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Building Model-Driven Decision Support System in Product Redesign Plan

Swee Kuik [1,*] and Li Diong [2]

[1] School of Business and Law, Central Queensland University, 160 Ann Street, Brisbane, Queensland 4000, Australia
[2] School of Commerce, University of Southern Queensland, West St, Darling Heights, Queensland 4350, Australia; lydiong@outlook.com
* Correspondence: s.kuik@cqu.edu.au; Tel.: +61-432-696-064

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Abstract: Product recovery strategy requires a thoughtful consideration of environmental implications of operational processes, undergone by a manufactured product in its entire product lifecycle, from stages of material processing, manufacturing, assembly, transportation, product use, product post-use and end-of-life. At the returns stream from product use stage, those parts and/or component assemblies from a used product have several disposition alternatives for recovery, such as direct reuse, remanufacture, recycle or disposal. Due to such complexity of the manufacturing processes in recovery, current decision methodologies focus on the performance measures of cost, time, waste and quality separately. In this article, an integrated decision model for used product returns stream is developed to measure the recovery of utilisation value in the aspects of cost, waste, time, and quality collectively. In addition, we proposed a model-driven decision support system (DSS) that may be useful for manufacturers in making recovery disposition alternatives. A case application was demonstrated with the use of model-driven DSS to measure recovery utilisation value for the used product disposition alternatives. Finally, the future work and contributions of this study are discussed.

Keywords: decision support system; product redesign; sustainable supply chain; product lifecycle; sustainable manufacturing

1. Introduction

Manufacturers are currently facing significant challenges on minimising used product disposal rate and landfill burdens within the returns stream [1–3]. Typically, the operations strategy to deal with those parts and/or components from used product to be reused, remanufactured and recycled in the manufacturing process is important. Although there are worldwide environmental authorities, such as governmental bodies and agencies, suppliers, manufacturers, distributors, retailers etc., that have emphasised on the development of sustainable manufacturing along a supply chain, total waste minimisation over its product lifecycle is still not easy to achieve at a satisfactory level [4–8]. One of the primary reasons is that there are dispositions alternatives for achieving increased used product utilisation upon returns [5,6,9–16]. The outcome of a large number of surveys involving more than 4000 managers from 113 countries by the Boston Consulting Management Group, has also revealed that 70% of global manufacturers and commercial product service providers have been implementing sustainable product design in their corporate strategy for the last six years, and nearly 20% have done so for the last two years [17].

The term product recovery is not a monolithic research agenda. It also commonly refers to the product redesign plan for returns stream in the manufacturing industries, by increasing recovery utilisation potential for the used manufactured products [18–26]. The existing research on product recovery focuses on various aspects of post-use operations, including environmentally conscious manufacturing and product recovery operations, reverse logistics plan, green supply chain management, product redesign plan, sustainable supply chain management and 3R methodologies (i.e., reuse/remanufacture/recycle related activities) [3,13–15,27–29].

Many companies found the use of real-time communication to surpass expectations, therefore allowing them to effectively analyse different data streams and create new policies or processes that benefit the company as a whole. The manufacturing industry has far superseded any other industry with its improvements on effectiveness and efficiency after implementing the advanced decision support system and communication technologies. The information age saw a shift in consumer behaviour, from physical purchases to online ones. These consumer behaviours have additionally forced businesses to rethink and reshape the methods in which they perform everyday processes, communicate with customers and plan for future events. This also includes the product lifecycle management for manufacturers by considering actual performance measures of used product in the aspects of cost, time, waste and quality.

In today's dynamic environment, substantial interest in sustainability by customers, businesses owners, governments, and community awareness is also driving many sectors in the manufacturing industries to engage with product recovery strategy and its implementation. Until now, numerous industry practitioners are still struggling with product redesign plans from returns streams. This may potentially increase the value of the used product utilisation [27,29–31]. The component disposition alternatives from the product use stage is prevalent. It is also known as recovery configuration option [27,29–31]. For example, those parts and/or components are to be directly reused, remanufactured, recycled, and disposed entirely from the returns stream, which is a practical challenge. The disposition alternatives need to take various manufacturing processes into considerations [11,28,32–34]. Therefore, the appropriate disposition for those parts, and/or components can generate increased recovery utilisation value over its product lifecycle [34–36]. In this article, an integrated decision model in the aspects of cost, time, waste and quality as measured in recovery utilisation value (RUV) is developed for manufactures to examine different component disposition alternatives (i.e., reuse, remanufacture, or recycle) for producing a manufactured product in the manufacturing industry. The objective of this study is to significantly increase the total number of reused, remanufactured and recycled components from the returns stream and reduce disposal rate of these used components. In addition, a model-driven decision support system (DSS) is also proposed by incorporating with the integrated decision model for manufacturers, in order to effectively evaluate the used components from the returns stream in a supply chain. This DSS serves as the computerised support for decision making.

Overall, this article is organised as follows: Section 2 presents relevant background and literature for product recovery operations and its critical-to-reprocess (CTR) activities. Then, the proposed integrated decision model related to this study used to evaluate recovery utilisation value in the aspects of cost, time, waste and quality of a manufactured product is discussed. In Section 3, a model-driven DSS that is used to facilitate the computerised support for decision making is presented. In addition, the model-driven DSS for the case application, which is used to estimate recovery utilisation value is also explained in details. In Section 4, the outcomes of a case application with its comparative study in relation to the model limitations and assumptions are then discussed. Finally, the conclusion and future work are summarised in Section 5.

2. Literature Review

The product lifecycle is often used to consolidate and gather customer and product requirements in order to meet the operations strategy based on design, introduction, growth, maturity and decline phases. However, environmental impacts due to large quantities of disposed used products for landfills are becoming the main concerns in today's world [4,13–15,37]. The usual practice along a supply chain considers the conventional material flows (e.g., sourcing from virgin material suppliers, etc.) from pre-manufacturing to use stages and finally to be disposed of entirely [4,7,8,19]. To achieve effective returns management, operational activities of all associated post-use operations are relatively important to be examined when deciding recovery disposition alternatives of used products [13,27,38]. Two key things are then reviewed in the literature, which are CTR operations, and viewpoint of the assessment aspects for decision makers.

2.1. Critical-to-Reprocess Operations

Upon returns, the used manufactured product has to undergo various quality inspections and checks based on the manufacturer's specific requirements, before being releasing for further processing [31,39]. Some of these further processing activities include mechanical joint operations-related activities, such as welding, brazing, soldering and bonding, assembly/disassembly operations-related activities and techniques including various types of threaded mechanical fasteners [40,41]. In order to manage product returns with recovery, the operations strategy of various recovery related operational activities are to be evaluated thoroughly before implementing a 3R strategy [13]. The scope of the recovery related operational activities are then classified as critical-to-reprocess (CTR) operations for disassembling, assembling, cleaning, refurbishing, repairing, rectifying, segregating, crunching, sorting, etc. [13,16,38,41–43] and summarised in Table 1.

Table 1. CTR associated with recovery related operational activities.

