and Xirouchakis (2004) suggest a two-phase heuristic algorithm aims at minimizing various costs related to the disassembly process [45]. Kim et al. (2003) present a heuristic algorithm that deals with multiple product types with parts commonality and try to minimize the setup cost, disassembly operation cost and inventory holding cost [46].

Disassembly sequencing focuses on determining the best order of operations when separating a product into its constituent parts or sub parts [47]. Similar to scheduling, sequencing for disassembly is also concerned with timing as the main decision metric. Various methodologies have been made to minimize the sequencing steps and improve the overall process efficiency. Kaebernick et al. (2000) propose a method using cluster graphs to solve sequencing problem. The cluster graph is created by sorting the components of a product into different levels based on their accessibility for disassembly [48]. Lambert (2006) present a methodology which employs Binary Integer Linear Programming (BILP) to deal with sequence-dependent costs and disassembly precedence graph representation [49]. Tripathi et al. (2009) develop an Ant Colony Optimization (ACO)-based metaheuristic to obtain the optimal disassembly sequence and the level of disassembly. In their study, a fuzzy disassembly sequencing problem was formulated with respect to the uncertainty inherent in quality of the returned products [50].

In all, the main objective of scheduling and sequencing in remanufacturing as presented in the above brief review, is aimed at improving the operation of deconstructing the collected cores. Both of them are utilized to methods to reduce process complexity as well as the number of required steps thus saving the time and cost of disassembly.

2.3 Furniture Research

Most of the products studied in the environmentally conscious manufacturing and product recovery (ECMPRO) are electronic devices and automotive. There is a dearth of research addressing the remanufacture of furniture, despite their great potential as a successful business venture. Our literature review realized that Life Cycle Assessment (LCA) is the relatively common practice objective quest for furniture related research with respect to environmental considerations. Babarenda Gamage (2008) propose a case study of an office chair [51]. The study analyzed the life cycle of the office chair and developed an improved design alternative. Iritani et al. (2015) analyzed sustainable strategies using LCA techniques for assessing the environmental performance of a wardrobe. The output of the analysis generated two sustainable strategies for the product [52].

Nevertheless, there are several literature records that address sustainability of the design of furniture. Chaves (2008) propose a method for the development of design and environmental sustainability tools focusing on furniture [32]. The study was divided into three steps: LCA, Environmental Design Priority Indicators (EDPI), and the guideline generation through a participatory research. González-García (2011) assesse various types of wooden products in order to obtain their LCA result and further utilized their results to generate improved eco-design stratagies for different products [25]. Costa et al. (2015) combined service design principles and LCA to conceptualize sustainable Product Service System (PSS) models for both office furniture design and manufacturing company (as a system) [33].

For other furniture research regarding green aspects of furniture production, there are papers aim at the willingness of customers to purchase environmentally conscious-manufactured products and the incentives that motivates the customers to buy greener furniture. Knauf (2015) propose a multi-model market research on consumer attitudes towards different materials used in the furniture [53]. He concludes that consumers tend to connect heavy weight material with high durability. However, after addressing the environmental benefit of other material, consumers show the willingness to forego the durability of metallic structures for environmentally friendly furniture. Abbey et al. (2015) present a study that shows the willingness of a consumer to purchase remanufactured household product has high correlation with product discount, especially for the consumer segement that is interested in product functionlity [54].

2.4 Multi Criteria Decision Making (MCDM)

Environmentally conscious manufacturing aims at using resources efficiently as well as reducing the generated waste and emissions through the entire product life cycle. Product recovery is another practice that helps improve sustainability by reducing the consumption of virgin material and energy. Both of these practices have to deal with strict environmental regulations, society expectation and customer requirements. Moreover, since various kinds of indicators need to be included in the process, Multi Criteria Decision Making (MCDM) techniques appear to be the appropriate tool for implementation. MCDM helps the decision maker to compare attributes of different indicators or criterion towards the generation of alternatives, especially when elements are imprecise or vague. In this section, we only present the techniques related to our work, namely fuzzy set theory, fuzzy analytical hierarchy process and fuzzy TOPSIS. For the better understanding of the MCDM techniques, we refer the reader to the study by Ilgin and Gupta (2010) [34].

2.4.1. Fuzzy Set Theory

Fuzzy set theory is one of the techniques used to process input data that is seldom incomplete and vague i.e. devoid of crisp values. The methodology was first introduced by Zadeh in 1965 [55]. In contrast to crisp sets which give clear binary in-or-out membership, fuzzy sets allows partial degree of membership into a classification. In classical theory, the common formats of a membership include binary value such as 0 or 1, Yes or No, True or False which means a variable within the set cannot belong to other sets. Fuzzy set theory uses variables with a range of real number values such as [0,1]. If the value assigned is 0, the variable does not belong to the set (i.e. no degree of membership). If the value assigned is 1, the variable belongs completely to the set (it has complete membership). Finally, any value assigned in between is considered a partial membership [56]. The level of the membership function can be measured by a numeric, categorical or linguistic variable. A linguistic variable is a variable whose values are words or phrases in a natural or artificial language [57]. For example, speed is a linguistic variable if its values are assumed to be the fuzzy variables labeled fast, not fast, very fast, not very fast, etc. It is however numeric if it given as 0, 10, 20, 30, etc., and categorical if entered as {0-10}, {11-20}, {21-30}, etc. The idea of linguistic variables provides an approximate characterization of phenomena which are too complex or poorly-defined to be described in conventional quantitative terms.

A fuzzy number $\widetilde{M}$ is a convex normalized fuzzy set such that $\widetilde{M} = \{(\chi, \mu_{\widetilde{M}}), \chi \in R\}$, where χ takes its values from the real line, $R: -\infty < \chi < +\infty$, and $\mu_{\widetilde{M}}$

is a continuous mapping from R to the closed interval membership degree $[0,1]$. Fuzzy numbers are usually defined within Membership Functions (MFs). Most commonly used fuzzy membership functions include triangular, trapezoidal, sigmoidal and Gaussian as shown in Figure 11 a, b, c, and d [58].

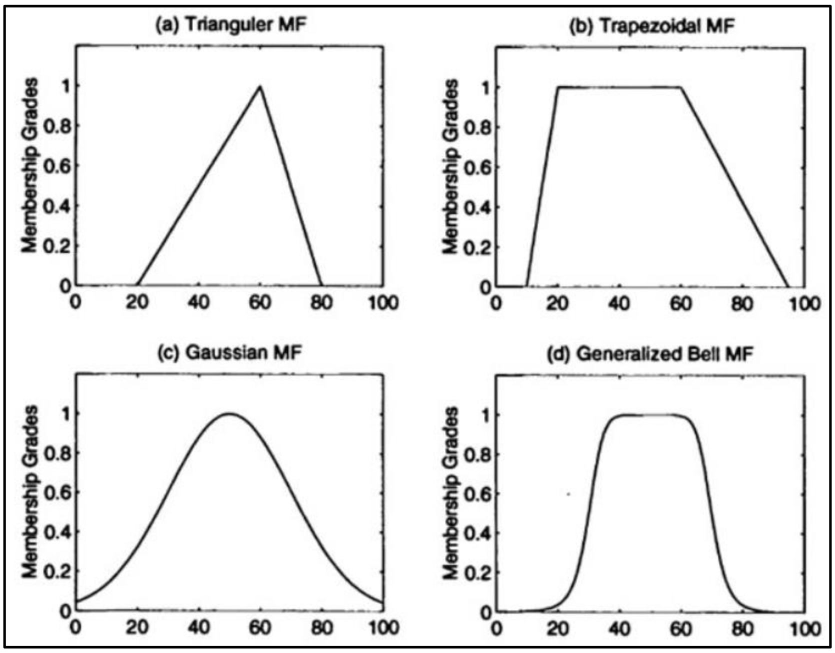

Figure 11. Examples of four classes of parameterized MFs: (a) triangular (x; 20, 60, 80); (b) trapezoidal (x; 10, 20, 60, 95); (c) Gaussian (x; 50, 20); (d) bell-shaped (x; 20, 4, 50) [58]

Triangular fuzzy numbers (TFN) are commonly used due to their computational simplicity and usefulness for information processing in the fuzzy environment. Triangular fuzzy numbers can be defined as a triplet (l, m, u) shown in Figure 12. The parameters l, m, u respectively indicate the smallest possible value, the most promising value, and the largest possible value that describe a fuzzy event [59].

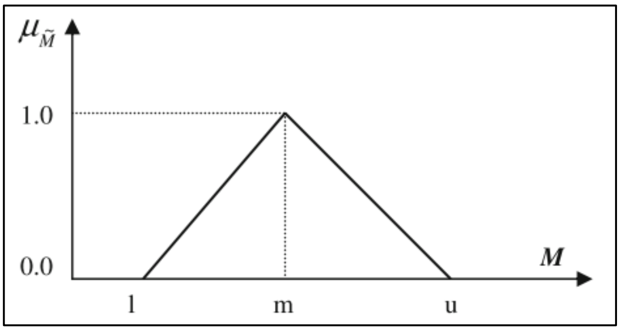

Figure 12. Triangular fuzzy number [59]

There are various operations on TFNs. We only list main operations for positive fuzzy numbers. Let two positive triangular fuzzy numbers be $\tilde{a}$ and $\tilde{b}$ parameterized by triplet (l_1, m_1, u_1) and (l_2, m_2, u_2) then [60]:

$$\tilde{a}(+)\tilde{b} = (l_1 + l_2,\ \ m_1 + m_2,\ \ u_1 + u_2)$$

Equation 1

$$\tilde{a}(-)\tilde{b} = (l_1 - l_2,\ \ m_1 - m_2,\ \ u_1 - u_2)$$

Equation 2

$$\tilde{a}(\times)\tilde{b} = (l_1 \times l_2,\ \ m_1 \times m_2\ ,\ \ u_1 \times u_2)$$

Equation 3

$$\tilde{a}(/)\tilde{b} = (l_1/u_2,\ \ m_1/m_2\ ,\ \ u_1/l_2)$$

Equation 4

$$\tilde{a}^{-1} = (l_1, m_1, u_1)^{-1} = (\frac{1}{l_1}, \frac{1}{m_1}, \frac{1}{u_1})$$

Equation 5

$$\tilde{a} \cdot k = (l_1 \cdot k,\ \ m_1 \cdot k,\ \ u_1 \cdot k), k \in R | k > 0$$

Equation 6

The distance between two triangular fuzzy numbers can be calculated by the vertex method [61]:

$$\mathrm{d}(\tilde{a}, \tilde{b}) = \sqrt{\frac{1}{3}[(l_1 - l_2)^2 + (m_1 - m_2)^2 + (u_1 - u_2)^2]}$$

Equation 7

2.4.2. Fuzzy analytic hierarchy process

The analytical hierarchy process (AHP) is a multi-criteria decision making tool proposed by Saaty (1980) [60]. AHP uses simple mathematics to support decision makers in weighting definite and intangible criteria against each other. It helps in determining the relative importance of a set of activities in a multi-criteria problem. The method has been widely used by decision makers and researchers since its initial proposal. However, two characteristics of applying AHP in crisp environments are often criticized in the literature: (1) its use of unbalanced scales of judgment and (2) the absence of uncertainty [62]. Therefore, Van Laarhoven and Pedrycz (1983) employed a fuzzy approach in the AHP to overcome the limitations [61]. The newly developed method utilizes linguistic variables to deal with decision makers' uncertain judgments. A diagram of fuzzy AHP are illustrated in Figure 13 [63].

