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Performance measurement of product returns with recovery for sustainable manufacturing

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ABSTRACT

Today's lifecycle of new and emerging products, increase in labour costs in developed countries and user's expectations or behaviours including frequently upgrading items with latest features, influence the growth rate of product disposal to landfill. To reduce the negative impact on the environment, global manufacturers need to take responsibility for designing sustainable products and implementing cleaner production systems for 3R operations (3*R–Reuse/Remanufacture/Recycle*). Nevertheless, there is still a lack of comprehensive measures for assessing product returns with recovery settings. In this paper, a framework for performance evaluation using design for six sigma methodology is developed to estimate utilisation value of a manufactured product with recovery settings, which accounts for total recovery cost, manufacturing lead-time, minimisation for landfill waste and quality characteristic. Finally, a numerical example based on these performance attributes to assess product utilisation value is presented.

1. Introduction

Due to rapid changes in advanced technology development and a need for the introduction of new innovative products in the markets, research on product returns with recovery options has emerged as an important research area [1–3]. Environmental directives such as WEEE (waste electrical, electronic and equipment), RoHS (restriction of hazardous substances), ELVs (end-of-life vehicles) and EuP (energy-using product), ISO 24700:2005 standard and guideline have been proposed for controlling environmental impacts associated with manufacturing processes [4–6]. These proactive initiatives also stipulate original equipment manufacturers (OEMs) to account for the environmental degradation of landfill due to the product disposal and to consider product returns with recovery operations.

In recent years, returns management process has been recognised as one of the key supply chain management processes by Supply Chain Operations Reference (SCOR) model and the Global Supply Chain Forum (GSCF) framework for promoting environmental conscious manufacturing [7–9]. Nevertheless, the quantitative performance evaluation and analysis of the returns management process still remains a challenge due to the limitation of performance assessment guidelines, which can address the complexity of recovery operations and collection related activities [4,10]. Subsequently, the involvement of various multiple suppliers, manufacturers, retailers, consumers and collection agents within supply chain networks is a another crucial bottleneck in designing optimised product returns workflow with recovery settings [11]. Therefore, performance evaluation with returns workflow for manufacturers should include selection of the appropriate measures and methods for interpreting outcomes of recovery operations and improvement analysis.

Guide et al. [12] highlighted seven primary characteristics of uncertainties within product recovery activities such as uncertainty of timing and quality returns, the need to balance returns and demand management, disassemblability of returned items, complications of mix-material matching restrictions and stochastic routings for material flow and uncertainty of processing times. To account for all the risks of uncertainties, which are related to recoverable items, a proposal for the trade-off method to assess performance measurement is used to examine the utilisation value of recoverable content for a manufactured product. The purpose of this method, which is based on this trade-off scenario, aims to satisfy environmentally conscious practices associated with economic benefits for a manufactured product with recovery settings and to meet the requirements of a primary or secondary market, which remains unexplored and limited [7]. In general, this paper is concerned with the implementation of the performance assessment for recovery operations as a strategic enabler towards

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sustainable manufacturing. An attempt is also made to examine the performance attributes of cost, time, waste and quality of a manufactured product with recovery settings.

2. Literature review

There are concerns about social responsibility and extended producer responsibility (EPR) for waste minimisation management strategy when considering sustainable development [13,14]. Further, waste disposal costs and operating costs associated with virgin materials usage are steadily increasing [15]. Therefore, a need for minimising disposal of used products to landfill has arisen [3,16,17].

In comparison with conventional manufacturing, any alternative for reclaiming resources helps on reduction of energy consumption, material extractions and landfill of the used product [3,18]. Hence, the performance assessment for returns management process needs to include aspects such as financial or rebate incentives by manufacturers [3,19], reverse logistics and administration of returned items [13,15,20] as well as the operational processes for sub-assembly or disassembly [21], recovery processes [22–24], and disposal of hazardous or non-hazardous items [3,7]. As a result of these critical aspects, a trade-off method may be a preferable option for assessing product returns with recovery settings [7,11,25].