CTR Operations	Description
(1) Material Flows	Arrangement for supplying raw materials and assembly parts and/or component from direct or indirect vendors and/or suppliers [4,7,25,26,39,44]
(2) Assembly/Dis-assembly related activity	Production facilities needed for assembly/disassembly (i.e., manual/semi-automated/automated processes) associated activities [5,6,12,28,45–47]
(3) Reuse related activity	Manufacturing infrastructure and facilities needed for cleaning, handling, sorting, inspecting and testing activities [5,12,27,30,47–49]
(4) Remanufacture related activity	Manufacturing infrastructure and facilities needed for rectifying, repairing and replacing parts and/or components [5,12,27,30,31,47–49]
(5) Recycle related activity	Manufacturing infrastructure and reprocessing facilities needed for shredding, separating, sorting, inspecting and testing [5,11,12,27,30,32,33,37,38,47–49]
(6) Disposal Treatment	Manufacturing infrastructure and treatment facilities needed for segregating non-hazardous or hazardous portions in product or component [4,8,19,20,24,50,51]
(7) Returned arrangement activity	End-of-life arrangement for sorting activities, returns authorisation and administration works, and rebate whenever needed [4,5,10,11,33,35,36,38,41,49]

For achieving high efficiency in planning and arrangement for returned product with recovery, these CTR operations are further examined and improved for practical implementation [5,49,50]. In existing literature reviews, several researchers have already developed performance evaluation and assessment models based on some of these recovery operations for returns management [4,5,8,12,19–21,38,51]. Nevertheless, none of them consider integrating all these operational issues with the CTR operations into a single integrated decision model for making a holistic judgment when selecting the appropriate recovery disposition alternative for a used product in the return stream [6,47,52–54].

The descriptions and definitions of these CTR operations are reviewed to understand the practical constraints. Each of these CTR operations are still largely based on the manufacturers' requirements. It also has the significant influence on organisational performance and operational achievements. By developing an integrated decision model, manufacturers and their decision-makers are able to use it for evaluating and verifying used product's recovery disposition alternatives, before they commence various improvement strategies.

2.2. Product Disposition Decision

In the literature of product recovery related research, there are numerous developed assessment models to examine various assembly or disassembly operations, reuse, rebuild, recycle, disposal and collection related activities as part of their returns handling and management processes. Some researchers have explored the assessment models in different perspectives. However, there is still a need to simplify and formulate a representation model for analysing and assessing all CTR operations and selecting an appropriate recovery disposition alternative based on a trade-off consideration. To assess the overall performance of recovery related activities, a number of performance measurements in operations need to be considered and established for assessment. Table 2 reviews recent literatures of the current performance measures used in recovery and grouped into the aspects of recovery cost, manufacturing lead-time, waste minimisation and reliability.

Table 2. Review of current performance measures in recovery.

Operational Improvement Aspects	Description
Recovery cost	Recovery cost for producing a manufactured product, includes costs of acquiring materials, parts and/or components for assembly and/or disassembly related activities for the purpose of reusing, remanufacturing, and recycling [4,5,10–12,33,37,38,41,51,55]
Manufacturing lead-time	Lead-time for recovery operations include various operational and/or non-operational related activities, such as machine setup, testing, inspection, control, sorting, etc. when reusing, remanufacturing and recycling parts and/or component for producing a manufactured product [4,5,10–12,33,35–38,41,51,55–58]
Waste minimisation	Weight recovery proportion for producing a manufactured product, includes various combinations of reused, rebuilt, recycled or virgin parts and/or components [4,5,11,12,31,32,37–39,49,50,55,59,60]
Quality performance	Reliability describes the ability of a manufactured product to perform well under stated operating condition for a specified period of time. This is one of the important aspects if the product fails during post-use stage or within warranty period. A trade-off decision disposition may be a compromise option for manufacturers and consumers [61–66]

In early years, Merkhofer, Conway, and Anderson developed a guiding framework of the multiple attribute utility decision model to handle hazardous waste management facilities in various location [67]. Sandborn and Murphy also proposed a performance evaluation model to examine economic and environmental aspects for the electronic industries, and study the operations of assembly, disassembly and secondary disassembly [68]. For the integrated approach in product redesign plan, Xing, Belusko, Luong and Abhary developed an integrated product upgradability framework for a few specified engineering, economic and environmental constraints and metrics, such as economic cost, maintenance and reliability of the manufactured product [69].

In fact, the manufacturing processes and its practical recovery related activities are also some of the prevalent aspects to be considered in sustainable manufacturing. Emphasis is still needed on the practical relationship between product redesign activities and manufacturing aspects. In this domain, Fleischmann and Bloemhof-Ruwaard examined product reuse and recycling within reverse logistics for maximising the organisational profits [9]. Liu and Lai also considered the product design aspects by incorporating and configuring new and recycled components for a manufactured product and to achieve minimum environmental consequences [58]. In most of the manufacturing cases, these performance assessment frameworks focused only on the individual profits in product redesign and manufacturing perspectives based on the deterministic scenario, such as source, manufacture, or distribution channels for optimal economic effectiveness due to the operational variations and complexity in handling product returns and recovery management.

In addition to the economic perspectives, the decision models for product returns stream in manufacturing industry have been developed by the researchers of Bufardi et al. [22,42] and Diaz and Marsillac [22,42]. Their decision models include criteria of the cost effectiveness and environmental impacts separately for performance assessment when deciding product use and returns scenario. To achieve a balance of these economic and environmental benefits in terms of cost, time, waste and quality, an appropriate disposition alternative will generally help manufacturers for increasing its recovery value of a manufactured product over its product lifecycle. However, the decision models should be more flexible to control and monitor manufacturing processes and justify technical aspects for a used product. A trade-off compromise is often required for the returns and disposition decision of used products that is examined based on four important aspects as shown in Table 2.

These four important aspects are summarised from the literature review for product recovery and decision dispositions as follows: (i) Minimising recovery associated costs of a manufactured product; (ii) achieving significant reduction of product components and materials for landfill; (iii) minimising manufacturing lead-time when producing a manufactured product; and (iv) improving quality performance that is measured in terms of reliability of a manufactured product in different market segments (such as primary or secondary markets). The viewpoint of these important aspects for environmentally conscious manufacturing and product recovery for improvement is a challenge. Many researchers proposed and applied different operations strategies individually for recovery cost reduction, manufacturing lead-time of a used product for disassembly, waste reduction from returns stream [4,5,10–12,33,37,38,41,51,55]. From a practical perspective, the overall performance of recovery utilisation value should be measured based on the recovery cost, manufacturing lead-time, increased number of reused, remanufactured and recycled components and reliability.

3. System Architecture: A Model-Driven DSS

The system architecture of a model-driven DSS has the hardware infrastructure and software application package. It is divided into user-interface management, data acquisition management, and knowledge management. The integrated decision analysis model can then be incorporated with the system architecture for implementation as shown in Figure 1.

In the following section, the integrated decision analysis model of the DSS for recovery utilisation value of the used product in the returns stream is developed. The integrated decision model for decision makers is based on the economic and environmental justifications, which are associated with cost, time, waste and quality as a whole. By considering the CTR operations of the returns management as presented in Section 2.1, the integrated decision model is built for evaluation purposes. It can also be applied to determine disposition alternatives of various types of combined modules, and/or component from used manufactured products in different sectors of the industrial applications. An analysis of these disposition alternatives for manufacturers aims to improve their recovery strategies and operational performance within the organisation.