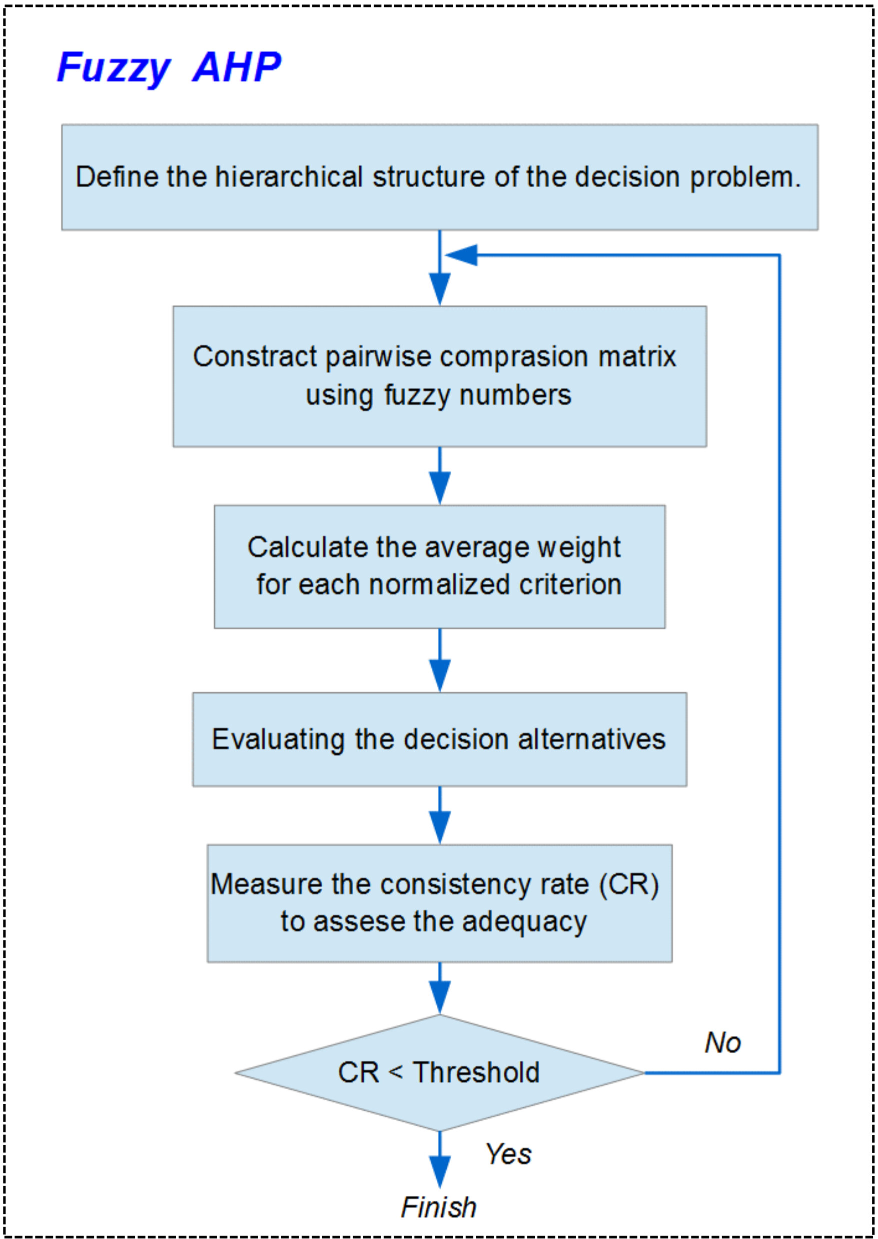

Figure 13. A diagram of fuzzy AHP [63]

At present, fuzzy AHP has become one of the most employed tools in solving ECMPRO problems, especially when it comes to dealing with various criteria for evaluating complex hierarchy problems. Yu et al. (2008) develop a method that uses fuzzy AHP to determine the most suitable recycling option for EOL products with respect to three different criteria: environmental impact, cost of recycling and recoverable materials [64]. Other researchers like Lu et al. (2007) [65], Grisi et al. (2010) [66], Ciftci and Buyukozkan (2011) [67], use fuzzy AHP to solve supplier selection problems regarding environmental factors. Chiou et al. (2012) present a method for selecting the most important criteria in reverse logistic implementation by using fuzzy AHP [68].

2.4.3. Fuzzy TOPSIS method

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method was first proposed by Hwang and Yoon (1981) [69]. The basic precept of their method was to rank the alternatives based on their closeness to both the positive ideal solution (PIS) and the negative ideal solution (NIS). The finest alternative should have the shortest distance from the PIS and the farthest distance from the NIS. In classical TOPSIS, the weights of the criteria are assigned with crisp values. However, in reality human preferences are uncertain and decision-makers might be reluctant or unable to assign crisp values when comparing alternatives [70]. As a result, fuzzy TOPSIS was developed by Chen et al. (2006) to mitigate the influence of human uncertainty when evaluating alternatives [71]. This improved method employs linguistic variables for assessing the weight of criteria and the ranking of alternatives. A detailed flowchart of the fuzzy TOPSIS method is shown in Figure 14.

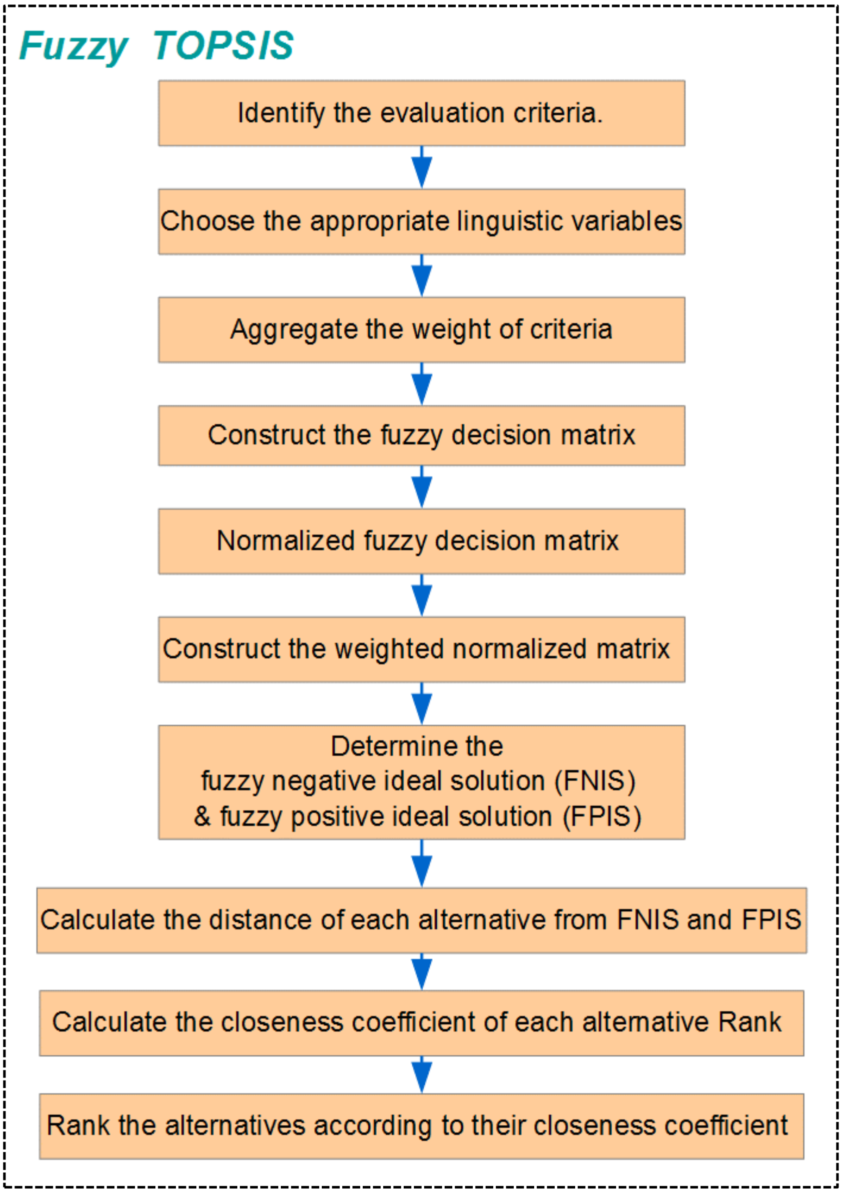

Figure 14. Flowchart of fuzzy TOPSIS [71]

Fuzzy TOPSIS has proven to be one of the most useful techniques in a variety of decision making problems [72]. Gao et al. (2010) develop a fuzzy TOPSIS model to serve as a design guideline for green products which considers various environmental factors and functionality [73]. Yeh and Xu (2013) implement fuzzy TOPSIS for evaluating recycling activities with respect to factors such as potential market margin, green technology innovation and safety at workplace [74]. Awasthi et al. (2010) use fuzzy TOPSIS to measure environmental performance of suppliers [75]. Kannan et al.

(2009) presented methodology that integrates interpretive structural modeling and fuzzy TOPSIS for selecting the best third party reverse logistics provider [76].

2.4.4. Comparison of fuzzy AHP and fuzzy TOPSIS methods

Both fuzzy AHP and fuzzy TOPSIS have been widely used in multi-criteria decision making processes and multi-criteria evaluation. However, each of them has its own features that render them better for certain applications. As the result, a suitability comparison has to be made in order to find the appropriate methodology to employ.

Based on the study done by Ertuğrul and Karakaşoğlu (2008), they employed both fuzzy AHP and fuzzy TOPSIS on the same facility location problem and tried to compare the generated results as well as the working processes of these methods. A brief summary of the differences and similarities between fuzzy AHP and fuzzy TOPSIS is given as follows [72]:

- When it comes to the amount of computations, fuzzy AHP requires more complex computations than fuzzy TOPSIS.
- Pair-wise comparisons for criteria and alternatives are made in fuzzy AHP, while there is no pair-wise comparison in fuzzy TOPSIS [77].
- TOPSIS does well in addressing rank reversal issue which means no optimal alternative is introduced during the ranking process.
- Fuzzy AHP is preferable for widely spread hierarchies compared with fuzzy TOPSIS.

- In the analysis of fuzzy AHP, the priority weight of criterion or alternative could be equal to zero. It means the criterion or alternative has not been considered. This is one of the disadvantages of this method.
- The ranking results generated by fuzzy AHP and fuzzy TOPSIS from the study are the same. The researcher indicates that when the decision maker stays consistent with himself/herself in evaluating the data, the ranking results will be the same.

Chapter 3

Methodology

In this chapter, the model for evaluating the remanufacturability of office furniture is presented. The proposed model consists of fuzzy TOPSIS method which is comprised of two basic stages: (1) identifying the evaluation criteria to be used in the model. In this stage, the criteria for evaluating the remanufacturability of office furniture are determined and the decision-making hierarchy is formed; (2) evaluating the furniture alternatives suitable for remanufacture using fuzzy TOPSIS and determining their rank.

3.1 Criteria selection

In order to obtain a holistic view of furniture remanufacturability, the proposed model considers three aspects including economic, social and environmental aspects. Furthermore, the corresponding criteria within each aspect are identified and a hierarchical model is formulated to evaluate of the remanufacturability ranking.

Economic Aspect:

The economic facet of the problem is generally related to the cost of the remanufacturing operation. Therefore, a breakdown of remanufacturing operation helps to identify the criteria for evaluating the economic aspect. In this model, only the cost of remanufacture is considered as the basis for the economic aspect, whereby the overall cost of remanufacture depends on the condition of the returned used office furniture as well as the expected quality level of the final products [78]. Since there is no generic process for handling office furniture remanufacturing, we adopt a number of common processes that are observed from existing literature as well as the general life cycle of office furniture. Figure 15 is used to demonstrate the general close-loop supply chain of office furniture.

