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ORIGINAL ARTICLE

Development of decision support system for fastener selection in product recovery oriented design

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Abstract Among the important strategies in sustainable product development is by maintaining product recovery and prolonging product life which are highly dependent on the ease of disassembly. When considering the design for disassembly, there are many fastener-associated factors to be considered such as structural, disassembly process and the pre-disassembly process. There are very few designs for disassembly methods that support the selection of fasteners for design for disassembly (DfD) concepts. Most of the tools developed are more applicable during later stages of the design process when more product information is available. The process of selecting a fastener for its functional characteristics itself is often vague. Additionally, the requirements for disassemblability further complicate the process. This paper proposes the development of a multi-criteria decision making model to assist designers in selecting fasteners for DfD. PROMETHEE was used to build a decision-making model to help the designers in selecting the fasteners that could perform their intended functions with ease of disassembly. A design case study is described to reflect the usefulness of the fasteners selection model.

Keywords Design for disassembly · Product recovery · Fasteners selection · Decision-making model · PROMETHEE

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1 Introduction

Sustainable product development has been a key issue in recent years especially with the stronger awareness in the depletion of natural resources and environmental degradation. In the EU, the heighten awareness of sustainable development is intensified with the introduction of various regulatory measures to ensure sustainable development such as end of life on vehicle directives, energy using products directives and waste of electrical electronic equipment that comply the necessary requirements of product recovery and waste management issues before a product is introduce into its market. Other countries have also responded with various regulatory requirements, such as Japan. In order to remain competitive in this situation, manufacturers must actively ensure product compliance. The production of waste has over burden effect to the landfill cost, which leads to municipalities in some countries to introduce waste tax to producers and consumers. Waste generation is now not only an environmental issue but an economic issue as well whereby the cost of disposing wastes can no longer be discounted as trivial. Product recovery not only reduces the ecological impact, but could also have a positive economic impact to industries through the sale of reused parts and materials. Product recovery is defined as the activities that lead to the salvaging of material and energy of products at its end of life [1].

Another form of strategy in ensuring waste generation to its minimum is by prolonging the life of products through proper maintenance. It further reduces the emission that is caused by product wear and inefficiency. Product recovery and maintenance depend largely on its ability to be disassembled. The introduction of product service supply as a product recovery strategy also have led to the need for better components salvaging whereby disassembly is a critical activity in its success [2]. Disassembly is also important in recycling as the separation of materials will improve recycling efficiency.

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For example, an illustration provided by [3] is the refrigerator recycling, where 96 % of recyclability can be achieved if fully disassembled, 60–80 % recyclability if partial disassembly of different targeted components are accomplished, and 50 % recyclability if only a crush without disassembly in addition to that the produce recycled material may not be of high quality.

According to [4], disassembly is a process in which a product is separated into its components and/or subassemblies by non-destructive or semi-destructive operations. The non-destructive operations constitute as reversible processes which do not damage the fastening mechanism itself, while semi-destructives usually do. In general, the process of disassembling a component requires two main processes which are the disjoining process (unfastening process when non-destructive disassembly is conducted) and removal of the components from the assembly structure. It was found that 32 % of the time required for disassembly is meant for fastener separation [5]. In several disassembly experiments conducted by the authors, it was found that the fastener separation time contributes 30–40 % of the total disassembly time. This showed that the fastener separation could greatly affect the disassembly cost despite of the disassembly motivation. Thus, designers need to carefully consider the design or selection of fasteners not just from the functionality point of view but also from the facilitation of disassembly which is the focus of this study.

During the design phase, the decision-making process is conducted throughout the entire design process and is the core of all activities. The decision made during the early stage of product development or design process contributes to 70–80 % of the design cost. The new paradigm shift in product design process is to increase the knowledge in the early stages of design so as to enhance the freedom of design and reduce cost. Decision making in the conceptual and preliminary design stages is multi level and multi criteria with uncertainty along with incomplete information in nature at times. Designers which are the decision maker (DM) are required to balance the multiple and often potentially conflicting attributes. Many criteria or attributes should be simultaneously taken into account whereby compromise becomes an essential part of decision making in design. In the early stage of engineering design, the decision made during the design process is mainly based on the designer's intuition built from his experience, values and preference. With the increasing complexity of design problems, decision making is almost an impossible task for a single DM to manage. Decision-making methods could facilitate the DM in making a proper decision for a complex problem. Multi-criteria decision making model have been used to assist designer and engineers in making trade-off decision such as found in [6–9]. The aim of this paper is to present a multi-criteria decision making model that assists designers in making design decision by considering the multi-criteria problem in selecting fasteners as one of the major obstacle in a disassembly. The decision making model must also consider that during the design process, design requirements constantly changes and many iterations that exist require fast trade-off studies.

2 Fasteners selection in design for disassembly

Two main elements in an assembly pair normally consist of the component and the fastener. Fasteners are used to hold two mated parts together which greatly influence the disassemblability of the parts. Fasteners are commonly classified into five distinct groups [10]. They are discrete fasteners, integral attachments, adhesive bonding, energy bonding, and others. Discrete fasteners are those that are independent of the parts to be joined. Common examples include screws, bolts, pins, rivets, and nails. Integral fasteners are those that are integrated into the parts to be joined. Most often, they do not require the use of tools to be joined. Common examples are snap fits, force fits, and complaints. Discrete and integral fasteners are often grouped as mechanical fasteners and most commonly used when nondestructive disassembly is required. Adhesive bonding are chemical-based fastener in which a joint is achieved through glues, chemical reactions or phase transition between two parts. Adhesive fasteners provide a good method to discretely hide a joint for better appearance. Although disassembly is possible, it is often difficult and causes surface scarring on the parts. Energy bonding consists of soldering, welding and plastic mould weld. In energy bonding, the joint is achieved by melting or plasticizing of either similar or dissimilar materials in between the joint of two parts. Other common fasteners that do not fall in any of the above classification such as Velcro, zippers and seams generally fall into the mechanical fasteners. For the purpose of this study, only the fasteners in the non-destructive family are considered.