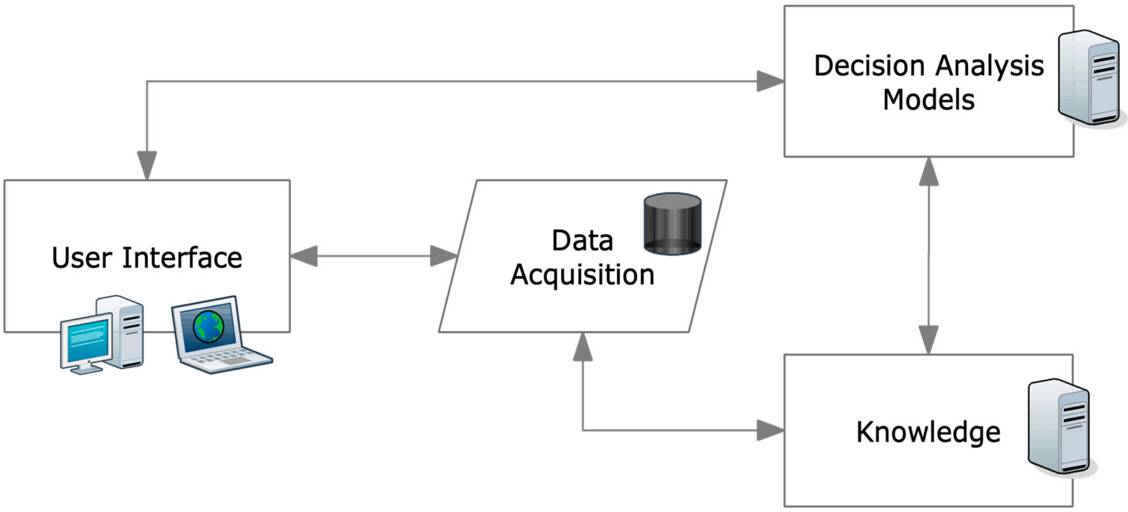

Figure 1. System architecture.

The integrated decision model considers aspects of the recovery costs, manufacturing lead-time, recovery proportion (i.e., to increase number of reused, remanufactured and recycled components), and reliability that are deterministic, and that are measured based on the industrial data. Further, this integrated decision model also aims to simplify the trade-off preference in terms of cost, time, waste, and quality. The key notation set, parameters used of the model and decision variables in the case application are summarised as follows.

3.1. Model Formulation

This section presents the formulation and development of an integrated decision model with recovery considerations for a manufactured product that has a modular structure. It means that the manufactured product may be produced, and/or replaced by different reused, remanufactured and recycled modules and components. The goal of an integrated decision model is to determine higher possible recovery utilisation value for producing a product when deciding disposition alternatives of separate components in returns stream. The trade-off preference based on the cost, time, waste and quality aspects may be useful when evaluating disposition alternatives. In the case application, there are four assessment aspects for this integrated model that are developed to determine an overall of the RUV for a manufactured product. The integrated model includes the assessment aspects of total cost with recovery, manufacturing lead-time, weight for recovery proportions and reliability. First, the total cost for a remanufactured product, TC_{REC}, with recovery considerations is formulated as the summation of the associated cost of producing a manufactured product with, C_{REC} (i.e., utilising reused, remanufactured or recycled components) and without recovery operations (i.e., producing components using virgin materials), C_{VIR}. It is also defined as follows:

$$TC_{REC} = C_{REC} + C_{VIR} \tag{1}$$

Based on the above notations, several equations are mathematically derived for the assessment of total recovery costs in details. For a manufactured product with recovery, the associated cost C_{REC} as assembled in a modular structure, is calculated as:

$$\begin{aligned} C_{REC} = \sum_{m=1}^{j} \sum_{i=1}^{n} \Bigg[X_{2,mi} \left(\sum_{op=3}^{5} C_{op,mi} \right) + X_{3,mi} \left(\sum_{op=3}^{6} C_{op,mi} \right) \\ + X_{4,mi} \left(C_{7,mi} + \sum_{op=2}^{5} C_{op,mi} \right) \Bigg] + \sum_{c=1}^{3} C_c \end{aligned} \tag{2}$$

Term 1 is the summation of cost associated with activities of the assembly/disassembly for cleaning direct reused component-module. Term 2 expresses the summation of cost associated with assembly, and/or disassembly component-module for cleaning and repairing. Term 3 represents the summation of cost associated with processing recycled component-module. Term 4 is the summation of cost associated with collection related activity for a product upon returns. For a manufactured product without recovery, the associated cost, C_{VIR}, as assembled in a modular structure is calculated based on the summation of cost associated with using virgin materials for production as shown in Equation (3):

$$C_{VIR} = \sum_{m=1}^{j} \sum_{i=1}^{n} \left[X_{1,mi} \left(C_{8,mi} + \sum_{op=1}^{3} C_{op,mi} \right) \right] \tag{3}$$

where the incurred costs with the *op*th operational process are then expressed in the following equations:

$$C_{1,mi} = C_{1,pr,mi} + C_{1,hold,mi} \tag{4}$$

$$C_{2,mi} = C_{2,maf,mi} + C_{2,insp,mi} + C_{2,test,mi} + C_{2,hold,mi} \tag{5}$$

$$C_{3,mi} = C_{3,joi,mi} + C_{3,assm,mi} \tag{6}$$

$$C_{4,mi} = C_{4,cl,mi} + C_{4,insp,mi} + C_{4,test,mi} + C_{4,hold,mi} \tag{7}$$

$$C_{5,mi} = C_{5,djoi,mi} + C_{5,das,mi} \tag{8}$$

$$C_{6,mi} = \gamma_{6,mi} C_{6,rpir,mi} + \beta_{6,mi} C_{6,rpl,mi} + C_{6,insp,mi} + C_{6,test,mi} + C_{6,hold,mi} \tag{9}$$

$$C_{7,mi} = \gamma_{7,mi} C_{7,rcywo,mi} + \beta_{7,mi} C_{7,rcyw,mi} + C_{7,hold,mi} \tag{10}$$

$$C_{8,mi} = \gamma_{8,i} C_{8,hz,mi} + \beta_{8,i} C_{8,nhz,mi} \tag{11}$$

$$X_{2,mi} + X_{3,mi} + X_{4,mi} = 1 \tag{12}$$

Equation (4) presents the procurement associated costs for the *i*th component. Equations (5)–(11) are the costs associated with the production, assembly, cleaning, disassembly repairing/replacing, recycling and disposal related treatment. Finally, Equation (12) is the binary decision variables for disposition used in the modelling.