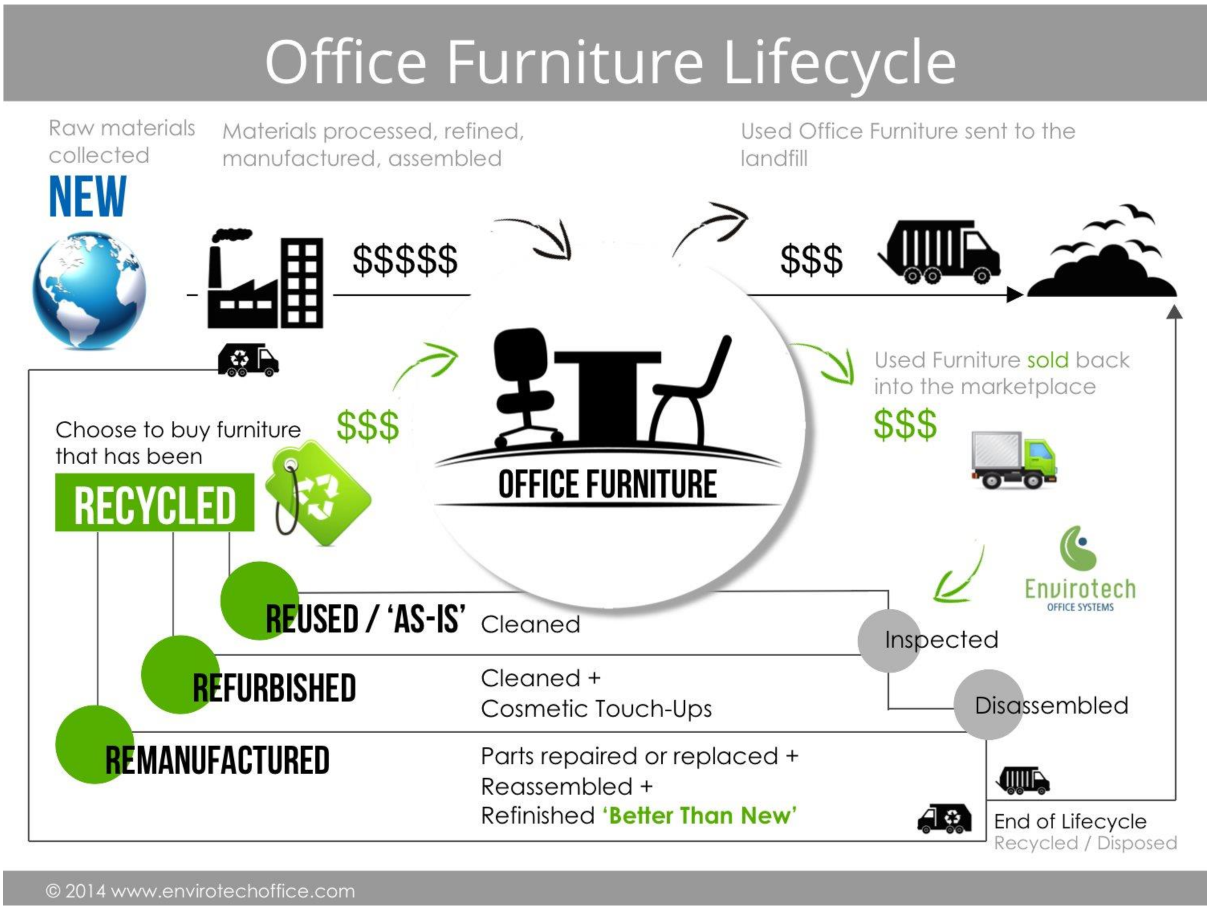

Figure 15. Life cycle of office furniture

Based on literature, the following remanufacturing processes of office furniture are identified [12] [79] [80]:

1. *Acquisition*: Collecting used office furniture (cores) is the first step in the remanufacturing process. Unlike virgin materials in traditional manufacturing, cores used in remanufacturing are obtained from the end users. The cores could either be collected by the original OEMs or third

party manufacturers. Typically, the price of acquisition varies by product and quality level which influences the cost of the remanufacturing process.

2. *Disassembly*: After the cores are obtained, the following step is disassembly. This stage allows for the selective separation of desired parts and materials. The common practice is to optimally schedule the disassembly process on time to meet customer demands. However, difficulties in disassembly, just like in any other material handling processes can increase the process time and the probability of damage to the product, which ultimately increases the total cost [81].

3. *Repair/replacement*: The collected cores may contain parts that are worn-out or damaged. In order to fulfill the required quality of the final product, a certain number of undesired components must be repaired, either fixed or replaced by new components. This means that the more the parts that require repair or replacement, the more expensive the remanufacturing cost [82].

4. *Reassembly*: After parts are repaired/replaced, the next step is put the components back together. Similar to disassembly, complexities in reassembly may increase the cost of remanufacture.

5. *Refinish*: Finally, for the remanufactured office furniture, there is a need for refinishing to render their appearances to be similar to new products. Therefore, refinishing (e.g. polishing) is required to restore the esthetics of the remanufactured products.

One basic stage in the remanufacturing process, which is missing in our model is the functional test procedure. We determine that though functional tests are critical for electronic and dynamic components, they may not be as significant in the remanufacturing process of furniture.

Social Aspect:

For the social aspect, our study focuses on how the remanufactured office furniture are accepted in the market. In other word, the willingness of the customers to purchase remanufactured office furniture. Though there are no prior studies indicating factors that influence customers' propensity to purchase remanufactured furniture, there is a recent trend in furniture market indicating that customers are attracted to furniture with versatile functionality [29]. For example, a chair that has a height adjustable function is more attractive to customers compared to a stool. To address this consumer trend, the evaluation model presented in our study considers the functionality of the remanufactured office furniture as a social criterion.

Environmental Aspect:

For the environmental aspect of evaluating remanufacturability of an office furniture, this study looks at the environmental benefits of remanufacturing. Generally, remanufacturing is seen as one of the most environmental friendly treatment for EOL products, because of its outstanding energy saving level. Compared to other EOL treatment such as recycling or reuse, the energy saving of remanufacturing can go up to 80% of the new product manufacturing [25]. Since the goal of implementing remanufacturing is to reduce both the consumption of virgin materials as well as the concomitant energy usage in the manufacturing process, the proposed evaluation model focuses on the energy saving potential of the remanufactured product.

In summary, the selected economic, social and environmental criteria are listed in Table 7, as well as a brief description of the assessment method used for each criterion.

Table 7. List of criterion and brief description of measurement

Aspect	Criterion		Assessment	Reference
Economic	C1	Acquisition	Is it difficult to collect the used office furniture for remanufacturing?	[79]
	C2	Disassembly	Is the required disassembly time reasonable?	[81]
	C3	Repair/replacement	Numbers of parts need to be repaired or replaced.	[82]
	C4	Reassemble	Is the required reassembly time reasonable?	[81]
	C5	Refinish	Considering the finishing of new product is the best level, what is the attainable finishing level for remanufactured one?	[83]
Social	C6	Functionality	Whether the function of the remanufactured product meet the expectation?	[29]
Environmental	C7	Energy saving	What is the amount of energy used for remanufacturing as a fraction of the energy used in the virgin manufacture of the equivalent new product?	[25]

After the criteria are identified, the hierarchy model for the proposed evaluation model can be developed as shown in Figure 16.

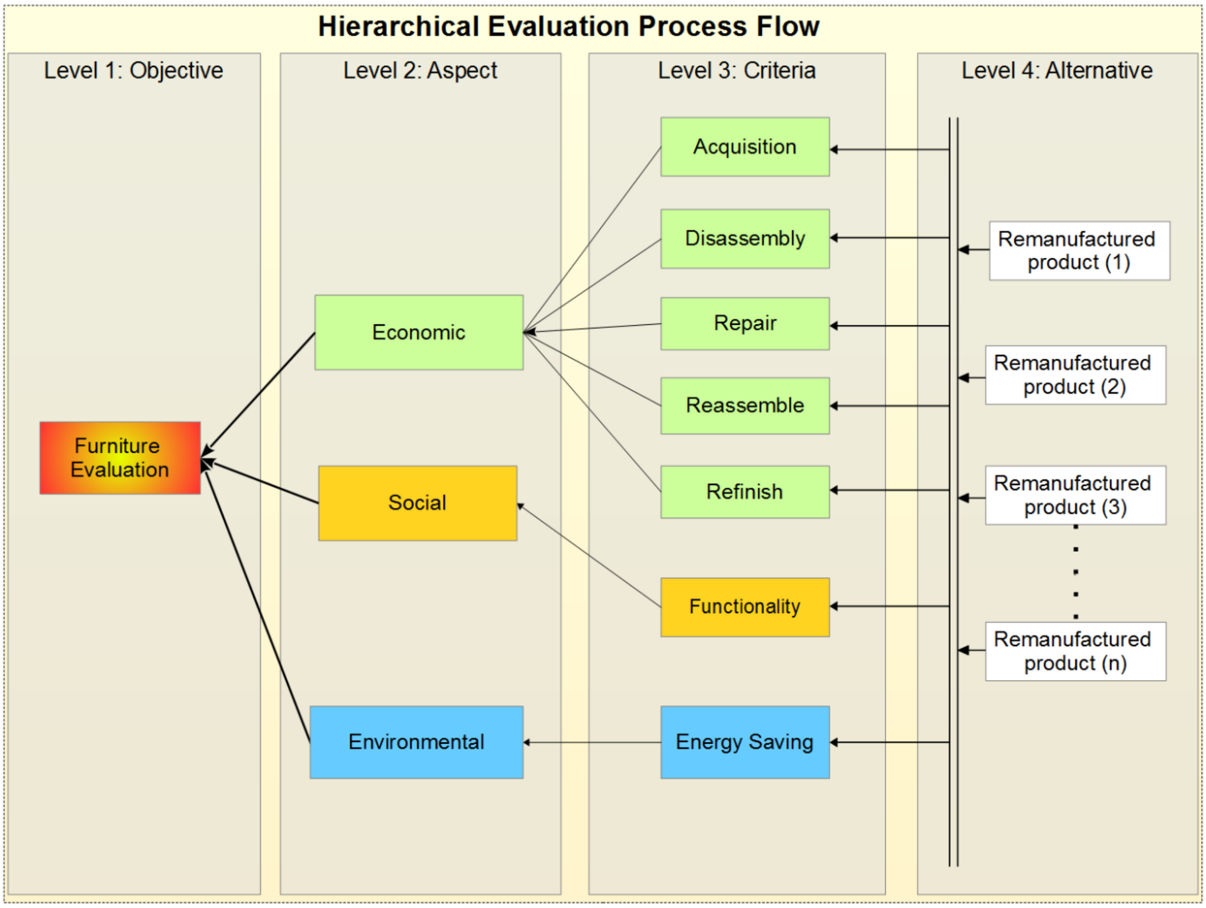

Figure 16. A hierarchical model for the evaluation of office furniture remanufacturability

3.2 Applying fuzzy TOPSIS for evaluation

The research problem in this Thesis consists of selecting the most remanufacturable product from a set of office furniture alternatives A_i $(i = 1, 2, \dots \dots m)$. These alternatives are evaluated using eight criteria C_j $(\mathrm{j} = 1, 2, \dots., \mathrm{n})$, which are considered to be independent of each other. The decision matrix for the eight criteria used to evaluate the alternatives is designated as $\widetilde{\mathrm{D}} = [X_{ij}]_{m \times n}$, where X_{ij} represents the fuzzy performance of the i th remanufactured office furniture with respect to the j th criterion. The weights of the criteria are given by the following weighting vector:

$$\tilde{w} = (w_1, w_2, \dots \dots, w_n)$$

The degree (values) of criteria is solicited from the decision-makers as linguistic variable and then transformed into triangular fuzzy numbers (TFN) defined on the interval [0, 1] using the triangular fuzzy membership function as illustrated in Figure 17.