Using trade-off considerations, a conventional 6R interpretation (*reduce/reuse/recycle/recover/remanufacture/redesign*), was initially proposed by a few researchers [23,26,27] for an agenda of sustainable manufacturing. Kuik et al. [7,11] classified waste minimisation along a supply chain to account for any complexity of the product returns workflow with recovery settings by proposing a strategy of 3R process improvement (*reuse/remanufacture/recycle*) level and 3R product design (i.e. *reduce/recover/redesign*) level towards sustainable development milestone as illustrated in Fig. 1. The product utilisation value (PUV) of a manufactured product, which is indicated by a solid trend line (see Fig. 1) is defined as the expected amount of the recoverable content for a manufactured product with 3R process improvement strategy. A few manufacturers are implementing recovery operations, including Caterpillar, Kodak, Mercedes-Benz engine components, IBM computers or Xerox electronics [3]. In comparison, the dotted trend line in Fig. 1 indicates expected amount of recoverable content for a manufactured product using an integrated approach by incorporating both 3R process improvement and 3R product design strategies. This approach is generally known as the design for product retirement (DFPR) and product end-of-life (EOL) planning [28,29], which is an alternative way of achieving maximum PUV with recovery settings to satisfy the stringent requirements of product disposal to landfill.

The estimated PUV from this integrated approach is recommended to incorporate a strategy of 3R process improvement concurrently with the design constraints of 3R product design strategy for maximising the value [7,8]. The proposal for this approach also comprises modularisation of product design, the consideration of design for assembly or disassembly, the limitation of hazardous coating materials and the utilisation of more remanufactured or reused components. To differentiate the definition of 3R process improvement and 3R product design strategies, minimisation of waste landfill by means of 3R process improvement and 3R product design strategies have been summarised by researchers [7,8,11]. At *'post-use'* stage, the performance measurement method for this scenario is still at a budding level, especially, for a manufactured product with recovery settings. This integrated approach will assist global manufacturers evaluate a trade-off scenario by considering the perspectives of total recovery cost, recovery manufacturing lead-time, minimisation for landfill and quality characteristics [11,30].

3. Product recovery for sustainable manufacturing

Product disposal to landfill is one of the major problems [30]. A 6R approach, which considers recoverable components for a manufactured product, provides a better opportunity for reducing resource consumptions, raw material extractions, and manufacturing lead-time. Kumar and Malegeant [31] discussed two prime constraints of closed loop supply chain management, such as no