Second, the manufacturing lead-time, MLT_{REC}, is expressed as the summation of manufacturing lead-time with, T_{REC} and without recovery, T_{VIR} as follows:

$$MLT_{REC} = T_{REC} + T_{VIR} \tag{13}$$

for a manufactured product with recovery, the total manufacturing lead-time, T_{REC} in a modular structure is calculated as:

$$T_{REC} = \sum_{m=1}^{j} \sum_{i=1}^{n} \left[X_{2,mi} \left(\sum_{g=2}^{4} T_{g,mi} \right) + X_{3,mi} \left(\sum_{g=2}^{5} T_{g,mi} \right) + X_{4,mi} \left(T_{6,mi} + \sum_{g=1}^{4} T_{g,mi} \right) \right] \tag{14}$$

Term 1 is the lead-time required to complete operational activities, such as assembling, cleaning and disassembling for direct reused component-module. Term 2 represents the lead-time required to complete activities for assembling, cleaning, disassembling, repairing and/replacing of the rebuilt component-module. Term 3 expresses the lead-time required for sorting and processing recycled component-module. For a manufactured product without recovery, total manufacturing lead-time,

T_{VIR}, in a modular structure is calculated as the summation of lead-time required for using virgin materials for production in the following:

$$T_{VIR} = \sum_{m=1}^{j} \sum_{i=1}^{n} \left[X_{1,mi} \left(T_{7,mi} + \sum_{g=1}^{2} T_{g,mi} \right) \right] \tag{15}$$

where the manufacturing lead-time associated with the gth operational process are expressed in the following equations:

$$T_{1,mi} = T_{1,set,mi} + T_{1,maf,mi} + T_{1,insp,mi} + T_{1,test,mi} \tag{16}$$

$$T_{2,mi} = T_{2,set,mi} + T_{2,joi,mi} + T_{2,insp,mi} + T_{2,test,mi} \tag{17}$$

$$T_{3,mi} = T_{3,set,mi} + T_{3,cl,mi} + T_{3,insp,mi} + T_{3,test,mi} \tag{18}$$

$$T_{4,mi} = T_{4,set,mi} + T_{4,djoi,mi} + T_{4,insp,mi} + T_{4,test,mi} \tag{19}$$

$$T_{5,mi} = T_{5,set,mi} + \alpha_{5,mi} T_{5,rpir,mi} + \varphi_{5,mi} T_{5,rpl,mi} + T_{5,insp,mi} + T_{5,test,mi} \tag{20}$$

$$T_{6,mi} = T_{6,set,mi} + \alpha_{6,mi} T_{6,rcycw,mi} + \varphi_{6,mi} T_{6,rcycwo,mi} + T_{6,insp,mi} + T_{6,test,mi} \tag{21}$$

$$T_{7,mi} = T_{7,set,mi} + \alpha_{7,mi} T_{7,hz,mi} + \varphi_{7,i} T_{7,nhz,mi} + T_{7,insp,mi} + T_{test,7,mi} \tag{22}$$

Equation (16) is the lead-time for processing component-module. Equations (17)–(22) are the lead-time required for assembling, cleaning, disassembling, repairing/replacing and recycling.

Third, the total waste minimisation with recovery, WM_{REC} is defined as the weight ratio of the recovery content used for producing a manufactured product as follows:

$$WM_{REC} = \frac{W_{REC}}{W_{TOL}} \tag{23}$$

where the weight proportion with recovery and total weight proportion for a manufactured product are calculated based on the following equations:

$$W_{TOL} = \sum_{m}^{j} \sum_{i=1}^{n} [X_{1,mi}(Z_{1,mi})] \tag{24}$$

$$W_{REC} = \sum_{m}^{j} \sum_{i=1}^{n} [X_{2,mi}(Z_{2,mi}) + X_{3,mi}(Z_{3,mi}) + X_{4,mi}(Z_{4,mi})] \tag{25}$$

Equation (24) is the summation of weight proportion for producing a manufactured product using only all virgin component-module that is known as W_{TOL}. Equation (25) is the summation of weight recovery proportion of the component-module as W_{REC}, where terms 1–3 are the weight recovery proportions of reused, rebuilt and recycled component-module respectively.

Fourth, the quality that is measured as the reliability characteristic when producing a manufactured product, QR_{REC} is fomulated as the multiplication of individual reliability ratio for the component/module with and without recovery:

$$QR_{REC} = R_{REC} \times R_{VIR} \tag{26}$$

As shown in Equation (27), for a manufactured product in a modular structure, the reliability with recovery, R_{REC} is the multiplication of reliability ratio of each recovered component-module:

$$R_{REC} = \prod_{m}^{j} \prod_{i=1}^{n} \left[X_{2,mi} \left(e^{-\left(\frac{l \times \delta_{2,i}}{\theta_{2,i}}\right)^{b_{2,mi}}} \right) + X_{3,mi} \left(e^{-\left(\frac{l \times \delta_{3,mi}}{\theta_{3,mi}}\right)^{b_{3,mi}}} \right) + X_{4,mi} \left(e^{-\left(\frac{\delta_{4,mi}}{\theta_{4,mi}}\right)^{b_{4,mi}}} \right) \right] \tag{27}$$

where Term 1 is the multiplication of reliability ratio of each reused component per module, Term 2 is the multiplication of reliability ratio of each rebuilt component per module and Term 3 is the multiplication of reliability ratio of each recycled component per module. In addition, the reliability for a manufactured product without recovery, R_{VIR}, is defined as multiplication of each individual reliability of each virgin component and/or module levels:

$$R_{VIR} = \prod_{m}^{j} \prod_{i=1}^{n} \left[X_{1,mi} \left(e^{-\left(\frac{\delta_{1,mi}}{\theta_{1,mi}}\right)^{b_{1,mi}}} \right) \right] \quad (28)$$

In current literature, numerous analytical assessment methods of recovery disposition alternatives have emerged as important research for economic and environmental aspects [27,29–31]. These quantitative methods aim to determine the utilisation value for a manufactured product with return streams. In fact, most of the analytical assessment methods in current literature are on the recovery evaluation with these assessment criteria that are assessed separately. The trade-off scenario among these criteria when assessing each of the recovery disposition alternative is less emphasised on performance evaluation in the manufacturing industries. To conduct an evaluation for utilising used products in the returns stream as discussed, the decision model is developed by integrating the important aspects of, MLT, WM, and QR as measured in RUV. The performance evaluation is then classified into two types of the assessment indicators for the selection of recovery redesign plan, such as the economic indicator (ECOI) and environmental indicator (ENVI). The relationship between its economic value of $ECOI_{TC}$ (i.e., total recovery costs with the subscript of TC) and $ECOI_{MLT}$ (i.e., manufacturing lead-time with the subscript of MLT) and environmental value of $ENVI_{WM}$ (i.e., weight proportion in recovery with the subscript of WM) and $ENVI_{QR}$ (i.e., reliability with the subscript of QR) are established to evaluate overall performance for RUV of the recovery configuration option for a manufactured product as shown in Equation (29).

$$RUV = f(ECOI_{TC}, ECOI_{MLT}, ENVI_{WM}, ENVI_{QR}) \quad (29)$$

The developed RUV is applied for evaluating different recovery disposition alternatives for used manufactured products. In fact, not all of the modules and/or components are able to be reused, remanufactured, and recycled due to certain technical specifications and practical constraints for numerous manufacturers. In order to demonstrate the usefulness of a developed decision model, a case study application for disposition recovery plan of product recovery configuration selection were conducted and discussed in the following sections. In the case application, the subscript of REC in RUV is related to the used components in recovery operations, and the subscript of VIR in RUV is related to the virgin components used for producing a manufactured product entirely. The term of "*Exist*" used in the Equations of (30)–(37) means that existing decision disposition alternatives of a used product that has been practising by manufacturers in industry. Manufacturers also prefer to use a set of recovery configuration options for comparative studies, which consists of mixed total number of used (i.e., reused, remanufactured and recycled components) and new components for producing a manufactured product. Therefore, the subscript of "*RA*" and "*RB*" used and formulated for benchmark ratio in the Equations (30)–(37) to represent two different sets of recovery configuration options in industry when producing a manufactured product.