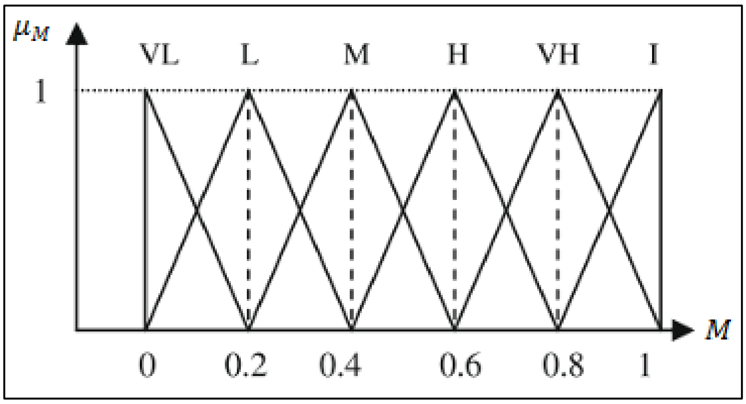

Figure 17. Membership function for linguistic variables

The corresponding triangular fuzzy numbers are shown in Table 8. The decision to use the triangular fuzzy mapping as was explained before is based its computational simplicity and usefulness for linguistic information processing in a fuzzy environment [59].

Table 8. Linguistic values and TFNs

Linguistic variables	Triangular fuzzy numbers (TFNs)
Very low (VL)	(0, 0, 0.2)
Low (L)	(0.1, 0.2, 0.3)
Medium low (ML)	(0.2, 0.35, 0.5)
Medium (M)	(0.4, 0.5, 0.6)
Medium high (MH)	(0.5, 0.65, 0.8)
High (H)	(0.7, 0.8, 0.9)
Very high (VH)	(0.8, 1, 1)

Whereas the final assessment of alternatives and their ranking are different in application, the proposed fuzzy TOPSIS evaluation model in this study is borrowed from the work of Chen et al. [71]. The proposed model utilizes fuzzy similarity instead of closeness in distance between two fuzzy ratings as a basis for ranking the alternatives. According to the study done by Luukka (2011), the application of fuzzy similarity can reduce the human selection influence when choosing the Fuzzy Positive Ideal Solution FPIS (best solution) and the Fuzzy Negative Ideal Solution FNIS (worst solution) which are essential for the final fuzzy rating of each alternative [84]. The steps of proposed model can be described as follows (adopted from [72]):

Step 1: At the initial stage, a group consisting of K decision-makers is formed. The linguistic fuzzy rating of each decision-maker (k) is solicited and is defined as a row matrix $\mathrm{D}_k(k = 1, 2, \ldots, K)$ for each furniture alternative (i) . These linguistic fuzzy ratings are transformed into triangular fuzzy numbers $\tilde{R}_k(k = 1, 2, \ldots, K)$ with membership function $\mu_{\tilde{R}_k \backsim (D_k)}$ for each furniture alternative (i).

Step 2: Choose the appropriate linguistic variables for the weight of the criteria as well as the rating for remanufactured office furniture.

Step 3: Aggregate the weight of criteria from each decision-maker to obtain the aggregated fuzzy weight $\tilde{w}_j$ of criterion j. Gather the ratings of decision-makers for each furniture alternative to gain the aggregated fuzzy rating $\tilde{\mathrm{R}}_{ij}$ of alternative i under criterion j.

Assume the fuzzy ratings of all the decision-makers are described as triangular fuzzy numbers $\tilde{R}_k = (a_k, b_k, c_k), k = 1, 2, \dots, K$. Then the aggregated fuzzy rating can also be defined as $\tilde{R} = (a, b, c)$, where

$$a = \min_k\{a_k\}, \quad b = \frac{1}{K}\ \sum_{k=1}^{K} b_k, \quad c = \max_k\{c_k\}$$

Equation 8

Let the fuzzy rating of the kth decision-maker be $\tilde{x}_{ijk} = (a_{ijk}, b_{ijk}, c_{ijk})$ and the importance weight be $\widetilde{w}_{jk} = \left(p_{\mathrm{jk}}, q_{j\mathrm{k}}, r_{\mathrm{jk}}\right)$, $i = 1, 2, \dots, m$, $j = 1, 2, \dots, n$ respectively. Then the aggregated fuzzy ratings $(\tilde{x}_{ij})$ of alternatives with respect to each criterion can be found as $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$, where

$$a_{ij} = \min_k\left\{a_{ijk}\right\}, \quad b_{ij} = \frac{1}{K}\sum_{k=1}^{K} b_{ijk}, \quad c_{ij} = \max_k\left\{c_{ijk}\right\}$$

Equation 9

Similarly, the aggregated fuzzy weights $(\widetilde{w}_j)$ of each criterion can be calculated as $\widetilde{w}_j = (p_j, q_j, r_j)$, where

$$p_j = \min_k\left\{p_{jk}\right\}, \quad q_{jk} = \frac{1}{K}\sum_{k=1}^{K} q_{jk}, \quad r_{j3} = \max_k\left\{r_{jk}\right\}$$

Equation 10

Step 4: Construct the fuzzy decision matrix

$$\widetilde{\mathrm{D}} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix},$$

$$\widetilde{w} = (\widetilde{w}_1, \widetilde{w}_2, \dots, \widetilde{w}_n)$$

Equation 11

where $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$ and $\widetilde{w}_j = (p_j, q_j, r_j)$ can be approximated by positive triangular fuzzy numbers.

Step 5: Normalize the constructed decision matrix. The linear scale transformation is used to transform various criteria scales into a comparable scale. Hence, the normalized fuzzy decision matrix $\tilde{\mathrm{R}}$ is obtained as

$$\tilde{\mathrm{R}} = \left[\tilde{r}_{ij}\right]_{m\times n} \quad i = 1, 2, \dots, m, \; j = 1, 2, \dots, n.$$

where:

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right),$$

$$c_j^* = \max_i c_{ij}$$

Equation 12

Step 6: Considering the importance of each criterion, the weighted normalized decision matrix is generated by multiplying the importance weights of evaluation criteria and the values in the normalized fuzzy decision matrix. The weighted normalized decision matrix is expressed as

$$\tilde{\mathrm{V}} = \left[\tilde{v}_{ij}\right]_{m\times n} \quad i = 1, 2, \dots, m, \; j = 1, 2, \dots, n$$

where

$$\tilde{v}_{ij} = \tilde{r}_{ij}(\cdot)\tilde{w}_j$$

Equation 13

Step 7: Then, the fuzzy positive ideal solution (FPIS, $A^{\oplus}$) is determined as:

$$A^{\oplus} = (\tilde{v}_1^{\oplus}, \tilde{v}_2^{\oplus}, \dots, \tilde{v}_n^{\oplus}),$$

Equation 14

where

$$\tilde{\mathrm{v}}_j^{\oplus} = \max_i \{v_{ij3}\}$$

$$i = 1, 2, \dots, m, \; j = 1, 2, \dots, n$$

In this case, the index 3 indicated the highest triangular fuzzy number from the weighted normalized decision matrix.

Step 8: Calculate similarity of each alternative to the FPIS by using the weighted normalized decision matrix and use it as a measurement to make the ranking.

As an illustration, let $\widetilde{\mathrm{A}}$ and $\widetilde{\mathrm{B}}$ be two TFNs, where $\widetilde{\mathrm{A}} = (a_1, a_2, a_3)$ and $\widetilde{\mathrm{B}} = (b_1, b_2, b_3)$. Fuzzy similarity is computed as [85]:

$$\mathrm{S}(\tilde{A}, \tilde{B}) = 1 - \frac{\sum_{i=1}^{3} |a_i - b_i|}{3}$$

Equation 15

Likewise, following Equation 15, the similarity of each alternative to the FPIS with respect to criterion j is calculated as:

$$S_v(\tilde{v}_{ij}, \tilde{v}_j^{\oplus})$$

Finally, the aggregate similarity of each alternative to the FPIS is computed by averaging over all the criteria as follows:

$$\mathrm{S}_i^{\oplus} = \frac{1}{n} \sum_{j=1}^{n} S_v(\tilde{v}_{ij}, \tilde{v}_j^{\oplus})$$

Equation 16

Chapter 4

Model Validation and Case Study

4.1 Model validation

In order to demonstrate the validity of our proposed evaluation model for solving multi-criteria decision problems, we applied the model to other similar research problems to validate its capability. In this section, a multi-criteria location decision problem is utilized for model validation.

4.1.1. Illustrative example used for model validation

Ertuğrul and Karakaşoğlu (2008) applied fuzzy TOPSIS to solve a facility location problem which considers favorable labor climate, proximity to markets, community considerations, quality of life, and proximity to suppliers and resources when selecting the best location for the facility [72]. The hierarchical structure of facility location selection process is illustrated in Figure 18 which is similar to our proposed evaluation model (see Figure 16) since they both have single hierarchy for the multi-criteria decision problem.

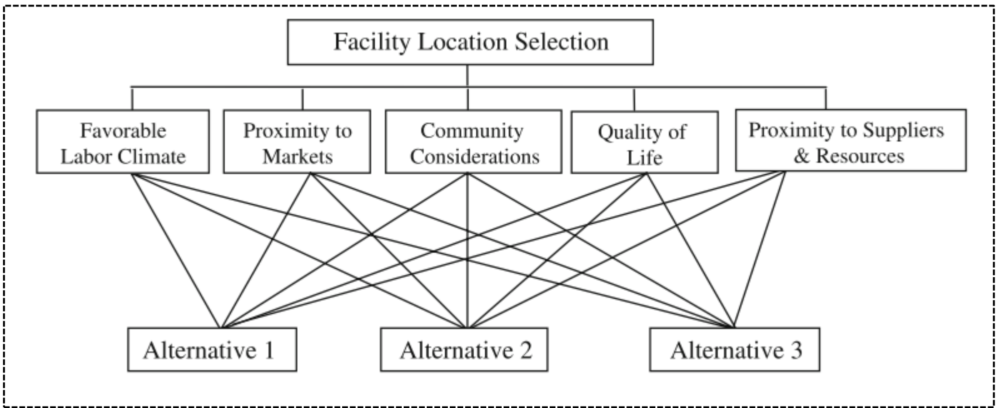

Figure 18. Hierarchical structure of facility location selection process [72]

In addition to the problem hierarchy, both evaluation models require decision-makers to give weights to the criteria and rate the alternatives with linguistic variables represented by triangular fuzzy numbers. Figure 19 and 20 show the linguistic variables that are used for weighting the criterion as well as rating the alternatives.

Linguistic variables	Triangular fuzzy numbers
Very low (VL)	(0, 0, 0.2)
Low (L)	(0.1, 0.2, 0.3)
Medium low (ML)	(0.2, 0.35, 0.5)
Medium (M)	(0.4, 0.5 ,0.6)
Medium high (MH)	(0.5, 0.65, 0.8)
High (H)	(0.7, 0.8, 0.9)
Very high (VH)	(0.8, 1,1)

Figure 19. Linguistic variables for importance weight of each criterion [72]

Linguistic variables	Triangular fuzzy numbers
Very poor (VP)	(0, 0, 2)
Poor (P)	(1, 2, 3)
Medium poor (MP)	(2, 3.5, 5)
Fair (F)	(4, 5, 6)
Medium good (MG)	(5, 6.5, 8)
Good (G)	(7, 8, 9)
Very good (VG)	(8, 10, 10)

Figure 20. Linguistic variables for ratings [72]

In the facility location problem, there are three decision-makers who provide the weights of each criterion and the ratings of three location alternatives. Thus, the validation problem entails three decision-makers, three location alternatives and five decision criteria. Figures 21 and 22 contain the solicited weights and ratings from three decision-makers. The considerations in the model are the evaluation criteria, denoted as C_1, C_2, C_3, C_4 and C_5.