Disassemblability of a part highly depends on the type of fastening element that is employed. Therefore, the selection of fasteners is the main contributor for an efficient design for disassembly (DfD) design. The general guideline for DfD also calls for the proper selection of fasteners as its key elements. Even in design for assembly (DfA), selection of fasteners is regarded as an important element in achieving efficient DfA design [11]. Shu and Flowers [12] in their study of remanufacturing found that in the case of a printer disassembly, the selection between a weld and screws will increase remanufacturing cost nearly doubled.

Fasteners selection is an important decision-making process but very few literatures are available as found by [13–15]. Designers often rely on past experiences, trials and errors or very vague guidelines when selecting fasteners. To add to the problem, the decision in selecting a fastener now needs to be a balancing act between assembly, disassembly and joint function requirements. In [14], an application for fasteners selection using fuzzy logic method is developed. Meanwhile, [13] used a relational database in their fasteners selection application. Both focus more on the operational, processing and economics of the fastener. The above literatures also do not explicitly mention the distribution weights among the various factors of consideration. In addition, [15] found that there was no in-depth studies done on the unfastening process and did a detailed study on the effect of fastener attributes towards the unfastening time of various fasteners. Nonetheless, there are still other factors than fastener attributes that will influence the disassembly time. On the other hand, [16] developed a model which used analytical network process (ANP) in evaluating the fasteners for disassemblability. Disassemblability factors were given the priority but other factors such as appearance, damage potential and design complexity were included as well in the decision making. The model required multiple scenarios to be generated for the evaluation process which was cumbersome as the characteristics of the ANP method itself would not allow for an effective trade-off process. The evaluation of alternative was based on the qualitative preference selection which might not accurately explain the designer's preference. A method for selecting fasteners for remanufacturing based on the statistical data obtain from manufacturers is introduced [12]. It is important to note that during the conceptual design process, requirements are often ambiguous which sometime require trade-off among the various factors. Trade-off study was not explicitly included in most of the methods described above.

All of the above methods have been useful. It is the aim of this research to further add to the knowledge and understanding of fasteners selection for product recovery that is a multi-criteria problem of mixed quantitative and qualitative characteristics. This study attempts to develop a multi-attribute decision making model for the selection of fasteners with the focus on disassembly. In order to achieve this, the PROMETHEE method was used in developing the decision making model.

3 Promethee decision-making model

There are several multi-criteria decision making (MCDM) methods that are available to provide a solution for this particular application such as technique for order preference by similarity to ideal solution (TOPSIS), elimination and choice translating reality (ELECTRE), joint probability decision-making, equivalent cost analysis, multi-attribute utility theory and analytic hierarchy process (AHP). The PROMETHEE methodology was chosen primarily because it can easily and interactively facilitate trade-off [17, 18]. PROMETHEE is also known to be one of the most efficient in the field and is implemented using the software called Decision Lab. PROMETHEE is an evolving MCDM method whereby new updates are developed to solve limitations of the original method. PROMETHEE measures the preference between two alternatives (A against B) on a criteria (J) using a preference function P_j (A, B).

A weighted average of the preference function is calculated to obtain a rank ordering of the alternatives. PROMETHEE I provides a partial pre-ordering of the alternatives through a pair-wise dominance comparison of positive and negative outranking flows, while, PROMETHEE II provides a complete pre-ordering through a comparison of net outranking flows. PROMETHEE has been applied in numerous problems in selection and have been found to be of benefit [7, 19, 20]. The use of PROMETHEE in design decision making is limited in the literatures. Nonetheless, the PROMETHEE method is used because it suits to the problem at hand.

In developing the PROMETHEE model, there are several quantitative estimations and qualitative rating procedures to support the evaluation of the alternative on the various criteria. The use of both quantitative and qualitative data to support decision making is one of the advantageous characteristics of PROMETHEE. The weightings of the criteria are dependent entirely on the PROMETHEE user input in which could be a very daunting task for a designer with high numbers of criteria. But this is also advantageous in trade-off studies whereby designers simulate selection possibilities by modifying their priorities. In order to assist designers in making their preference of the weight, AHP is used to determine them. Nonetheless, default weight value is first determined by using factorial analysis of designer survey. Figure 1 shows the conceptual framework of the proposed model.

4 Parameters for decision model

The PROMETHEE II for the problem under study was carried out in the procedures below:

1. Defined the problem and determined the objectives. In this study, the problem was identified from the question of "how to select the suitable fastener from the available alternatives?"
2. Identified the alternatives (a_j) available. The alternatives are fastener concepts. It is common that certain parts have multiple elements to join it. So various configurations which might consist of single or multiple elements/ fastener was considered as the alternatives.
3. Determined the criteria elements g_j (where j: 1, 2, 3… J) and the corresponding criteria goals whether to maximise or minimise that govern the problem of selecting a fastener for disassembly.

Based on the literature, an extensive list of factors that affected disassembly had been identified and from that, the factors relevant to fasteners were singled out to be used in the PROMETHEE model [21–25]. Nonetheless, several non-