3.2. Model Application

In this section, a case application is selected from the electronic assembly company in Singapore. It is a multi-national company, which was established in 1972 as a sales regional office. In the early 1980s, the company started production assembly of air compressors. It produces different selection ranges of air compressor products from five to seven pistons models. The list of the components used for producing compressor models are the thrust bearing and race slide washer, bearing guide ring, cam rotor and etc. The total number of parts and/or components is approximately 64 including sub-assemblies. There are more than four production lines in assembly. Under the recovery redesign plan by a case company, there are few recovery practices (i.e., using mix-mode of virgin and used components) that have been running for reproducing a manufactured product from returns stream. However, the overall performance of recovery utilisation value, *RUV* has not been systematically measured at this stage. Current disposition alternatives were based on the discussion of technical teams from operations management and design personnel to decide. In this pilot study, the selected five core modules were suggested by the design team for evaluation using a model-driven DSS. The benchmark ratios of Equations of (30)–(35) were established with case company's team for assessment and derived the *RUV* as an overall performance evaluation in the Equation (38). The manufactured product has the Spinner Motor Welded Bracket (Module AA), Spinner Motor (Module BB), Hex Head Cap (Module CC), Drilled Motor Case (Module DD) and Wire Harness (Module EE). Each of these modules is required to be assembled with some separate components as shown Table 3 under this study. In addition, the manufacturing information of the air compressor was obtained from the case company. In practice, there are many separate modules used for air compressor assembly and design. This case company has numerous indirect and direct vendors, and/or sub-assembly suppliers that possessed production facilities for recovery and manufacturing operations.

Table 3. Number of components per module for each product.

<table>
<tr><th>No. Component per Module, Qty.</th><th>Proposed 'RA'</th><th>Proposed 'RB'</th></tr>
<tr><td>ZA/module AA</td><td colspan="2">3</td></tr>
<tr><td>ZB/module BB</td><td colspan="2">2</td></tr>
<tr><td>ZC/module CC</td><td colspan="2">3</td></tr>
<tr><td>ZD/module DD</td><td colspan="2">5</td></tr>
<tr><td>ZE/module EE</td><td colspan="2">3</td></tr>
</table>

In this study, the integrated decision model, including data obtained from cost, time, waste and quality were basically moderated by the case company. The economic and environmental indicators were then translated based on the company' requirements as discussed below for a practical and meaningful analysis. There were four performance measures of cost, time, waste and quality, which were associated with the integrated decision model in DSS to be considered for the analysis. Based on the discussions with the company for the production capabilities and design specifications and conditions, only two selected recovery configuration options were recommended for implementation in current production facilities. Therefore, the proposed recovery configuration options of labelled say as '*RA*' and '*RB*' for a manufactured product are used for comparison in the case application.

Table 3 summarises the company's requirements of two new proposed recovery configuration options. Each set of these proposed recovery configuration options with the disposition decision variables are then recommended by the case company, such as, $X_{1,mi}$, virgin *i*th component for the *m*th module, $X_{2,mi}$, reused *i*th component for the *m*th module, $X_{3,mi}$ for rebuilt *i*th component for the *m*th module, and $X_{4,mi}$ *i*th component for the *m*th module. These separate components in a module based on a 3R strategy were assumed under the condition of wear-out life that was longer than its technology cycle and the depreciation values over a certain period remained constant. The decision makers of a case company could then assess *RUV* of each recovery configuration for comparison. The comparison of recovery configuration options was conducted based on the hypothetical propositions as discussed with the case company. The case application was then studied and analysed with the proposed recovery configuration options of '*RA*' and '*RB*' and compared them with existing manufactured product (i.e., henceforth shall be known as '*Exist*').

If the benchmark ratio for cost, time, waste and quality was met, an organisational improvement was considered to align with the objectives of waste reduction in terms of used product disposal to landfill against the manufacturer's goal and other environmental legislative compliances.

The following benchmark ratio were established with regards to the practical case company in this article as follows:

(a) The economic indicator of this case application is represented as a ratio of the performance benchmark that is more than or equal to one. Then, $ECOI_{TC}$ and $ECOI_{MLT}$ for proposed recovery configuration option of '*RA*' and '*RB*' are written as follows in Equations (30)–(33):

$$ECOI_{TC} = \left(\frac{TC_{Exist}}{TC_{REC}}\right)_{RA} \geq 1 \tag{30}$$

$$ECOI_{TC} = \left(\frac{TC_{Exist}}{TC_{REC}}\right)_{RB} \geq 1 \tag{31}$$

$$ECOI_{MLT} = \left(\frac{MLT_{Exist}}{MLT_{REC}}\right)_{RA} \geq 1 \tag{32}$$

$$ECOI_{MLT} = \left(\frac{MLT_{Exist}}{MLT_{REC}}\right)_{RB} \geq 1 \tag{33}$$

(b) The environmental indicator of this case application is represented as a ratio of the performance benchmark that is approximately close or equal to one. Then, $ENVI_{WM}$ and $ENVI_{QR}$ for proposed product configuration of '*RA*' and '*RB*' are written as follows in Equations (34)–(37):

$$ENVI_{WM} = \left(\frac{WM_{REC}}{WM_{SET}}\right)_{RA} \approx 1 \tag{34}$$

$$ENVI_{WM} = \left(\frac{WM_{REC}}{WM_{SET}}\right)_{RB} \approx 1 \tag{35}$$

$$ENVI_{QR} = \left(\frac{QR_{REC}}{QR_{Exist}}\right)_{RA} \approx 1 \tag{36}$$

$$ENVI_{QR} = \left(\frac{QR_{REC}}{QR_{Exist}}\right)_{RB} \approx 1 \tag{37}$$

(c) In existing literature, there are many researchers and industry practitioners, who have successfully applied and have then recommended the use of the trade-off preference diagram in practical case assessment for manufacturing industries [4,12,14,15,19,69]. In this case application, a trade-off preference diagram for analysing recovery configurations of '*RA*' and '*RB*' was modified to suit the company, and then applied for assessing economic benefits and environmental impacts when producing a manufactured product with different recovery configuration options. An overall quantitative value of RUV_{REC}, for this case application as shown in Equation (38) was formulated to evaluate the utilisation value of recoverable content of a manufactured product in terms of the economic and environmental indicators. Equation (38) is calculated as the summation of each of the areas under a right angled triangle for the trade-off preference diagram as follows:

$$\begin{aligned} RUV_{REC} = &\left(\tfrac{1}{2} \times ECOI_{TC} \times ENVI_{QR}\right) + \left(\tfrac{1}{2} \times ECOI_{TC} \times ENVI_{WM}\right) \\ &+ \left(\tfrac{1}{2} \times ECOI_{MLT} \times ENVI_{QR}\right) \\ &+ \left(\tfrac{1}{2} \times ECOI_{MLT} \times ENVI_{WM}\right) \end{aligned} \tag{38}$$

By substituting Equations (30)–(37) into Equation (38), recovery configurations of RUV_{REC} for a manufactured product can then be expressed as follows in Equation (39) and be applied in the case application:

$$\begin{aligned} RUV_{REC} = {} & \left(\frac{1}{2} \times \frac{TC_{Exist}}{TC_{REC}} \times \frac{QR_{REC}}{QR_{Exist}}\right) + \left(\frac{1}{2} \times \frac{TC_{Exist}}{TC_{REC}} \times \frac{WM_{REC}}{WM_{SET}}\right) \\ & + \left(\frac{1}{2} \times \frac{MLT_{Exist}}{MLT_{REC}} \times \frac{QR_{REC}}{QR_{Exist}}\right) \\ & + \left(\frac{1}{2} \times \frac{MLT_{Exist}}{MLT_{REC}} \times \frac{WM_{REC}}{WM_{SET}}\right) \end{aligned} \tag{39}$$

4. Results and Discussion

In the case application of integrated decision model in DSS, two sets of recovery configuration options of *'RA'* and *'RB'* were used for comparisons. In the first step, all virgin materials and normal manufacturing processes were assumed, and any existing practices by case company were considered. In Table 4, the first column of the information "*Exist*", which was mainly on recycling strategy, was gathered from the case company. In the second step, the subsequent disposition alternatives from the returns stream were then determined by case company. In the final step, the RUV_{REC} for options were then calculated based on Equation (39).