Criteria	Decision-makers		
	D_1	D_2	D_3
C_1	VH	VH	VH
C_2	H	VH	VH
C_3	VH	H	H
C_4	MH	H	MH
C_5	H	H	H

Figure 21. Importance weight of criteria from three decision-makers [72]

Criteria	Alternatives	Decision-makers		
		D_1	D_2	D_3
C_1	A_1	VG	G	VG
	A_2	G	VG	G
	A_3	MG	MG	G
C_2	A_1	G	VG	VG
	A_2	MG	F	F
	A_3	MG	F	MG
C_3	A_1	F	MG	MG
	A_2	G	VG	VG
	A_3	VG	G	VG
C_4	A_1	G	VG	G
	A_2	MG	MG	MG
	A_3	F	F	MG
C_5	A_1	G	G	VG
	A_2	G	G	MG
	A_3	MG	MG	G

Figure 22. Ratings of the three alternatives by decision-makers under five criteria [72]

After weights and ratings are solicited, the linguistic variables have to be converted to triangular fuzzy numbers in order to generate the input data for the evaluation model. Figure 23 shows the converted data.

	A_1	A_2	A_3	Weight
C_1	(7, 9.33, 10)	(7, 8.67, 10)	(5, 7, 9)	(0.8, 1, 1)
C_2	(7, 9.33, 10)	(4, 5.5, 8)	(4, 6, 8)	(0.7, 0.93, 1)
C_3	(4, 6, 8)	(7, 9.33, 10)	(7, 9.33, 10)	(0.7, 0.87, 1)
C_4	(7, 9.33,10)	(5, 6.5, 8)	(4, 5.5, 8)	(0.5, 0.7, 0.9)
C_5	(7, 8.67,10)	(5, 7.5, 9)	(5, 7, 9)	(0.7, 0.8, 0.9)

Figure 23. Fuzzy decision matrix and fuzzy weights of three alternatives [72]

Later, the converted data is used to generate the normalized fuzzy decision matrix $\tilde{R}$ and weight normalized fuzzy decision matrix $\tilde{V}$ (shown in Figure 24 and 25) in order to provide the required information for the final evaluation of the three alternatives.

	A_1	A_2	A_3
C_1	(0.7, 0.93, 1)	(0.7, 0.87, 1)	(0.5, 0.7, 0.9)
C_2	(0.7, 0.93, 1)	(0.4, 0.55, 0.8)	(0.4, 0.6, 0.8)
C_3	(0.4, 0.6, 0.8)	(0.7, 0.93, 1)	(0.7, 0.93, 1)
C_4	(0.7, 0.93,1)	(0.5, 0.65, 0.8)	(0.4, 0.55, 0.8)
C_5	(0.7, 0.87,1)	(0.5, 0.75, 0.9)	(0.5, 0.7, 0.9)

Figure 24. Normalized fuzzy decision matrix [72]

	A_1	A_2	A_3
C_1	(0.56, 0.93, 1)	(0.56, 0.87, 1)	(0.4, 0.7, 0.9)
C_2	(0.49, 0.87, 1)	(0.28, 0.51, 0.8)	(0.28, 0.56, 0.8)
C_3	(0.28, 0.52, 0.8)	(0.49, 0.81, 1)	(0.49, 0.81, 1)
C_4	(0.35, 0.65, 0.9)	(0.25, 0.46, 0.72)	(0.2, 0.39, 0.72)
C_5	(0.49, 0.69, 0.9)	(0.35, 0.6, 0.81)	(0.35, 0.56, 0.81)

Figure 25. Weighted normalized fuzzy decision matrix [72]

The process of alternative evaluation used in the selected paper followed the fuzzy TOPSIS flowchart shown in Figure 14. For the selected paper, the closeness coefficient (CC_i) is defined to rank all possible alternatives. A closeness coefficient of each alternative is obtained by calculating the distances of each alternative score from the fuzzy positive ideal solution (FPIS) and the fuzzy negative ideal solution (FNIS). The equations for obtaining FPIS and FNIS are:

$$A^{\oplus} = (\tilde{v}_1^{\oplus}, v_2^{\oplus}, \dots, v_n^{\oplus}),$$
$$A^{\ominus} = (\tilde{v}_1^{\ominus}, v_2^{\ominus}, \dots, v_n^{\ominus})$$

Equation 17

where

$$\tilde{v}_j^{\oplus} = \max_i\{v_{ij3}\} \text{ and } \tilde{v}_j^{\ominus} = \min_i\{v_{ij1}\},$$
$$i = 1, 2, \dots, m, \; j = 1, 2, \dots, n$$

The distance of each alternative from FPIS and FNIS are calculated as [71]:

$$d_i^{\oplus} = \sum_{j=1}^{n} d_v\left(\tilde{v}_{ij}, \tilde{v}_j^{\oplus}\right), \qquad i = 1, 2, \dots, m$$
$$d_i^{\ominus} = \sum_{j=1}^{n} d_v\left(\tilde{v}_{ij}, \tilde{v}_j^{\ominus}\right), \qquad i = 1, 2, \dots, m$$

Equation 18

Then a closeness coefficient (CC_i) is generated to rank all possible alternatives. The closeness coefficient represents the distances to the FPIS $(A^{\oplus})$ and FNIS $(A^{\ominus})$ simultaneously. CC_i of each alternative is calculated as [86]:

$$CC_i = \frac{d_i^{\ominus}}{d_i^{\oplus} + d_i^{\ominus}} \;, \qquad \mathrm{i} = 1, 2, \dots, \mathrm{m}$$

Equation 19

FPIS and FNIS for the facility selection problem are shown in the following:

$$A^{\oplus} = [(1,1,1),(1,1,1),(1,1,1),(0.9,0.9,0.9),(0.9,0.9,0.9)]$$

$$A^{\ominus} = [(0.4,0.4,0.4),(0.28,0.28,0.28),(0.28,0.28,0.28),(0.2,0.2,0.2),(0.35,0.35,0.35)]$$

Using the data from the selected paper, the ranking of the alternatives is derived from the following calculations, including distances from FPIS and FNIS as well as closeness coefficient of each alternative. The distance between three alternatives $(A_1,\ A_2,\ A_3)$ to FPIS and FNIS are shown in Figures 26 and 27.

	C_1	C_2	C_3	C_4	C_5
$d(A_1, A^*)$	0.26	0.30	0.51	0.35	0.27
$d(A_2, A^*)$	0.27	0.52	0.31	0.47	0.37
$d(A_3, A^*)$	0.39	0.50	0.31	0.51	0.38

Figure 26. Distances between $A_i = (i = 1,2,3)$ and FPIS (A^*) with respect to each criterion [72]

	C_1	C_2	C_3	C_4	C_5
$d(A_1, A^-)$	0.47	0.55	0.33	0.49	0.38
$d(A_2, A^-)$	0.45	0.33	0.53	0.34	0.30
$d(A_3, A^-)$	0.34	0.34	0.53	0.32	0.29

Figure 27. Distances between $A_i = (i = 1,2,3)$ and FNIS (A^-) with respect to each criterion [72]

The final results of $d_i^{\oplus}$, $d_i^{\ominus}$, CC_i and ranking of the alternative is shown in Figure 28.

	A_1	A_2	A_3	Ranking order
d_i^*	1.69	1.93	2.10	
d_i^-	2.23	1.95	1.82	
CC_i	0.57	0.50	0.46	$A_1 > A_2 > A_3$

Figure 28. Result of $d_i^{\oplus}$, $d_i^{\ominus}$, CC_i and final ranking for selected paper solution [72]

4.1.2. Results of the validation process

Our proposed evaluation model follows the same concept as the fuzzy TOPSIS method in [72]; except in comparing alternatives, wherein we calculate for the fuzzy similarity of each alternative to the FPIS as opposed to calculating for the closeness coefficient to both FPIS and FNIS. Generally, calculating fuzzy similarity requires less computations and minimizes the potential for inconsistency caused by the human judgment [84]. The calculations of fuzzy similarity are illustrated in Equations 14, 15 and 16.

We utilize the same data from the selected paper [72] to demonstrate our model evaluation process, which applies the fuzzy similarity for the final ranking. Here, we only present the assessment of alternatives by calculating their fuzzy similarity to the FPIS and further obtain the ranking order.

After converting the solicited weights of criteria and the rating of alternatives, the weighted normalized decision matrix that we obtain is exactly similar to the one obtained by Ertuğrul and Karakaşoğlu (2008) as presented earlier in Figure 25:

	A_1	A_2	A_3
C_1	(0.56, 0.93, 1)	(0.56, 0.87, 1)	(0.4, 0.7, 0.9)
C_2	(0.49, 0.87, 1)	(0.28, 0.51, 0.8)	(0.28, 0.56, 0.8)
C_3	(0.28, 0.52, 0.8)	(0.49, 0.81, 1)	(0.49, 0.81, 1)
C_4	(0.35, 0.65, 0.9)	(0.25, 0.46, 0.72)	(0.2, 0.39, 0.72)
C_5	(0.49, 0.69, 0.9)	(0.35, 0.6, 0.81)	(0.35, 0.56, 0.81)

and the FPIS the we obtained is exactly as theirs i.e.

$$A^{\oplus} = [(1,1,1),(1,1,1),(1,1,1),(0.9,0.9,0.9),(0.9,0.9,0.9)]$$

We then use Equations 15 and 16 to compute the fuzzy similarity of the three alternatives and determine their ranking as shown in Tables 9 and 10.

Table 9. Similarities between FPIS and weighted normalized fuzzy decision matrix

	C_1	C_2	C_3	C_4	C_5
$S(A_1)$	0.83	0.79	0.53	0.72	0.79
$S(A_2)$	0.81	0.53	0.77	0.58	0.69
$S(A_3)$	0.67	0.55	0.77	0.54	0.67

Calculating the fuzzy similarity of each alternative,

$$S(A_1) = \frac{0.83 + 0.79 + 0.53 + 0.72 + 0.79}{5} = 0.73$$

$$S(A_2) = \frac{0.81 + 0.53 + 0.77 + 0.58 + 0.69}{5} = 0.67$$

$$S(A_3) = \frac{0.67 + 0.55 + 0.77 + 0.54 + 0.67}{5} = 0.64$$

Table 10. Fuzzy similarity of each alternative and its ranking order

	Fuzzy similarity	Ranking order
Alternative 1	0.73	$A_1 > A_2 > A_3$
Alternative 2	0.67	
Alternative 3	0.64	

As demonstrated in the above computations of generating the final ranking for the alternatives, the results from the selected illustrative example in [72] and our proposed evaluation model are exactly the same hence validating that the proposed model algorithm has the capability of solving multi-criteria decision making problem. Additionally, the use of fuzzy similarity simplifies the computation and comparison process. For instance, we no longer need to calculate the FNIS as well as the closeness coefficient in our proposed model. This helps to improve the computation efficiency when dealing with increasing number of alternatives.

4.2 Case study

Our case study aims to evaluate the remanufacturability of a series returned office furniture (cores) and further determine which ones could be remanufactured. We choose three pieces of office furniture, namely siento chair, airtouch table and garland double pedestal desk from the CaseSteel Company as our alternatives herein denoted as $(A_1,\ A_2,\ A_3)$. The detailed information regarding these selected office furniture is provided by the LCA study done by Spitzley et al. (2006) [87]. Despite the fact that their study was solely directed toward calculating the environmental impact of these alternatives, it was the most detailed literature that we found providing adequate information on the bill of materials, material recovery rates and total energy usage. Quite a bit of needed information was missing, including market evaluation, product return rates, product assembly times and repair/replacement of components and expected product finish. As the result, some assumptions are made in order to fill the gaps between the acquired LCA information and our case study scenario. The detailed information of the selected office furniture is presented below:

1) Siento chair: An ergonomic executive seating in a wood office environment.