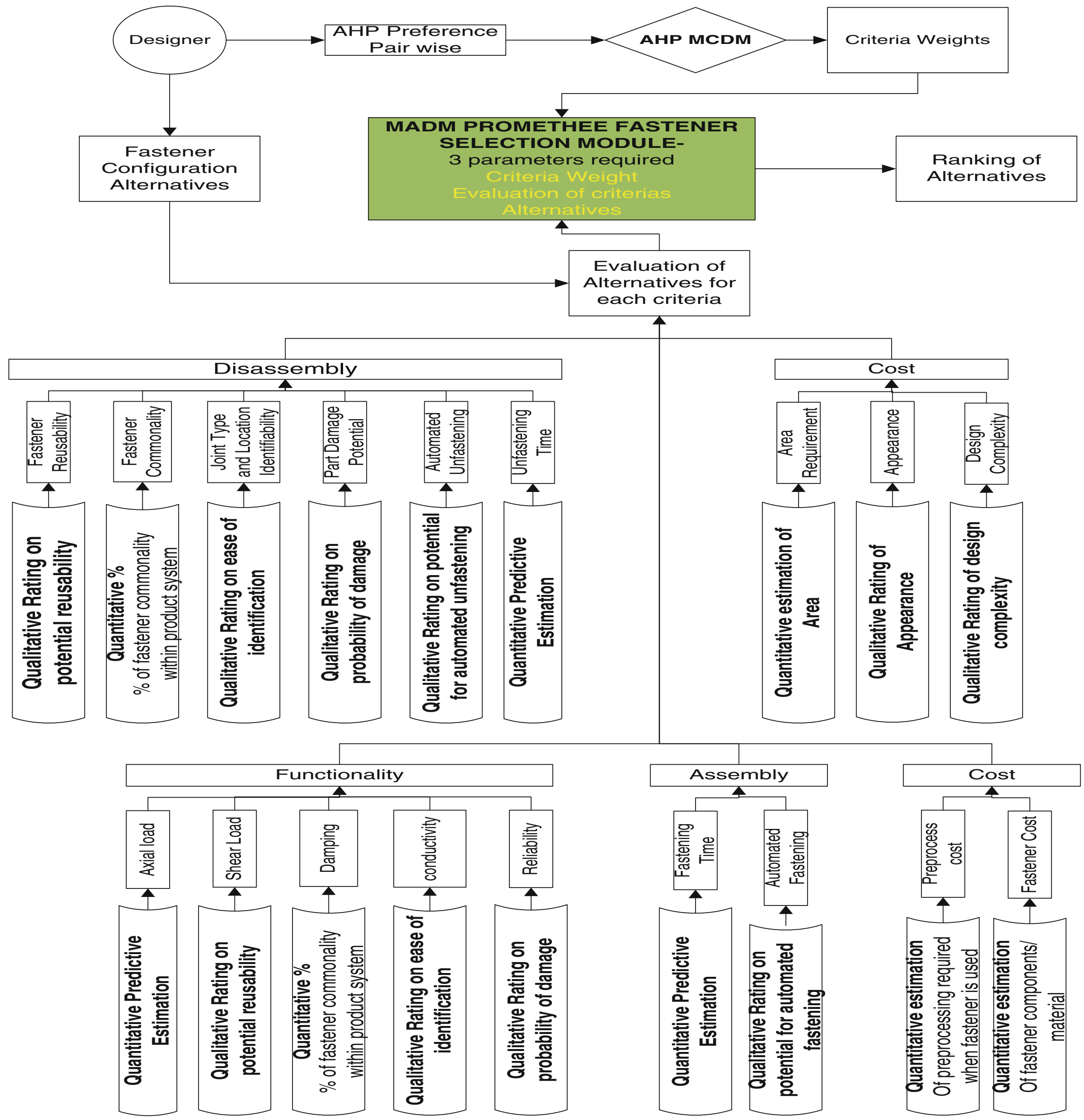

Fig. 1 The decision-making process of the proposed in the conceptual framework

disassembly-related factors, such as assembly time and cost, were included as it could significantly influence the decision in selecting fastener configurations for a part. The functional factors such as strength, reliability and operational conditions were assumed to be pre considered by the designers and the various alternative fastener configurations would have similar or acceptable values.

The criteria that were used in the PROMEETHE decision making model are as follows;

1. Unfastening time—it has the most influence when a fastener for disassembly is selected. The unfastening time corresponds with the increase in labour costs of disassembling a part. This quantitative criterion is supported by a predictive estimation calculator that estimates the unfastening time with a consideration of factors that can affect the unfastening time such as the fastener type, specific attributes, direction of removal, type of tool used and accessibility to the fastener.
2. Identifiability—fasteners are often difficult to identify and locate which causes the disassemblability of a part to become poor. Some fasteners are easily identifiable and yet there are others that are more obscure or difficult to be distinguished. The time it takes to identify the type of fasteners has a direct impact towards the disassembly cost. Identifiability is a qualitative criterion.
3. Reusability—in maintenance, reusability of a fastener is an important issue. A fastener that can be reused

is favourable as it would reduce the cost and time of maintenance. Reusability is a qualitative criterion.

4. Unfastening automation—possible automation is also the choice of demanufacturing. Unfortunately, the type of fastener used may influence the level of automation and the cost of automation. This is a qualitative criterion.
5. Part damage—during the unfastening process, there exists a probability that the part intended for maintenance, reuse or remanufacture, may be damaged. Damaged parts due to the unfastening process will incur new costs, such as for repairs or even losses due to the part being scrapped. This is a qualitative criterion.
6. Commonality—the use of a standardised fastener within a product system is one of the guidelines within DfD. This is a quantitative criterion.
7. Fastening time—the fastening time is the most important among other functional factors when considering a fastener. It has a direct influence towards product cost. This quantitative criterion is supported by a calculator for estimating the fastening time based on the predictive model, it will further support in determining the fastening time for each alternative fastener configuration. The predictive estimate will take into account the type, specific attributes, insertion direction, type of tools used, and the handling of fasteners.
8. Fastening automation—the fasteners selection significantly influences the possibility of automated assembly operations of the product which often present the desirable trait of a product. This is a qualitative criterion.
9. Fastener cost—for most, product cost plays a great concern. This parameter differentiates the cost of the fastener itself. This is a quantitative criterion.
10. Preparation cost—for certain types of fasteners there are requirements for preparation work, such as drilling a hole for rivets or bolts, preparing taps for screws and cleaning of surface for adhesive tapes. Some of the preparation costs add to the hidden cost of using a selected type of fastener.
11. Design complexity—when a fastener is selected, it thus creates a certain level of complexity in which the designer incorporate into the design of the part. This is a qualitative criterion.
12. Appearance—in certain parts, such as the ones on the exterior of consumer products, the aesthetic values have large influence towards the type of fasteners to be used, while in others, such as the interior components, may not put emphasis on the aesthetic values of the fasteners. This is a qualitative criterion.
13. Conductivity—although the main function of a fastener is to join two parts together but in certain products the fastener also functions as a conductor of either heat or current.
14. Damping—fasteners may also be required to function as a dampener levels. Different type of fasteners will differ in their robustness in dampening vibrations.
15. Reliability—the reliability of a fastener to maintain a joint is critical in ensuring a part's ability to perform its function.
16. Area requirement—each fastener will require a certain spatial area that varies depending on the type and configuration of the fastener.