Table 4. Decision disposition of the components per module by a manufacturer.

No. Component per Module, Qty.	*'Exist'*—Manufacturer	Proposed Recovery Configuration Option *'RA'*	Proposed Recovery Configuration Option *'RB'*
ZA/module AA	1 Recycle and 2 Virgin	3 Reuse.	1 Reuse and 2 Reman.
ZB/module BB	1 Recycle and 1 Virgin	2 Virgin.	2 Virgin.
ZC/module CC	2 Recycle and 1 Virgin	2 Reuse and 1 Recycle;	2 Reman and 1 Reuse.
ZD/module DD	3 Recycle and 2 Virgin	1 Reuse; 2 Reman and 2 Virgin.	2 Reman; 2 Recycle and 1 Reuse.
ZE/module EE	1 Recycle and 2 Virgin	2 Reuse and 1 Recycle.	3 Recycle.

The reasons for demonstrating both of these recovery configuration options, were to show the differences of the chosen recovery configuration options in this case company for evaluation, which could directly impact an overall RUV_{REC} for a manufactured product in terms of cost, time, waste and quality from returns stream. Table 4 provides an overview of different sets of recovery configuration options. This study focused on the proposed recovery options of "*RA*" and "*RB*" to see the difference of overall performance evaluation of RUV_{REC}.

Tables 5–8 show the input data for cost, time, and quality from the case company. All these input data were used to calculate the recovery cost, manufacturing lead-time, and reliability. In term of the recovery proportion estimation, this information was obtained from the case company under the materials resource planning (MRP) system. It means that $WM = 1$ is an ideal case of 100% recovery, and $WM = 0$ represents that all will dispose to landfill after the use stage, (e.g., 0.6203 means 62.03% of a manufactured assembly is utilised with about 37.97% that rejected and transferred to landfill). In this study, based on Table 4, both "*RA*" and "*RB*" have a value of 62.03%.

Table 5. Input data and calculation for recovery costs per component from a manufacturer.

	Component/Module	$C_{1,i}$	$C_{2,i}$	$C_{3,i}$	$C_{4,i}$	$C_{5,i}$	$C_{6,i}$	$C_{7,i}$	$C_{8,i}$
Product	ZA/module AA	0.58	1.37	0.25	1.15	0.13	1.88	0.48	1.32
	ZB/module BB	1.72	5.87	0.45	1.53	0.25	1.23	0.54	2.24
	ZC/module CC	0.55	3.94	0.32	1.36	0.32	0.98	0.48	2.24
	ZD/module DD	0.75	4.56	0.68	1.47	0.68	1.23	0.24	2.85
	ZE/module EE	0.25	3.98	0.21	1.85	0.21	1.01	0.17	2.12

Table 6. Collection activity costs per product from a manufacturer.

Collection Activity Costs per Product	$C_{1,collect}$	$C_{2,collect}$	$C_{3,collect}$	$C_{4,collect}$
'Exist'	0.05	0.125	0.251	0.137
Proposed *'RA'*/*'RB'*	0.25	0.214	0.362	0.325

Table 7. Input data and calculation for manufacturing lead-time per component in minutes.

	Component per Module in Minutes	$T_{1,i}$	$T_{2,i}$	$T_{3,i}$	$T_{4,i}$	$T_{5,i}$	$T_{6,i}$	$T_{7,i}$
Product	ZA/module AA	0.81	1.17	0.68	1.23	2.21	0.56	5.58
	ZB/module BB	0.74	1.85	1.01	1.13	2.12	0.41	2.74
	ZC/module CC	0.56	1.62	1.01	1.47	1.56	0.21	3.22
	ZD/module DD	0.72	1.36	0.74	1.71	2.14	0.12	4.12
	ZE/module EE	0.35	1.25	0.65	1.12	3.48	0.14	3.21

Table 8. Input data and calculation for quality in terms of reliability characteristics.

	Module Level	Module AA	Module BB	Module CC	Module DD	Module EE
Product	*'Exist'*	0.9781	0.9924	0.9812	0.9801	0.9751
	'RA'	0.9753	0.9834	0.9835	0.9723	0.9723
	'RB'	0.9753	0.9834	0.9835	0.9723	0.9623

The proposed decision model as presented in Section 3.2 was then applied to evaluate the RUV_{REC} for manufactured products with two sets of recovery configuration options. The results and comparison between these recovery configuration options by case company are illustrated in Tables 9 and 10.

Table 9. A summary of the product configurations for comparison.

Configuration	*'Exist'*	Proposed *'RA'*	Proposed *'RB'*
Cost (TC)	$110.41	$66.19	$83.88
Time (MLT)	85.19 min	72.81 min	83.25 min
Waste (WM)	0.4958	0.6203	0.6203
Quality (QR)	0.9102	0.8918	0.8826

Note: WM = 1 means an ideal case of 100% recovery, and WM = 0 represents all will dispose to landfill after use stage, (e.g., 0.6203 means 62.03% of a manufactured assembly is utilised with about 37.97% that rejected and transferred to landfill).

Table 10. A summary of the RUV_{REC}.

Product Configuration	RUV_{REC}
Proposed *'RA'*	2.746
Proposed *'RB'*	2.251

A trade-off preference diagram of cost, time, waste and quality for these recovery configuration "*RA*" and "*RB*" is illustrated in Figure 2. The results from "*RA*" and "*RB*" show the difference in terms of cost, time, waste and quality, and Table 9 shows the individual values of each aspects for "*RA*" and "*RB*". The recovery configuration option, "*RA*" is outperformed by "*RB*". By using Equation (39), the overall performance index of RUV_{REC} can be measured, which is about 2.746 and 2.251 respectively as tabulated in Table 10.