Table 11. Siento chair material composition and total product weight [87]

Material	Weight (lb)	Sample
Steel	32.3	
Plastic	14.6	
Non-ferrous metals	13.4	
Leather	2.6	
Other	1.7	
Total Product Weight	**64.7**	
Energy consumption (MJ)	**1350**	

Table 12. Joint types of siento chair [87]

Types of joints	5	% of joint in total parts
Total joints	58	
Total parts	243	23.8%

* Reference for rating criteria (Disassembly & Reassembly)

2) Airtouch table: Featured with a flat work space adjustable from 26” to 43” in height while supporting up to 25 lbs.

Table 13. Airtouch table material composition and total product weight [87]

Material	**Weight (lb)**	**Sample**
Steel (inc, iron & stainless)	50.4	
Particleboard	33.1	
Aluminum	28.0	
Laminate	3.2	
Adhesive and Plastics	1.1	
Total Product Weight	**116**	
Energy consumption (MJ)	**3290**	

Table 14. Joint types of airtouch table [87]

Types of joints	4	% of joint in total parts
Total joints	38	
Total parts	150	25.3%

* Reference for rating criteria (Disassembly & Reassembly)

3) Garland double pedestal desk: Featured with a stand alone 72” x 36” work surface and versatile storage spaces.

Table 15. Garland double pedestal desk material composition and total product weight [87]

Material	**Weight (lb)**	**Sample**
Particleboard	159.3	
Steel	52.9	
Plywood	40.2	
Cherry	8.6	
Other wood/Paper	3.1	
Adhesive and Finishes	1.9	
Baking Material	1.6	
Plastics	1.5	
Total Product Weight	**269**	
Energy consumption (MJ)	**3452**	

Table 16. Joint types of garland double pedestal desk [87]

Types of joints	1	% of joint in total parts
Total joints	266	
Total parts	423	62.8%

* Reference for rating criteria (Disassembly & Reassembly)

First, to begin the evaluation process, a committee of decision-makers is formed. In our case, we assume that there are three decision-makers (D_1, D_2, D_3) in the committee. Secondly, the evaluation criteria are determined. In our case, we consider seven criteria, namely acquisition (C_1), disassembly (C_2), repair/replacement (C_3), reassemble (C_4), refinish (C_5), functionality (C_6), energy saving (C_7). The hierarchical structure for case study is shown in Figure 29, whereby the evaluation criteria (level 3) are informed by the choice of the aspects in consideration (level 2), i.e. economic, social and environmental, which are in turn determined by the fundamental objective of the study (level 1).

Third, linguistics variables and their respective triangular fuzzy numbers are chosen to provide weights (measure if importance) to criteria as well as a rating for each furniture alternative as presented in Tables 17 and 18. Fourth, the ratings of the alternatives with respect to each decision criterion are elicited from the decision maker. We note that Table 19, which shows the material recovery rate, and Table 20 which provides information on the status of returned office furniture and the associate remanufacturing process measures are used to provide background information to construct the rating of some of the decision criteria. We provide a rating scale for decision-makers to use as a guideline for rating the alternatives with respect to each decision criterion as illustrated in Table 21.

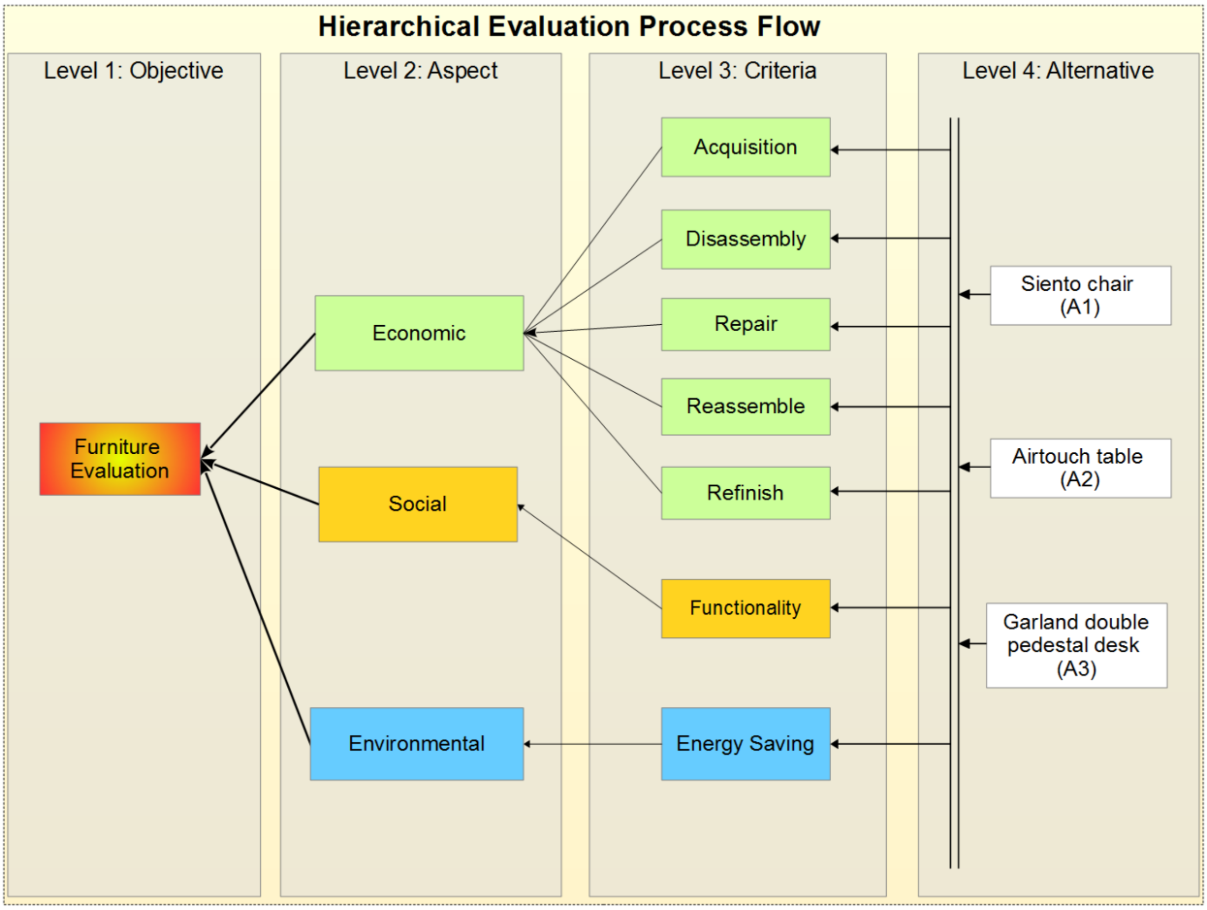

Figure 29. The hierarchical structure for case study problem

For the status of the returned office furniture is listed in Table 20, the status contains assumptions base on the LCA information provided by Spitzley et al. (2006) [87].

Table 17. Linguistic variables for weight of each criteria

Linguistic variables	Triangular fuzzy numbers (TFNs)
Very low (VL)	(0, 0, 0.2)
Low (L)	(0.1, 0.2, 0.3)
Medium low (ML)	(0.2, 0.35, 0.5)
Medium (M)	(0.4, 0.5, 0.6)
Medium high (MH)	(0.5, 0.65, 0.8)
High (H)	(0.7, 0.8, 0.9)
Very high (VH)	(0.8, 1, 1)

Table 18. Linguistic variables for rating the alternatives

Linguistic variables	Triangular fuzzy numbers (TFNs)
Very poor (VP)	$(0, 0, 2)$
Poor (P)	$(1, 2, 3)$
Medium poor (MP)	$(2, 3.5, 5)$
Fair (F)	$(4, 5, 6)$
Medium Good (MG)	$(5, 6.5, 8)$
Good (G)	$(7, 8, 9)$
Very good (VG)	$(8, 10, 10)$

Table 19. End-of-life waste management scenario based on EPA data for durable goods in municipal solid waste [87]

Material in Waste Stream	**Recovery Rate**	**Comment**
Ferro metals	28%	
Magnesium	60%	
Zinc	60%	
Aluminum	0%	According to source negligible for durable goods Polyethylene
Non-ferro metals (others)	60%	
Polyethylene (PE)	5.5%	
Polyethylene terephthalate (PET)	5.5%	
Polypropylene (PP)	5.5%	
Polyvinylchloride (PVC)	5.5%	
Plastics (others)	5.5%	
Wood	35%	U.S. EPA 2011; includes waste from residential, commercial, and institutional sources
Paper	55%	According to source for containers and packaging

Table 20. Status of returned office furniture and the associate remanufacturing process measures

<table>
<tr><th></th><th colspan="2">Assumption</th><th>Core</th><th>Status</th></tr>
<tr><td rowspan="3">Product return rate</td><td colspan="2" rowspan="3">We assume a chair has a higher return rate than a table or desk due to its frequent movement, which might cause damage to the chair itself and further shorten the usage time of the chair.</td><td>S chair</td><td>40%</td></tr>
<tr><td>A table</td><td>30%</td></tr>
<tr><td>G desk</td><td>30%</td></tr>
<tr><td rowspan="3">Disassembly time</td><td colspan="2" rowspan="3">We use data derived from the LCA study [87] to aim the decision-maker when determining the potential disassembly time of each alternative. In this study, as will be presented in the case examples, we consider the number of types of joints and the ratio of joints with respect to other components as a measure of ease or difficulty in disassembly.</td><td>S chair</td><td>Tab. 12</td></tr>
<tr><td>A table</td><td>Tab. 14</td></tr>
<tr><td>G desk</td><td>Tab. 16</td></tr>
<tr><td rowspan="3">Numbers of parts need to be repaired or replaced.</td><td colspan="2" rowspan="3">We assume all the joint components of each alternative need to be replaced. Additionally, we use material recovery rate* to calculate the potential parts that are good without repair or replace.
• $\text{Material recovery rate} \times \text{material used} = \text{parts without repair/replace } (\alpha)$
• $\frac{\text{Joints}}{Total\ parts} = none\ joint\ parts\ \text{ratio}(\beta)$
• $\text{Status} = 0.8(\alpha) \times 0.2(\beta)$</td><td>S chair</td><td>50.12%</td></tr>
<tr><td>A table</td><td>55.34%</td></tr>
<tr><td>G desk</td><td>38.88%</td></tr>
<tr><td rowspan="3">Reassembly time</td><td colspan="2" rowspan="3">We use data derived from the LCA study [87] to aim the decision-maker when determining the potential Reassembly time of each alternative.</td><td>S chair</td><td>Tab. 12</td></tr>
<tr><td>A table</td><td>Tab. 14</td></tr>
<tr><td>G desk</td><td>Tab. 16</td></tr>
<tr><td rowspan="3">Percentage of the returned core that is good without refinish.</td><td colspan="2" rowspan="3">We use material recovery rate* to calculate the potential parts that are good without refinish.
• $\text{Material recovery rate} \times \text{material used for appearance of the product} = \text{\% of parts without refinish}$</td><td>S chair</td><td>4.6%</td></tr>
<tr><td>A table</td><td>52%</td></tr>
<tr><td>G desk</td><td>52%</td></tr>
<tr><td rowspan="3">Functionality</td><td>S chair</td><td colspan="3">Height adjustment, back adjustment, 5 spinning wheel</td></tr>
<tr><td>A table</td><td colspan="3">Height adjustable table surface</td></tr>
<tr><td>G desk</td><td colspan="3">Desk with built-in storage spaces.</td></tr>
<tr><td rowspan="3">Energy saving</td><td colspan="2" rowspan="3">We use material recovery rate* and energy consumption to calculate the potential energy saving.
$\text{Material recovery rate} \times \text{material used} \times \text{energy consumption for new one} = \text{energy saved in remanufacturing}$</td><td>S chair</td><td>43.6%</td></tr>
<tr><td>A table</td><td>55.3%</td></tr>
<tr><td>G desk</td><td>52.6%</td></tr>
</table>