There are six different types of preference function commonly used in PROMETHEE which are type I (usual criterion), type II (U-shape criterion), type III (V-shape criterion), type IV (level criterion), type V (V-shape criterion with indifference threshold criterion), and type VI (Gaussian criterion). Two of them are used in this study, the type IV level and type VI Gaussian preference function which is explain below. Details of the rest of the preference functions can be referred to [26]. There are no strict guidelines available in the literature to suggest the applications of specific preference function but the most commonly used function for quantitative values is the Gaussian criterion, while for qualitative criteria the U shape, V shape and level criterion are often used. From the literatures, it is observed that the preference function is selected based on the type of data and the DM requirements of the degree of preference control. The level preference function depends on two boundary parameter values, q an indifference boundary and p a strict preference boundary. The Gaussian preference function is used whereby the preference at low differences of criteria values increases slowly by the increase of the difference value, starting from zero. With large differences of criteria values the preference function in this case is gradually approaching one. The application of the Gaussian preference function requires the statistical standard deviation of the criteria data. The preference increases rapidly at values of differences close to the standard deviation. Both of the types of the preference function were chosen based on the type of data and the degree of preference control required for the different requirements of the criteria. Based on the preference function, the threshold matrix was formed using the strong preference threshold value (pj) and indifference threshold value (qj) for each of the criterion. Table 1 shows the criterion's preference functions used of the various criteria.

The assigning of weights is one of the drawbacks in PROMETHEE as it does not provide a way to generate the criteria weights. Criteria weights have to be predetermined by the decision maker. The proposed model utilised AHP to generate the weights based on the designer's/DM's pair wise preference ranking. The use of AHP to determine it can also assist the designer to conduct a trade-off between the various

Table 1 Criteria preference function used

Criteria	Type	Preference function	Issues
Unfastening time	Quantitative	Gaussian	Disassembly for service and end of life
Identifiability	Qualitative	Level	
Reusability	Qualitative	Level	
Unfastening automation	Qualitative	Level	
Part damage	Qualitative	Level	
Commonality	Quantitative	Gaussian	
Damping	Qualitative	Level	Auxiliary functions
Conductivity	Qualitative	Level	
Reliability	Qualitative	Level	
Fastening time	Quantitative	Gaussian	Assembly
Fastening automation	Qualitative	Level	
Preprocessing cost	Quantitative	Gaussian	Cost
Fastener cost	Quantitative	Gaussian	
Area requirement	Quantitative	Gaussian	Design
Design complexity	Qualitative	Level	
Appearance	Qualitative	Level	

criterions simulating different scenarios. The use of AHP is not covered in this paper; instead a random number was used to simulate its effects to the ranking.

Once the above steps were taken, the Decision Lab software would be able to calculate the positive and negative outranking flows from which the PROMETHEE I could determine the partial pre order of the decision ranking. By net ranking flow of the PROMETHEE II, a complete ranking of the alternatives could be determined. Then, the walking weights tool available in Decision Lab is used to understand the effects of putting varying importance values on each of criterion in order to simulate the different design policy scenarios. This would allow the designer to trade-off importance value of specific criteria against others. Figure 2 shows the process flow of developing the PROMETHEE model and its corresponding graphical windows provided in the Decision Lab software used in this study.

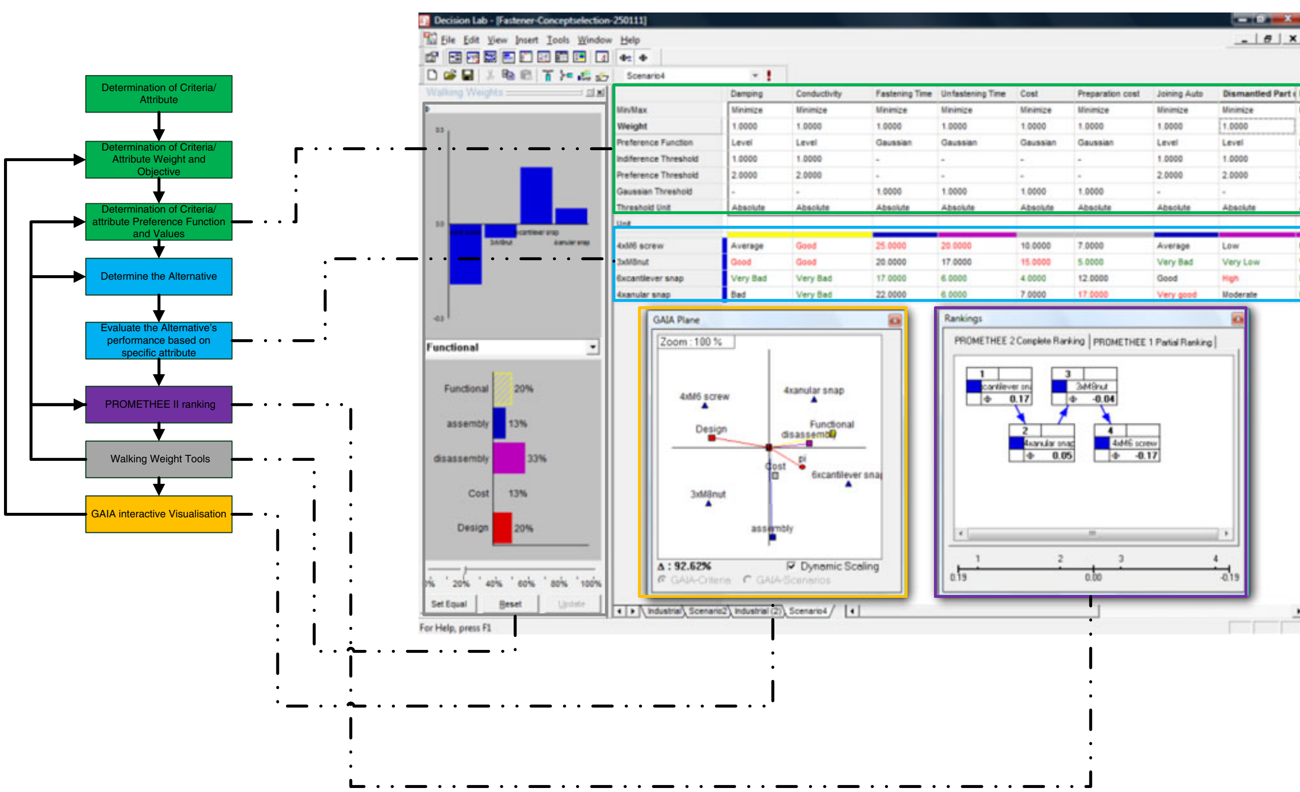

Fig. 2 The execution process of PROMETHEE and its corresponding graphical input–output window in Decision Lab