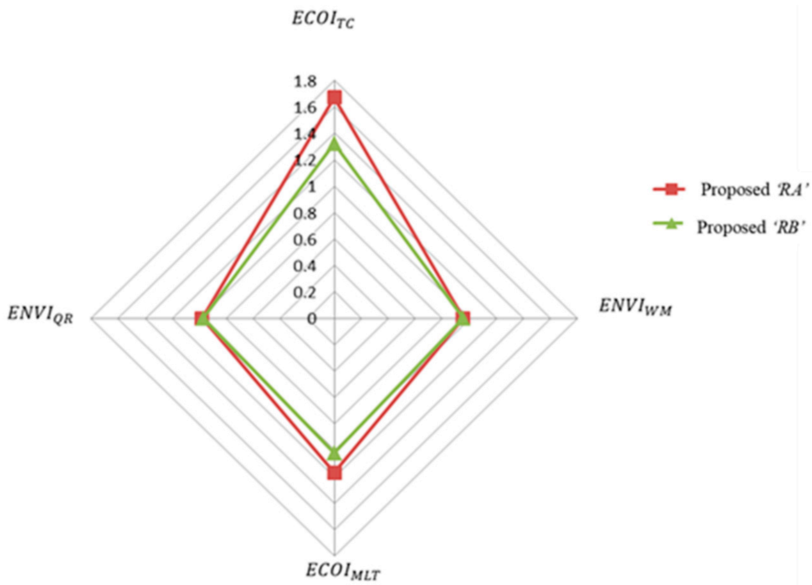

Figure 2. Trade-off preference diagram for proposed '*RA*' and '*RB*'.

In addition, the trade-offs quantification among these aspects considered in Figure 2 shows that product '*RA*' option is a highly recommended solution based on the quantitative RUV_{REC}. By comparing product recovery configuration options, the total cost in the recovery of product configuration '*RB*' (i.e., *TC* = *$83.88*) was significantly higher than product configuration '*RA*' (i.e., *TC* = *$66.19*). In terms of quality according to the reliability attribute, it is about 89.26% for product configuration '*RA*' and 89.18% for product configuration '*RB*'. The manufacturing lead-time for product configuration '*RA*' of 72.81 min was generally lower than that of product configuration '*RB*' of 83.25 min, and that of the existing manufactured product of 85.19 min. However, the estimated waste reduction for both products '*RA*' or '*RB*' was accounted to be approximately 62.03% of the recoverable content.

As a result, all of these trade-off considerations were crucial in determining an appropriate disposition of the recovery configuration options in the manufacturing industry. The integrated decision model in this study is highly recommended, and useful for manufacturers to make a holistic judgement by evaluating and analysing all four important aspects, and to estimate the RUV_{REC} when selecting an appropriate recovery configuration option in the returns stream.

This decision model is developed and applied to case application with aims to reduce overestimation issues on assessing recovery operations, by considering recovery cost effectiveness for implementation. The performance evaluation based on total recovery cost, manufacturing lead-time, waste minimisation of product disposal to landfill and quality in reliability characteristics can actually serve as a decisive role in the selection of an appropriate recovery configuration when designing returns management processes. Based on the results obtained from RUV_{REC} estimations, the proposed product configuration option, '*RA*' outperformed the proposed product configuration option '*RB*'. In other words, the disposition strategy considered has provided an assessment that the proposed configuration option '*RA*' could achieve better performance than '*RB*' in terms of recovery cost and manufacturing lead-time, waste minimisation and quality performance. Therefore, the manufacturer could then consider implementing product configuration option '*RA*' for future recovery improvement plan.

In practice, reliability is one of the critical dimensions of quality. It also deals with product performance over a specified time period. There are several papers that focus on product reliability and variations using the Weibull distribution [61–66]. The Weibull function is still subject to the different shape parameters in practice. At the return streams from product use stage, those parts and/or component assemblies from a product have several disposition alternatives for recovery, such as direct reuse, remanufacture, recycle or direct disposal. Not all components are set to be reused, and some other components may need to be remanufactured or recycled. A set of recovery configuration options in this study have different disposition alternatives for each component. The determination of shape parameters has to be used for evaluation in this study, based on the component data and information under the some experimental tests in the case company. The additional experimental data for reliability tests need to be conducted.

The case company focused on two different recovery configuration options of manufactured product "*RA*" and product "*RB*" for evaluation. Nevertheless, the integrated decision model in DSS is capable of evaluating the trade-off and their relationships when determining RUV_{REC} for a manufactured product. In future research, manufacturers have shown their interests to determine recovery configuration options that can be based on the existing production capability, technical specifications, as well as technical constraints from the suppliers and/or vendors. These specifications still need to be examined in detail; for example, wear-out life, technology cycle, design lifecycle, functionality of the returned items and quality of the returned items. In addition, there are also few practical limitations of the developed model that needs for further evaluation, such as environment impacts for logistics, air emission quality, water consumptions, electricity usage and etc. for the product lifecycle.

5. Conclusions

The model-driven DSS in this article enables the manufactures to evaluate recovery utilisation, values of used products from the returns stream and to use computerised support in decision making. At the returns stream, those parts and/or component assemblies from a used product may have several disposition alternatives for recovery, such as direct reuse, remanufacture, recycle or disposal. Different sets of the recovery configuration options used in case application for comparative studies including the total number of used separate components (i.e., reused, remanufactured and recycled components) and new separate components. In addition, the trade-off preference diagram in DSS for recovery configuration options as shown in Figure 2, may also be useful for manufacturers to check the aspects of cost, time, waste and quality individually. The overall performance index of RUV_{REC} in Equation (39) is established and measured the recovery configuration options.

This article provides several significant contributions. Firstly, the recovery configuration options by a case company were studied at the returns stream to increase economic and environmental benefits. Past research studies as discussed in Section 2, tend to oversimplify performance evaluation of the product recovery, which focuses mainly on evaluating recovery cost as a key measure for decision making. Secondly, there are various different types of product modules and/or components for manufacturing, assembling/disassembling, remanufacturing, recycling, reusing, and collection management related activities. An integrated decision model in the DSS can be used and evaluated for recovery disposition alternatives of used products in the manufacturing industry. Thirdly, the model-driven DSS was applied to show its usefulness and insights and promote computerised support in decision making for manufacturers.

For future work, an integrated decision model in the DSS can also be extended to optimise different sets of recovery configuration options in the returns stream, and then to achieve significant improvement levels in RUV_{REC} as suggested by a case company.