Table 21. Assessment fundamentals for rating alternatives

Criteria	Assessment
Acquisition	Based on the product return rate.
	VP P MP F MG G VG 0% 15% 30% 45% 60% 75% 90% 100%
Disassembly	Assume threshold disassembly time is 60% of original assembly time. What percentage of the original assembly time is needed for remanufacturing.
	VG G MG F MP P VP 0% 10% 20% 30% 40% 50% 60% Above 60% % of original assembly time used
Repair/ replacement	Percentage of the total parts that are ***good*** without repaired or replaced.
	VP P MP F MG G VG 0% 15% 30% 45% 60% 75% 90% 100% % of parts is ***good*** to use
Reassemble	Time for reassembly as a percentage of a new product assembly time.
	VP P MP F MG G VG 0% 15% 30% 45% 60% 75% 90% 100%
Refinish	Percentage of the returned core that is ***good*** without refinish.
	VP P MP F MG G VG 0% 15% 30% 45% 60% 75% 90% 100%
Functionality	Whether the function of the remanufactured product meet the expectation?
	VP P MP F MG G VG Totally dislike, Tend to dislike, Little worse than fair, Fair, Little better than fair, Tend to like, Totally prefer
Energy saving	What is the amount of energy used for remanufacturing as a fraction of the energy used in the virgin manufacture of the equivalent new product?
	VP P MP F MG G VG 0% 15% 30% 45% 60% 75% 90% 100% % of energy saved

Tables 22 and 23 are the decision criteria ratings and alternative ratings respectively, solicited from the three decision-makers independent decision-makers. For illustration purposes, we used three independent thinkers in academia, who are conversant with this research but are not industry practitioners. Real case scenario would use company executives who are directly involved with the remanufacturing process and product marketing.

Table 22. Weights of criteria solicited from three decision-makers

Criteria	Decision-makers		
	D_1	D_2	D_3
C_1	VH	H	MH
C_2	H	M	MH
C_3	M	H	H
C_4	VL	M	VL
C_5	H	L	H
C_6	VH	MH	MH
C_7	H	MH	H

Table 23. Ratings of the three alternatives by decision-makers under seven criteria

Criteria	Alternatives	Decision-makers		
		D_1	D_2	D_3
C_1	A_1	G	MP	MH
	A_2	F	P	F
	A_3	F	P	F
C_2	A_1	VG	MG	G
	A_2	MG	MG	VG
	A_3	F	P	MP
C_3	A_1	MG	F	F
	A_2	G	F	MG
	A_3	MP	MP	MP
C_4	A_1	P	F	P
	A_2	P	F	MP
	A_3	P	MP	P
C_5	A_1	P	VP	VP
	A_2	G	F	F
	A_3	G	F	F
C_6	A_1	VG	MG	G
	A_2	VG	MG	G
	A_3	VG	MG	G
C_7	A_1	MG	MP	F
	A_2	G	F	MG
	A_3	G	F	MG

Fifth, the linguistic variables (ratings) from decision-makers in Tables 22 and 23 are converted into triangular fuzzy numbers to form the fuzzy decision matrix and fuzzy criteria weights as shown in Table 24.

Table 24. Fuzzy decision matrix and fuzzy weights of three alternatives

	A_1	A_2	A_3	Weight
C_1	(0.5, 4.05, 9)	(1, 4, 6)	(1, 4, 6)	(0.5, 0.816, 1)
C_2	(5, 8.16, 10)	(5, 7.66, 10)	(1, 3.5, 6)	(0.4, 0.65, 0.9)
C_3	(4, 5.5, 8)	(4, 6.5, 9)	(2, 3.5, 5)	(0.4, 0.7, 0.9)
C_4	(1, 3, 6)	(1, 3.5, 6)	(1, 2.5, 5)	(0, 0.16, 0.6)
C_5	(0, 0.66, 3)	(4, 6, 9)	(4, 6, 9)	(0.1, 0.6, 0.9)
C_6	(5, 8.16, 10)	(5, 8.16, 10)	(5, 8.16, 10)	(0.5, 0.76, 1)
C_7	(2, 5, 8)	(4, 6.5, 9)	(4, 6.5, 9)	(0.5, 0.75, 0.9)

Sixth, the fuzzy decision matrix and fuzzy weights are then used to form the normalized fuzzy decision matrix as shown in Table 25. Then weighted following Equation 13 to form the weighted normalized fuzzy decision matrix in Table 26.

Table 25. Normalized fuzzy decision matrix

	A_1	A_2	A_3
C_1	(0.05, 0.45, 1)	(0.11, 0.44, 0.66)	(0.11, 0.44, 0.66)
C_2	(0.5, 0.81, 1)	(0.5, 0.76, 1)	(0.1, 0.35, 0.6)
C_3	(0.44, 0.61, 0.89)	(0.44, 0.72, 1)	(0.22, 0.38, 0.55)
C_4	(0.16, 0.5, 1)	(0.16, 0.58, 1)	(0.16, 0.41, 0.83)
C_5	(0, 0.07, 0.33)	(0.44, 0.66, 1)	(0.44, 0.66, 1)
C_6	(0.5, 0.81, 1)	(0.5, 0.81, 1)	(0.5, 0.81, 1)
C_7	(0.22, 0.55, 0.88)	(0.44, 0.72, 1)	(0.44, 0.72, 1)

Table 26. Weighted normalized fuzzy decision matrix

	A_1	A_2	A_3
C_1	(0.02, 0.36, 1)	(0.05, 0.36, 0.66)	(0.05, 0.36, 0.66)
C_2	(0.2, 0.53, 0.9)	(0.2, 0.49, 0.9)	(0.04, 0.22, 0.54)
C_3	(0.17, 0.42, 0.8)	(0.17, 0.5, 0.9)	(0.08, 0.27, 0.5)
C_4	(0, 0.08, 0.6)	(0, 0.09, 0.6)	(0, 0.06, 0.5)
C_5	(0, 0.04, 0.3)	(0.04, 0.4, 0.9)	(0.04, 0.4, 0.9)
C_6	(0.25, 0.62, 1)	(0.25, 0.62, 1)	(0.25, 0.62, 1)
C_7	(0.11, 0.41, 0.8)	(0.22, 0.54, 0.9)	(0.22, 0.54, 0.9)

Seventh, after the weighted normalized fuzzy decision matrix is formed, a sensitivity analysis on the fuzzy similarity numbers obtained for each alternative is performed based on the three methods of obtaining the fuzzy positive ideal solutions (FPIS). Hence, the resultant rankings from the three sensitivity analyses are compared to find out whether there are any inconsistencies among the final rankings. We first apply the three different methods for determining the fuzzy positive ideal solutions. In the first method, the maximum rating of each criterion across all alternatives is used to represent the FPIS of the particular criterion. The generated FPIS are shown in Table 27. For instance, the FPIS for $\boldsymbol{C_1}$ is indicated as {1,1,1} because the maximum $\boldsymbol{C_1}$ rating occurs as 1 for alternative $\boldsymbol{A_1}$. This procedure is repeated for all the seven criteria.

Table 27. FPIS determined using method I

Criteria	***FPIS***	(A_1)	(A_2)	(A_3)
$\boldsymbol{C_1}$	**(1, 1, 1)**	(0.02, 0.36, **1***)	(0.05, 0.36, 0.66)	(0.05, 0.36, 0.66)
$\boldsymbol{C_2}$	**(0.9, 0.9, 0.9)**	(0.2, 0.53, **0.9***)	(0.2, 0.49, **0.9***)	(0.04, 0.22, 0.54)
$\boldsymbol{C_3}$	**(0.9, 0.9, 0.9)**	(0.17, 0.42, 0.8)	(0.17, 0.5, **0.9***)	(0.08, 0.27, 0.55)
$\boldsymbol{C_4}$	**(0.6, 0.6, 0.6)**	(0, 0.08, **0.6***)	(0, 0.09, **0.6***)	(0, 0.06, 0.5)
$\boldsymbol{C_5}$	**(0.9, 0.9, 0.9)**	(0, 0.04, 0.3)	(0.04, 0.4, **0.9**)	(0.04, 0.4, **0.9***)
$\boldsymbol{C_6}$	**(1, 1, 1)**	(0.25, 0.62, **1***)	(0.25, 0.62, **1***)	(0.25, 0.62, **1***)
$\boldsymbol{C_7}$	**(0.9, 0.9, 0.9)**	(0.11, 0.41, 0.8)	(0.22, 0.54, **0.9***)	(0.22, 0.54, **0.9***)

Note: *Selected rating

The FPIS following method I is denoted as $A_I{}^{\oplus}$ and the matrix is presented below:

$$A_I{}^{\oplus} = [(1, 1, 1), (0.9, 0.9, 0.9), (0.9, 0.9, 0.9), (0.6, 0.6, 0.6), (0.9, 0.9, 0.9), (1, 1, 1), (0.9, 0.9, 0.9)]$$

The fuzzy similarity measures of the three alternatives are calculated with respect to the FPIS generated using method I and then used to determine their rankings as shown in Tables 28 and 29.

Table 28. Similarity measure between the FPIS and weighted normalized fuzzy decision matrix for each alternative with respect to each decision criterion using method I

	C_1	C_2	C_3	C_4	C_5	C_6	C_7
$S(A_1)$	0.46	0.64	0.56	0.62	0.21	0.62	0.54
$S(A_2)$	0.36	0.63	0.62	0.63	0.54	0.62	0.65
$S(A_3)$	0.36	0.36	0.38	0.58	0.44	0.62	0.65

Table 29. Fuzzy similarity of each alternative and its ranking order using method I

	Fuzzy similarity	Ranking order
Alternative 1	0.52	$A_2 > A_1 > A_3$
Alternative 2	0.58	
Alternative 3	0.50	

Finally, according to the fuzzy similarity of each alternative shown in Table 29, the ranking order is determined as $A_2 > A_1 > A_3$. As a result, the second alternative, the airtouch table, is the most appropriate product for remanufacturing, followed by the siento chair and then the garland desk.

The second method of determining the FPIS is by simply replacing all the rating of each criterion with 1, which means the most ideal situation under the criterion in question. The FPIS result is shown in Table 30.

Table 30. FPIS determined using method II

Criteria	***FPIS***	(A_1)	(A_2)	(A_3)
C_1	**(1, 1, 1)**	(0.02, 0.36, 1)	(0.05, 0.36, 0.66)	(0.05, 0.36, 0.66)
C_2	**(1, 1, 1)**	(0.2, 0.53, 0.9)	(0.2, 0.49, 0.9)	(0.04, 0.22, 0.54)
C_3	**(1, 1, 1)**	(0.17, 0.42, 0.8)	(0.17, 0.5, 0.9)	(0.08, 0.27, 0.55)
C_4	**(1, 1, 1)**	(0, 0.08, 0.6)	(0, 0.09, 0.6)	(0, 0.06, 0.5)
C_5	**(1, 1, 1)**	(0, 0.04, 0.3)	(0.04, 0.4, 0.9)	(0.04, 0.4, 0.9)
C_6	**(1, 1, 1)**	(0.25, 0.62, 1)	(0.25, 0.62, 1)	(0.25, 0.62, 1)
C_7	**(1, 1, 1)**	(0.11, 0.41, 0.8)	(0.22, 0.54, 0.9)	(0.22, 0.54, 0.9)

The FPIS for method II, denoted as $A_{II}{}^{\oplus}$ below:

$$A_{II}{}^{\oplus} = [(1,1,1),(1,1,1),(1,1,1),(1,1,1),(1,1,1),(1,1,1),(1,1,1)]$$

Likewise, the fuzzy similarity measures of the three alternatives are calculated with respect to the FPIS generated by method II and used to determine their rankings as shown in Tables 31 and 32.