5 Preliminary development

The development of the ongoing proposed model as a preliminary model was used to illustrate the potential application when selecting a fastener with disassembly as a focus requirement. An example of how the model could be utilised during conceptual design phase at which the available information is still vague but high flexibility for change was presented. The objective of the example scenario was merely to show the applicability of the proposed model in a conceptual design trade-off scenario and was not meant for detail engineering. The car door panel design as shown in Fig. 3 was used as the example for the case study. The polymer-based car door panel is required to be assembled to the steel door frame. Based on the requirements, a group of engineer came up with several concept ideas as alternatives to fasten the door panel to the door frame. It is assumed that the sizing of the concept alternatives has been done to ensure that the joint strength requirements have been satisfied.

There are four alternative fasteners that were considered by the design team, which were the use of four M6 screws alternative, three M8 nut alternative, six element cantilever snaps alternative and six element annular snaps alternative. Sketches of the preliminary concepts are shown in Fig. 3. The weights of the criteria were varied using the walking weight tool while the sub-criteria were considered as to be of equal importance. This was to simulate the effects of the ranking. Figures 4, 5, 6, and 7 show the result of trade-off analysis using the walking weight tool. Different scenario where specific criteria were given higher emphasis can be generated to understand its effect on the ranking in determining the optimal solution. Figure 4 shows the effect of the ranking when assemblability, disassemblability and design factors were given higher emphasis (Fig. 4a) in which the bolt–nut concept and cantilever snap concept had positive net flows with bolt–nut concept being ranked as the better alternative (Fig. 4b). In a different design policy scenario whereby functionality is the utmost priority for product reliability and quality, while maintaining relatively high importance on assembly–disassembly factors for efficient product manufacturing, servicing and end-of-life and cost is not a critical issue (Fig. 5a), the ranking shows that the cantilever snap concept is a better alternative (Fig. 5b). In a different scenario whereby a new design policy were introduce which focuses in providing very

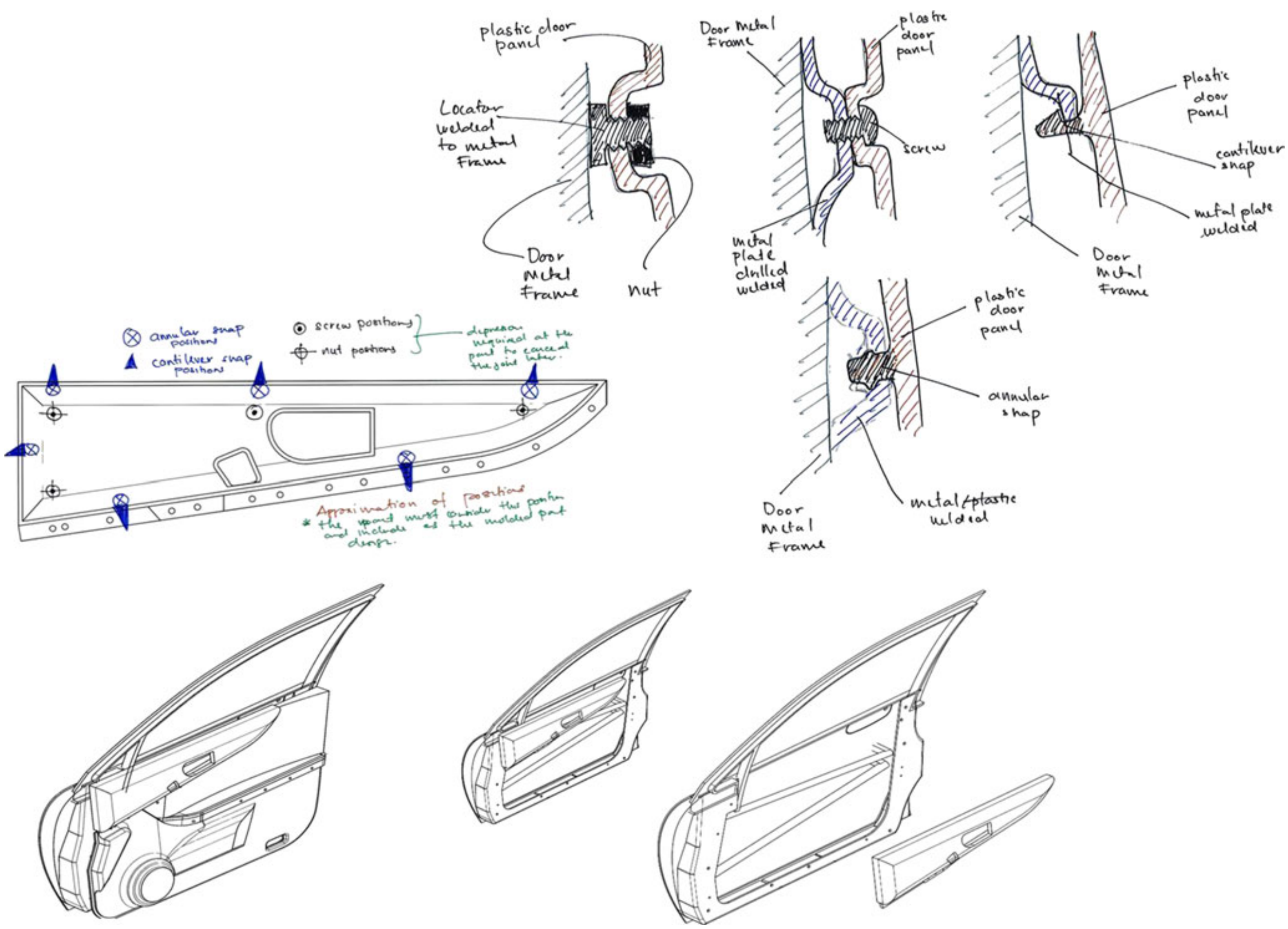

Fig. 3 Initial CAD model of door and sketches of the fastening concept alternatives during conceptual design