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Notations and Parameters

Decision variables:	
j	Maximum number of modules for a manufactured product
n	Maximum number of components of the mth module for a manufactured product
r	Decision Index of virgin, r = 1, reuse, r = 2, remanufacture, r = 3 and recycle, r = 4
m	is the mth module of the manufactured product, $(1, 2, \ldots, j)$
i	is the ith component of the module, where each component comprises a single material only, $(1, 2, \ldots, n)$
$X_{r,mi}$	$= 1$ is the ith component of the mth module, otherwise, = 0
Cost parameters:	
$C_{op,mi}$	The cost margin of the operational processes, $op = 1, 2, \ldots, 8$ of the ith component
$C_{1,mi}$	The total cost of new acquisition material of the ith component
$C_{1,pr,mi}$	The cost for procurement activity of the ith component
$C_{1,hold,mi}$	Inventory holding cost of the ith component (procurement)
$C_{2,mi}$	The total cost of manufacturing of the ith component
$C_{2,maf,mi}$	The cost of manufacturing of the ith component
$C_{2,insp,mi}$	Inspection cost of the ith component after manufacturing
$C_{2,test,mi}$	Testing cost of the ith component after manufacturing
$C_{2,hold,mi}$	Inventory holding cost of the ith component (manufacturing)
$C_{3,mi}$	The total cost for assembly of the ith component
$C_{3,joi,mi}$	The cost for mechanical joint assembly of the ith component (i.e., welding, brazing, adhesive, bonding, etc.)
$C_{3,assm,mi}$	The cost of assembly of the ith component (i.e., threaded fasteners, rivets, etc.)
$C_{4,mi}$	The cost of direct reuse of the ith component
$C_{4,cle,mi}$	The cost of cleaning of the ith component
$C_{4,insp,mi}$	Inspection cost of the ith component after cleaning
$C_{4,test,mi}$	Testing cost of the ith component after cleaning
$C_{4,hold,mi}$	Inventory holding cost of the ith component (reuse)
$C_{5,mi}$	The total cost for disassembly of the ith component
$C_{5,djoi,mi}$	The cost for mechanical joint disassembly of the ith component (i.e., welding, brazing, adhesive, bonding, etc.)
$C_{5,das,mi}$	The cost of disassembly of the ith component (i.e., threaded fasteners, rivets, etc.)
$C_{6,mi}$	Total cost of remanufacturing of the ith component
$C_{6,rpir,mi}$	The cost of repairing of the ith component
$C_{6,rpl,mi}$	The cost of replacing of the ith component
$C_{6,insp,mi}$	Inspection cost of the ith component after remanufacturing
$C_{6,test,mi}$	Testing cost of the ith component after cleaning
$C_{6,hold,mi}$	Inventory holding cost of the ith component (remanufacturing
$\gamma_{6,mi}$	=1 the ith component can be repaired, otherwise, =0
$\beta_{6,mi}$	=1 the ith component can be replaced, otherwise, =0
$C_{7,mi}$	The total cost of recycling of the ith component including shredding, separation and handling, etc., with or without disassembly.
$C_{7,rcywo,mi}$	The cost of shredding, separation and handling, etc. without disassembly of the ith component
$C_{7,rcyw,mi}$	The cost of shredding, separation and handling, etc. with disassembly of the ith component
$\gamma_{7,mi}$	=1 the ith component needs to be disassembled for recycling, otherwise, =0
$\beta_{7,mi}$	=1 the ith component needs not to be disassembled for recycling, otherwise, =0
$C_{7,hold,mi}$	Inventory holding cost of the ith component (recycling)
$C_{8,mi}$	The total cost of disposal and treatment of the ith component that is the incineration or landfill for hazardous or non-hazardous contents
$C_{6,hz,mi}$	The disposal cost with hazardous content of the ith component
$C_{6,nhz,mi}$	The disposal cost without hazardous content of the ith component

$\gamma_{8,mi}$	= 1 if the *i*th component with hazardous content, otherwise, =0
$\beta_{8,mi}$	= 1 if the *i*th component with non-hazardous content, otherwise, =0
C_c	The total cost of the returns activity, c of the returned item, incurred by the manufacturer
C_1	The cost of general administration of the item
C_2	The cost of sorting of the item
C_3	The cost of shipping and transporting of the item
Time parameters:	
$T_{g,mi}$	The lead-time for the operational process, $g = 1, 2, \ldots 7$ of the *i*th component
$T_{1,mi}$	The total lead-time of manufacturing of the *i*th component
$T_{1,set,mi}$	The time required of manufacturing setup job of the *i*th component
$T_{1,maf,mi}$	The time required of manufacturing of the *i*th component
$T_{1,test,mi}$	The time required of test activity of the *i*th component (manufacturing)
$T_{1,insp,mi}$	The time required of inspection activity of the *i*th component (manufacturing)
$T_{2,mi}$	The total lead-time for assembly of the *i*th component
$T_{2,set,mi}$	The time required of assembly setup job of the *i*th component
$T_{2,joi,mi}$	The time required of mechanical joint job of the *i*th component
$T_{2,assm,mi}$	The time required of subassembly job of the *i*th component
$T_{2,test,mi}$	The time required of test activity of the *i*th component (assembly)
$T_{2,insp,mi}$	The time required of inspection activity of the *i*th component (assembly)
$T_{3,mi}$	The total lead-time of direct reuse of the *i*th component
$T_{3,set,mi}$	The time required of direct reuse setup job of the *i*th component
$T_{3,cl,mi}$	The time required cleaning/processing job of the *i*th component
$T_{3,test,mi}$	The time required of test activity of the *i*th component (reuse)
$T_{3,insp,mi}$	The time required of inspection activity of the *i*th component (reuse)
$T_{4,mi}$	The total lead-time for disassembly of the *i*th component
$T_{4,set,mi}$	The time required of disassembly setup job of the *i*th component
$T_{4,djoi,mi}$	The time required of mechanical disjoint job of the *i*th component
$T_{4,das,mi}$	The time required of sub-disassembly job of the *i*th component
$T_{4,test,mi}$	The time required of test activity of the *i*th component (disassembly)
$T_{4,insp,mi}$	The time required of inspection activity of the *i*th component (disassembly)
$T_{5,mi}$	The total lead-time of remanufacturing of the *i*th component
$T_{5,set,mi}$	The time required of remanufacturing setup job of the *i*th component
$T_{5,rpir,mi}$	The time required of repairing of the *i*th component
$T_{5,rpl,mi}$	The time required of replacing of the *i*th component
$\alpha_{5,mi}$	=1, if the *i*th component is to be repaired, otherwise, =0
$\varphi_{5,mi}$	=1, if the *i*th component is to be replaced, otherwise, =0
$T_{5,test,mi}$	The time required of test activity of the *i*th component (remanufacture)
$T_{5,insp,mi}$	The time required of inspection activity of the *i*th component (remanufacture)
$T_{6,mi}$	The total lead-time of recycling of the *i*th component
$T_{6,set,mi}$	The time required of recycling setup job of the *i*th component
$T_{6,rcyw,mi}$	The time required of recycling with disassembly of the *i*th component
$T_{6,rcywo,mi}$	The time required of recycling without disassembly of the *i*th component
$\alpha_{6,mi}$	=1, if the *i*th component is for recycling with disassembly, otherwise =0
$\varphi_{6,mi}$	=1, if the *i*th component is for recycling without disassembly, otherwise =0
$T_{6,test,mi}$	The time required of test activity of the *i*th component (recycle)
$T_{6,insp,mi}$	The time required of inspection activity of the *i*th component (recycle)
$T_{7,mi}$	Total lead-time of disposal and treatment of the *i*th component
$T_{7,set,mi}$	The time required of disposal setup job of the *i*th component
$T_{7,hz,mi}$	The time required to dispose the *i*th component with hazardous content
$T_{7,nhz,mi}$	The time required to dispose the *i*th component without hazardous content
$\alpha_{7,mi}$	=1 if the *i*th component has hazardous content, otherwise, =0
$\varphi_{7,mi}$	=1 if the *i*th component has non-hazardous content, otherwise =0

$T_{7,test,mi}$	The time required of test activity of the *i*th component (disposal)
$T_{7,insp,mi}$	The time required of inspection activity of the *i*th component (disposal)
Waste parameters:	
W_{TOL}	Total mass of a manufactured product
W_{REC}	Total mass of the recovery proportion of a manufactured product
$Z_{r,mi}$	The mass proportion of the *i*th component
Quality parameters:	
$b_{r,mi}$	The Weibull shape parameter of the *i*th component
$\theta_{r,mi}$	The characteristic life for the *i*th component
$\delta_{r,mi}$	The average operating hours before the *i*th component is taken back

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