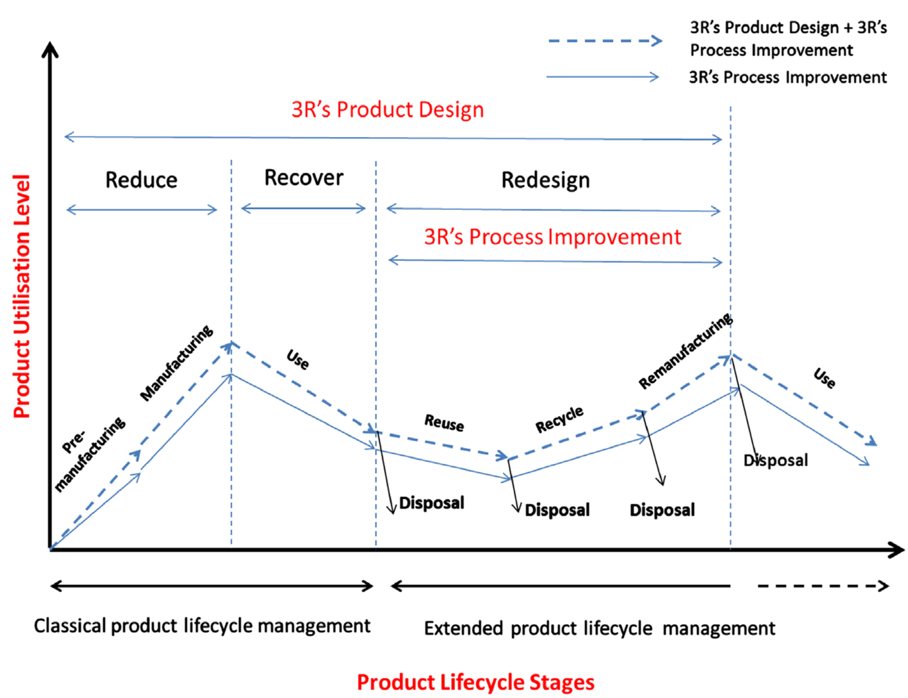

Fig. 1. Product utilisation value by implementing 6R approach.

market demand for secondary output and product deterioration. Gutowski et al. [32] also showed that recovery strategy for any returned product is not economically viable based on the perspective of energy consumption of a remanufactured product between *use* and *post-use* stages.

However, any returns stream and EOL planning should consider a strategic alliance between a manufacturer and recovery related organisations [11,31]. The scope of this EOL planning includes closed-loop activities for incoming and outgoing material flows, which are associated with the authorisation and administration activities, financial and rebate incentive by manufacturers, returned items for sorting and testing, transportation arrangement, assembly/disassembly operations, 3R recoverable manufacturing's opportunity, and disposal related activities for hazardous or non-hazardous materials [18,33,34]. Table 1 shows description of some of these sequential recovery operations, known as critical-to-reprocess (CTR) operations, which are the important for successful returns management in a supply chain. Although, a number of the performance measurement for sustainable supply chain management and product recovery operations have been proposed in existing literature [4,18,35–37], an integrated approach with the benchmark trade-off relationships between economic benefits and environment protection is still lacking. Due to these trade-off complications, in a benchmarking analysis, there is a need for developing an appropriate performance measurement system to quantitatively evaluate the level of returns management process.

4. The formulation of theoretical framework through design for six sigma

From the introduction of Six Sigma methodology by Motorola in the early 1980s for improving product quality and services [38,39], the global organisations such as General Motors, Seagate International, Honeywell, Caterpillar, and others have adapted and utilised DMAIC (define, measure, analyse, improve and control) to eliminate process variation [40,41]. To redesign process improvement in operations, design for six sigma (DFSS) methodology known as IDOV (identify, design, optimise and validate) is recommended [42]. This section discusses the theoretical framework for performance assessment to evaluate quantitatively product returns with recovery settings using IDOV methodology.

4.1. Phase 1: Identifying performance attributes

One of the alternative ways to reduce landfill waste due to obsoleted products is to consider the option of returned products for 3R operations as well as arrange collection related activities from the retailers, consumers, suppliers, and distributors. The first

Table 1
CTR operations associated with recovery settings.

CTR operations	Sub-process breakdown
(1) New: virgin manufacturing	Acquisition and procurement of raw materials for manufacturing and forming activities
(2) Assembly/disassembly	Operational resources required, such as assembly/disassembly related machinery and technology development, labour arrangement and training investment, quality initiatives and continuous improvement programmes for assembly/disassembly operations
(3) 1R: Reuse (recoverable manufacturing)	Recoverable operations required involves any manual/semi-auto/auto processes by operators, newer technology machinery used for cleaning processes, handling, sorting, inspecting and testing any reusable component before direct reuse
(4) 2R: Remanufacture (recoverable manufacturing)	Recoverable operations involves operational processes of rectifying, repairing and replacing recoverable components that are failed to meet the minimum requirement as per operational constraints
(5) 3 R: Recycle (recoverable manufacturing)	Recoverable operations involves processing materials into new finished goods, such as the operational processes of shredding, separating, handling, sorting, inspecting and testing
(6) Disposal	Disposal operations involves operational processes of segregating and sorting non-hazardous or hazardous portions in product or component or material levels before sending to landfills
(7) Collection	Collection activities and arrangement after 'use' stage involves transportation, initial sorting activities, returns authorisation and administration works, and rebate incentives by manufacturers for any returned item