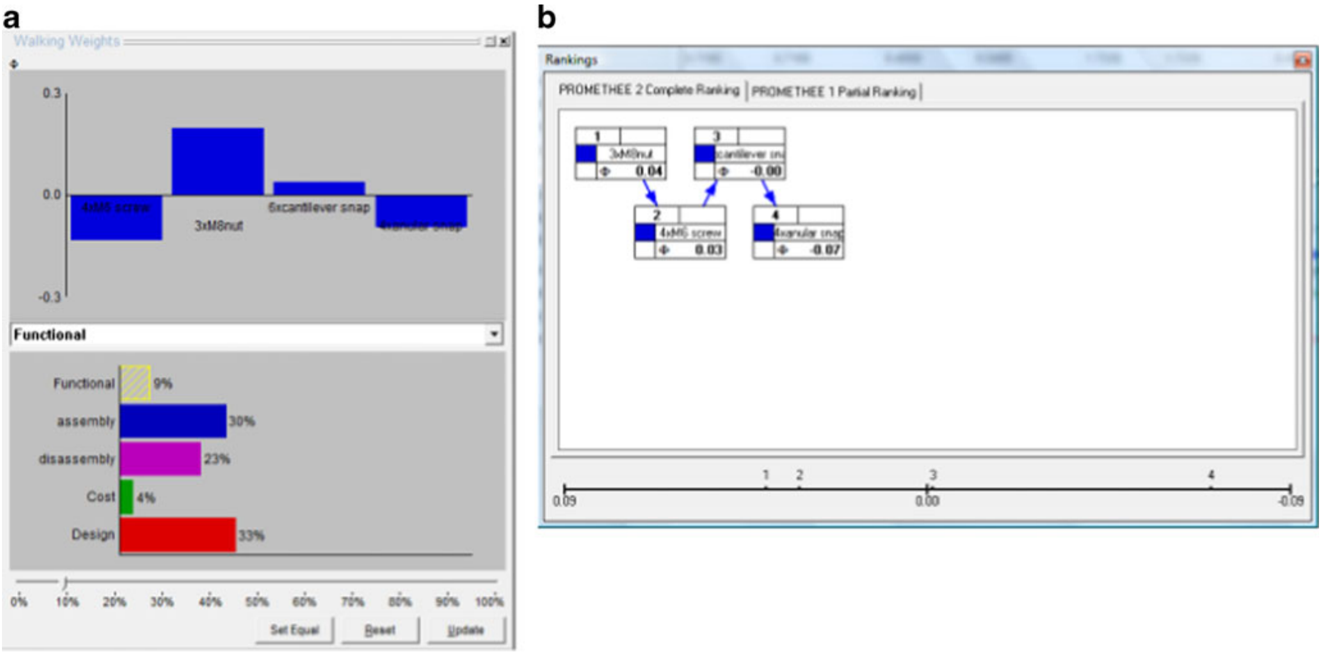

Fig. 4 **a** (*left*) and **b** (*right*) Scenario 1 with nut alternative ranked highest

durable, reliable and profound aesthetics, the design and functionality criteria were set as overly emphasized (Fig. 6a). It resulted in the screw and nut–bolt as the only concept with positive net flows (Fig. 6b). Although the screw is ranked higher than the nut–bolt concept in this instance, but difference of the positive net flow between this two is small. In another scenario in which the company pays very high emphasis in ensuring that the design aesthetically pleasing and caters for efficient recoverability at its end of life, the design and disassembly criteria were set to higher emphasis (Fig. 7a). The result of the ranking shows that only the cantilever snap and annular snap concept have positive net flows with annular snap being ranked first (Fig. 7b). This process depicts the evaluation of different scenarios by varying the design priorities (in this case between assembly, disassembly, costs, auxiliary functions and design issues) which were common trade-off activity in a design process.