Table 31. Similarity measure between the FPIS and weighted normalized fuzzy decision matrix for each alternative with respect to each decision criterion using method II

	C_1	C_2	C_3	C_4	C_5	C_6	C_7
$S(A_1)$	0.46	0.54	0.46	0.22	0.11	0.62	0.44
$S(A_2)$	0.36	0.53	0.52	0.23	0.44	0.62	0.55
$S(A_3)$	0.36	0.26	0.28	018	0.44	0.62	0.55

Table 32. Fuzzy similarity of each alternative and its ranking order using method II

	Fuzzy similarity	Ranking order
Alternative 1	0.41	$A_2 > A_1 > A_3$
Alternative 2	0.46	
Alternative 3	0.39	

Finally, according to the fuzzy similarity of each alternative shown in Table 32, the ranking order is determined as $A_2 > A_1 > A_3$. As a result, the ranking order is the same as the previous technique of determining the FPIS.

The third method of determining the FPIS is to look into each fuzzy triangular number of the ratings under each criterion, and the objective is to find the maximum number for each possibility category namely low, medium and high. The generated FPIS are shown in Table 33. For example, the FPIS for $\boldsymbol{C_1}$ is indicated as {0.05,0.36,1}. If we look into the fuzzy triangular numbers of the ratings under $\boldsymbol{C_1}$, the maximum value among the low possibility value occurs as 0.05 for alternative $\boldsymbol{A_2}$ and $\boldsymbol{A_3}$; for the medium possibility occurs as 0.36 for all the alternatives and for high possibility occurs as 1 for alternative $\boldsymbol{A_1}$. This procedure is repeated for all the seven criteria.

Table 33. FPIS determined using method III

Criteria	***FPIS***	(A_1)	(A_2)	(A_3)
C_1	**(0.05, 0.36, 1)**	(0.02, **0.36***, **1***)	(**0.05***, **0.36***, 0.66)	(**0.05***, **0.36***, 0.66)
C_2	**(0.2, 0.53, 0.9)**	(**0.2***, **0.53***, **0.9***)	(**0.2***, 0.49, **0.9***)	(0.04, 0.22, 0.54)
C_3	**(0.17, 0.5, 0.9)**	(**0.17***, 0.42, 0.8)	(**0.17***, **0.5***, **0.9***)	(0.08, 0.27, 0.55)
C_4	**(0, 0.09, 0.6)**	(**0***, 0.08, **0.6***)	(**0***, **0.09***, **0.6***)	(**0***, 0.06, 0.5)
C_5	**(0.04, 0.4, 0.9)**	(0, 0.04, 0.3)	(**0.04***, **0.4***, **0.9***)	(**0.04***, **0.4***, **0.9***)
C_6	(**0.25**, **0.62**, **1**)	(**0.25***, **0.62***, **1***)	(**0.25***, **0.62***, **1***)	(**0.25***, **0.62***, **1***)
C_7	(**0.22**, **0.54**, **0.9**)	(0.11, 0.41, 0.8)	(**0.22***, **0.54***, **0.9***)	(**0.22***, **0.54***, **0.9***)

Note: *Selected rating

The FPIS using method III denoted as $A_{III}{}^{\oplus}$ below:

$$A_{III}{}^{\oplus} = [(0.05, 0.36, 1), (0.2, 0.53, 0.9), (0.17, 0.5, 0.9), (0, 0.09, 0.6), (0.04, 0.4, 0.9), (0.25, 0.62, 1), (0.22, 0.54, 0.9)]$$

Tables 34 and 35 summarize the similarity measures and the resulting alternative rankings generated using method III.

Table 34. Similarity measure between the FPIS and weighted normalized fuzzy decision matrix for each alternative with respect to each decision criterion using method III

	C_1	C_2	C_3	C_4	C_5	C_6	C_7
$S(A_1)$	0.88	0.72	0.81	0.96	1	1	1
$S(A_2)$	0.99	0.73	0.75	0.95	0.66	1	0.88
$S(A_3)$	0.99	1	1	1	0.66	1	0.88

Table 35. Fuzzy similarity of each alternative and its ranking order using method III

	Fuzzy similarity	Ranking order
Alternative 1	0.92	$A_2 > A_1 > A_3$
Alternative 2	0.98	
Alternative 3	0.90	

According to the fuzzy similarity of each alternative shown in Table 32, the ranking order is determined as $A_2 > A_1 > A_3$. Using the forgoing sensitivity analysis, we have shown that the proposed methodology is resilient with respect to the three methods of determine the FPIS. However, we realize that there is a difference in the range the

Fuzzy similarity values, i.e. {0.52, 0.58 0.50}, {1, 1, 1}, and {0.05,0.36,1}. We deduce that method II presents the lowest Fuzzy similarities because the actual status of all alternatives are being compared to the ideal situation. Secondly, method I compares the actual status of the alternatives to the best amongst them, while method III, which presents the highest Fuzzy similarity compares each alternative's status to the data that was generated from the decision makers.

4.3 Study Numerical Results Discussion

In this case study we implement the proposed multi-criteria decision making model to determine the remanufacturability of three products: siento chair, airtouch table and garland double pedestal desk from the CaseSteel Company. We incorporated three remanufacturing aspects, i.e. economic, social and environmental into the multi-criteria decision model. These three aspects are broken down further into seven decision criteria, i.e. namely acquisition (C_1), disassembly (C_2), repair/replacement (C_3), reassembly (C_4), refinish (C_5) all of which a related to the economic aspect, functionality (C_6), which is related to the social aspect and energy saving (C_7), related to the environmental aspects.

Our results show that reassembly (C_4), functionality (C_6), and energy saving (C_7) have generally similar importance in all the three products. To the contrary, acquisition (C_1), disassembly (C_2), repair/replacement (C_3) and refinish (C_5) seem to have inconsistent importance. In particular, our results indicate that the disassembly of the siento and the airtouch products have a higher similarity measure (0.64 and 0.63 respectively) than the garland table (0.36). We infer that since the garland table has 60% of its components as joints, this makes it less suitable for fast disassembly.

Secondly, the refinish similarity measure which is related to the product recovery rate and recovery quality is least for the siento chair (0.22) followed by the garland table (0.44) and lastly the airtouch (0.54). The surface material of the latter two products is predominantly made of wood, which has a higher recovery rate (35%) and may not require much work to improve their quality. To the contrary, the siento chair's surface material is leather, whose recovery rate is much lower (5.5%), thus may need complete replacement to return the products' aesthetics to as-new condition.

Finally, when the similarity measure with respect to the seven criteria are averaged, the airtouch table emerges as having the higher average similarity measure of (0.58) followed by the siento chair (0.52) and finally the garland table (0.50). As was mentioned in Chapter 3, the similarity measure i.e. the distance between the fuzzy remanufacturability number of each product and the positive ideal solution (FPIS) was used because it's been proven to provide the most consistent results than the other comparative fuzzy measures, i.e. the closeness coefficient [84].

From face value, it may be that the similarity measures of 0.58, 0.52 and 0.50 are not significantly dissimilar. There is no proposed measure of test of significance when it comes to comparing the similarity measures of alternative products. However, other applications that have incorporated the similarity measure have proposed a categorical assessment status, such as proposed by Luukka (2011) [84] following the work done by Chen et al.(2006) [71]. Both studies focus on a multi-criteria supplier selection problem for a high-tech manufacturing industry and use the same input data for their model. The only difference between the two research papers is that the latter proposes a selection solution using the closeness criteria, while the former proposes a framework that uses the similarity index. Figure 30 illustrates the supplier approval table proposed in both papers. In short, the table in Figure 30 illustrates how the similarity and closeness coefficient results can be used to not only categorize suppliers into classifications of approval, but also rank the suppliers within each category.

We envision that following collaborative efforts between our research team and a furniture remanufacturing company, such an approval table could be established to classify products into a similar table of remanufacturability status, and further rank (prioritize) the products' suitability for remanufacture within each category. Secondly, we envision that each remanufacturing company would set a threshold (for instance a similarity index of 0.3), below a product could be declared unsuitable for remanufacture.

Similarity value	Assessment status
$S_i \in [0, 0.5)$	Do not recommend
$S_i \in [0.5, 0.7)$	Recommend with high risk
$S_i \in [0.7, 0.8)$	Recommend with low risk
$S_i \in [0.8, 0.9)$	Approved
$S_i \in [0.9, 1.0]$	Approved and preferred

Figure 30. Approval status regarding similarity [84]

Chapter 5

Conclusion and Future Work

The need to evaluate products' potential for remanufacture has arisen in the recent past and researchers are developing decision support tools and protocols to address this need. Increasing awareness of the environmental concerns related to technological changes, product innovations, advanced material usage and shorter product life cycles has necessitated the need for governments to set up regulations that mandate companies to implement end of life management of their products. This is particularly so for automotive and IT products.

Although furniture have great potential growth with regards to their remanufacturing value, there is not much research into their potential for remanufacture. The overall goal of this research is to provide the first exploratory study that fills this research gap. We propose a new framework to evaluate the remanufacturability of office furniture. The evaluation model considers three aspects of the decision problem namely, economic, social and environmental. The assessment of the remanufacturability is a multi-criteria decision making (MCDM) problem. In order to solve the MCDM problem, we apply fuzzy TOPSIS to help with the evaluation of returned office furniture. Fuzzy logic is useful in decision analysis because of its versatility in dealing with input variables that are numeric, categorical or linguistic, this enables a decision maker to combine both precise and imprecise information. TOSIS on the other hand, which stands for Technique for Order of Preference by Similarity to Ideal Solution has been proven to enable the construction of a multi-criteria decision making framework that is based on choosing alternatives whose metrics of interests are closest to the most ideal solution, referred to as the Fuzzy Positive Ideal Solution.

In the proposed model, seven evaluation criteria were determined: acquisition, disassembly, repair/replacement, reassembly, refinish, functionality and energy saving. These criteria were assessed to determine the ranking order of the remanufacturability of each furniture alternative and further use the ranking to select the most appropriate one to remanufacture. The ranking is done by calculating and ordering the fuzzy similarity measure, i.e. the distance between the fuzzy remanufacturability number of each product and the positive ideal solution (FPIS). To test the validity of the proposed evaluation model, real data was obtained from a facility location problem in literature whereby the researchers present a multi-criteria decision problem whose goal is to determine the better geographical location for a textile company.

Finally, we test our model by presenting a case study of three furniture, in which the multi-criteria decision is the choice of the product that has the most potential for remanufacture. These three products, all of which are manufactured and sold by CaseSteel Inc. include the siento chair, the airtouch table and the garland desk. Our results show that the airtouch, an innovative height adjustable table is most remanufacturable, followed by the siento chair and lastly the garland desk, a heavy duty workstation.

This work, the first of its kind serves as the initial exploratory research into producing a decision support system for choosing the best products to remanufacture. The results could be enhanced by considering a categories of office furniture separately, i.e. comparing several chair types. In addition, we believe that the economic, social and environmental aspects are not all inclusive. More aspects that determine the potential of a product for remanufacture and resale should be incorporated. Due to time constraints, this phase of the project was completed before conversation to collaboration with an actual third party company that remanufactures a range of furniture was completed. We envision that the next phase will be strengthen by both anecdotal information from company executives and experts as well as real market, product and process data.

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