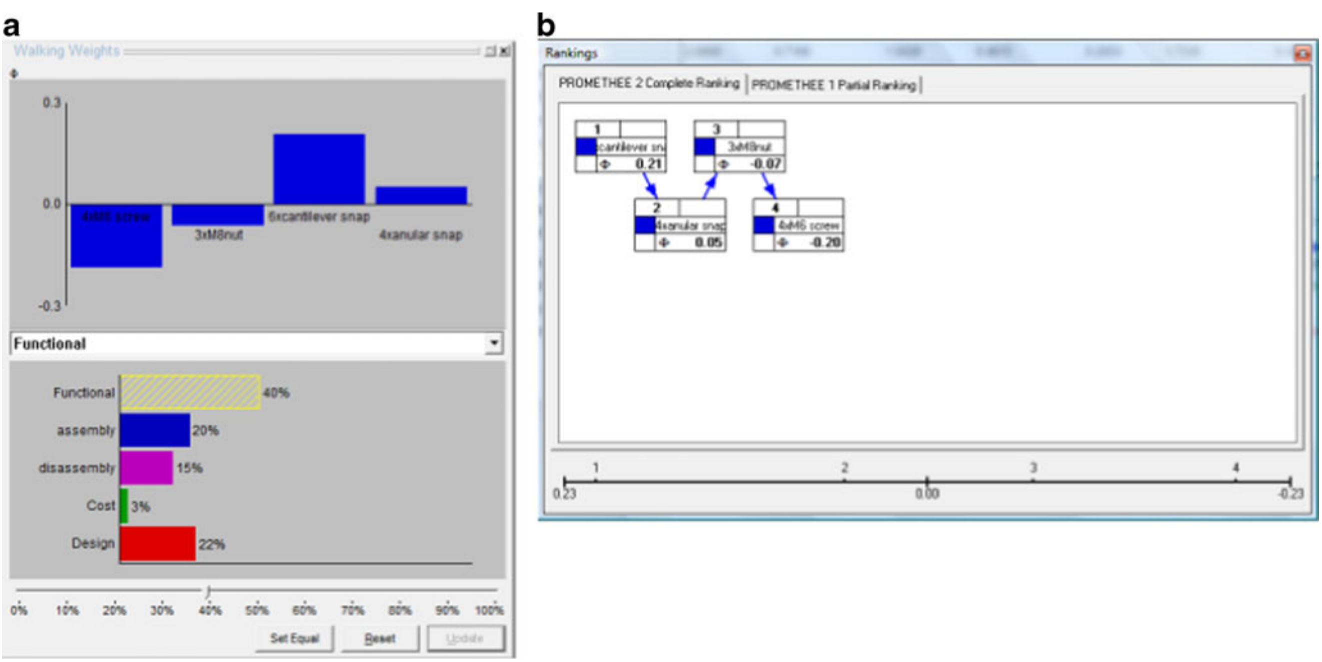

Fig. 5 **a** (*left*) and **b** (*right*) Scenario 2 with cantilever snap alternative ranked highest

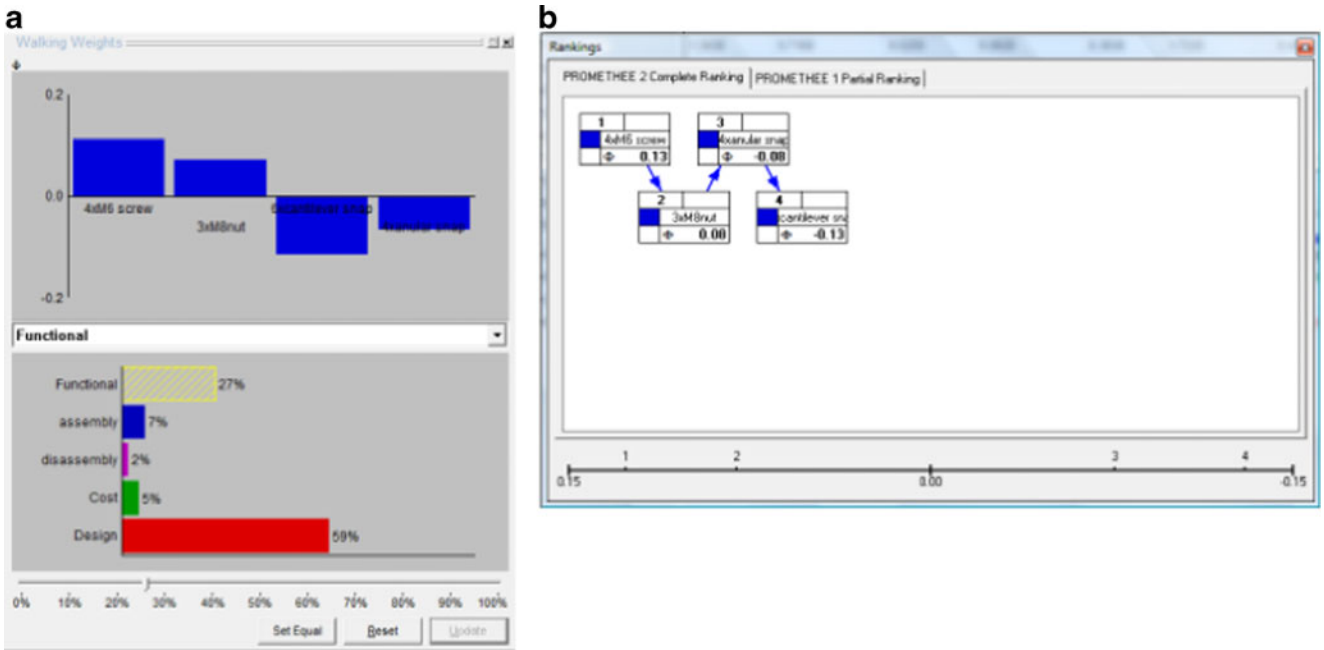

Fig. 6 **a** (*left*) and **b** (*right*) Scenario 3 with screw alternative is ranked highest

The geometrical analysis for interactive aid (GAIA) plane is used to visually represent the effects of the decision when the weights of the criteria varied (Fig. 8). The criteria influence is depicted by the lines that ended with a square. The longer the criteria's line, the more discriminating it is in the decision making. Criteria lines that are in approximately similar direction express similar preference while those in the opposite direction express conflicting preference. Criteria that are not related to each other are in the orthogonal direction. The most discriminating criteria in the current selection problem is the assembly criteria while cost is the least. Both the functional and disassembly criteria have been given similar preference while the design criteria are the conflicting criteria to both of these criteria. Cost and assembly criteria have also been given similar preference to each other. Alternative that are better in a particular criteria will be located in the direction of the corresponding criteria line. The pi line

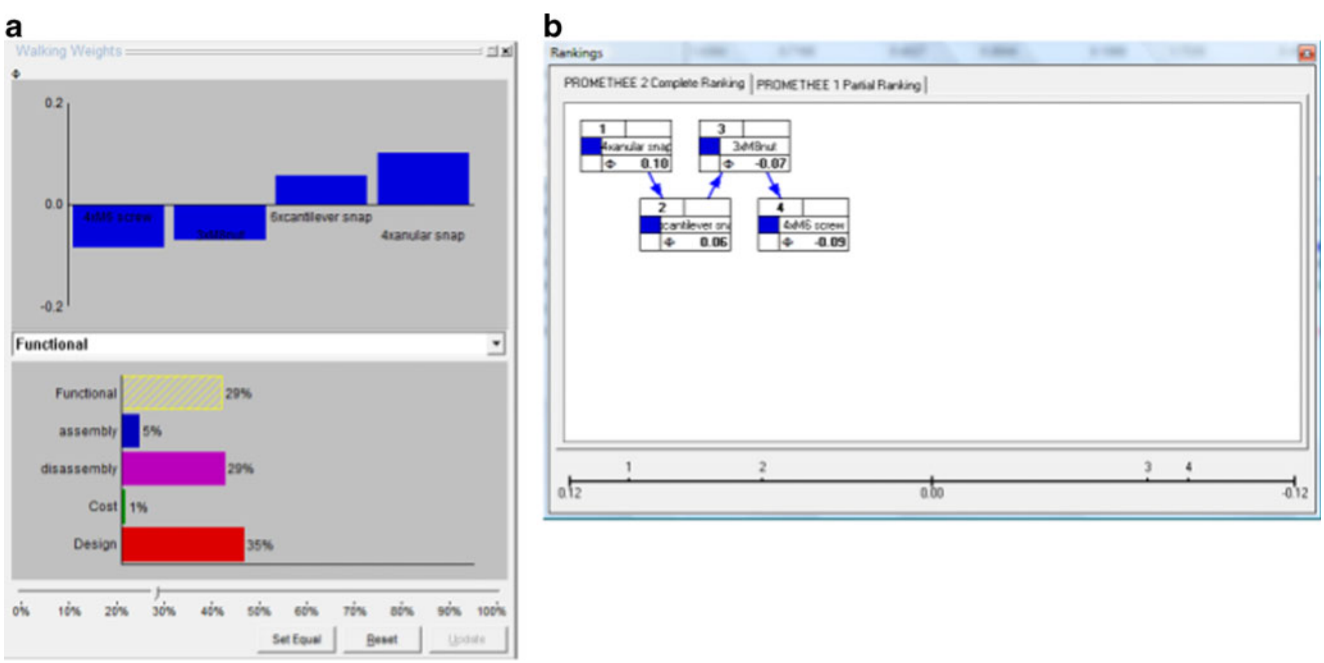

Fig. 7 **a** (*left*) and **b** (*right*) Scenario 4 with annular snap alternative ranked highest

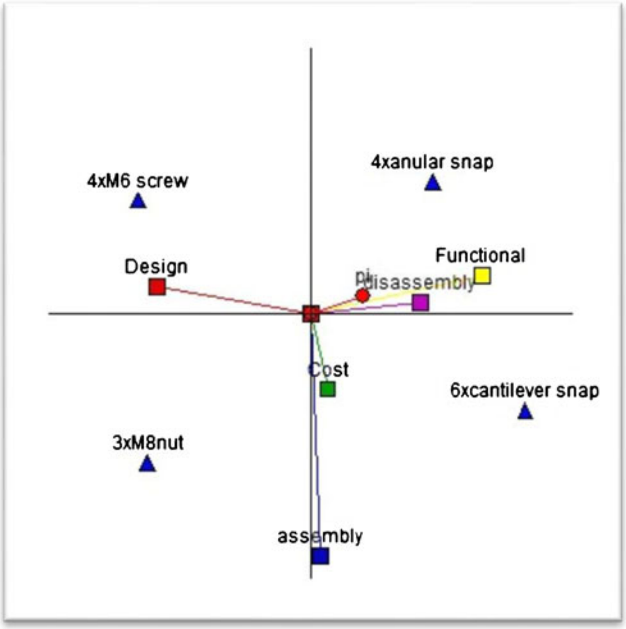

Fig. 8 Geometrical analysis for interactive aid (GAIA) plane of the fastener selection problem

(shown as the line that ends with red circle in Fig. 8) depicts the current decision direction based on the criteria preference of the decision maker. As the preference towards the criteria changes, the pi line direction changes accordingly to indicate the decision maker's preference. The visual aid provided by GAIA enables the designer to further understand his preferences and decision tendencies. Thus, providing a more systematic method of analysing their judgments in which improvements of the alternative concepts can be made.

The example shows that the use the PROMEETHEE model enabled designers to evaluate alternative fasteners based on a multi-criteria problem to make better design decisions. The proposed model developed using Decision Lab provides the designer the advantage of being able to rapidly analyse different scenario or sets of conditions in a trade-off study. By using the walking weight tool, the designers could easily change their design requirement priorities that depict different design policy by changing the weight on the criteria analysing the impact of the changes being made. This allows the designers to simulate his varying decision possibilities to suit to changes in product or organisational policies direction. The graphical representation of the decision using the GAIA plane tool also allowed the designer to analyse in detail his preferences or decision factor and how the design concepts fit within his decision framework. This will be useful in assisting the designer in improving and developing design changes to the concepts. Due to the nature of the PROMETHEE procedure itself, the adding of criteria or alternative could be done swiftly and efficiently. It must be emphasized once again that the decisions made at the design stage have great impact on the complete life cycle of a product. The use of the PROMETHEE model could allow the design decisions to be made more effectively.

6 Conclusion

Disassembly is a key process where most of the product recovery activity is dependent upon. In the disassembly process, the removal of fastening element has been found to have high influence towards the disassembly time and cost. Thus, the proper selection of fastener is critical in ensuring product's ability to be recovered. The inclusion of recoverability factors in the already complex fastener selection decision making necessitate the need for a structured approach to support designers in ensuring assemblies can be effectively recovered while maintaining the functional and cost requirements. This multi-factor problem will require rapid exploration and trade-off studies in identifying the optimal option throughout the iterative concept generation of a design process. This paper proposes a novel decision making model for the product recovery focused selection of fasteners based on a multi-criteria problem using the PROMETHEE multi-criteria decision making model. Although the PROMETHEE model was developed for the selection of fasteners for product recovery, other considerations were also incorporated which considerably influenced the selection of fasteners. The proposed model is expected to help designers make better decisions in selecting fasteners to be used in a product. It was also found to allow the designers to conduct trade-off between the various design criteria. In order to demonstrate the relevance of the model, an example of decision making process was presented. The example highlighted the power of using the PROMETHEE decision making model approach to merge both qualitative and quantitative issues into the design making related decisions. The proposed model is not intended to be used as the final authority in selecting the fastener but rather to support the designer with a structured approach of making selection decision of fastener with respect to product recoverability. The model is developed to compliment other design tools and approach that are currently used by designers. The model is still in its preliminary stage whereby some data are not available in which several assumptions were made namely on the preference values and the alternative performance values which was based on the authors own experience. Nonetheless, the assumption does not affect the applicability of the model's approach and with further work such assumption will based on more concrete data.

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