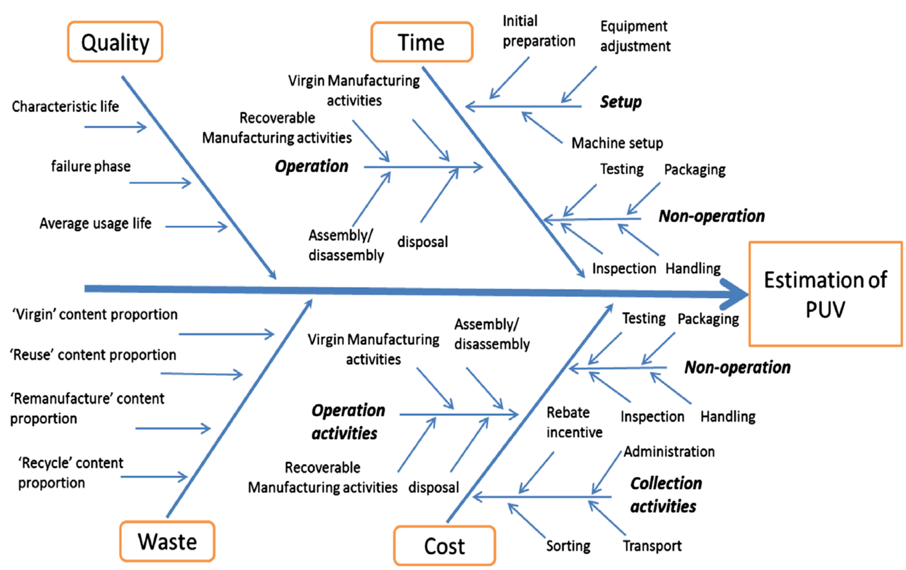

Fig. 2. Performance attributes that determine an estimation of PUV.

step of *DFSS-identify* phase involves identifying the performance attributes to quantitatively evaluate manufacturer's sustainability performance achievement in terms of economic and environmental benefits. As illustrated in Fig. 2, the critical parameters of the recovery operations exhibit some uncertain variability known as CTR operations. Therefore, an Ishikawa fishbone analysis was conducted to determine CTR operations of a manufactured product with recovery settings for the performance attributes of cost, waste, time and quality.

To model these proposed performance attributes accurately, all influential CTRs, which are discussed previously, are incorporated in the performance evaluation. Mathematical models of each performance attribute in accordance with these CTRs that are developed. Subsequently, these four performance attributes are recommended to simultaneously estimate PUV for a manufactured product with recovery settings, where optimised trade-off consideration is in terms of economic and environmental benefits. Then, an estimation of PUV is presented and used to predict sustainability performance level of a manufactured product with recovery settings, where performance attributes must meet objectives as follows:

1. Minimising the total recovery cost associated with the implementation of 3R operations,
2. Decreasing waste disposal to landfills by reclaiming the utilisation value of the recoverable content of a used product,
3. Reducing time-to-market by minimising manufacturing lead-time in recovery operations, and
4. Increasing quality of a manufactured product after recovery operations.

4.2. Phase 2: Designing performance measurement models

The primary goal of this *DFSS-design* phase is to understand the implications of returns workflow planning that are associated with CTR operations. These CTR operations are: virgin manufacturing activities, assembly/disassembly operations, 3R recoverable manufacturing related activities, and disposal or collection operations that are discussed in Section 3. The development of each representative model aims to assess an appropriate performance measurement of a manufactured product with recovery settings. This model can also be applied to existing procedures, such as the involvement of rethreading used tires [43], recycling cans and bottles for other purposes [44], any activity with refurbishing or upgrading electronic devices or consumer products [21].

4.2.1. Cost model

This section presents the development of a cost model with recovery settings that is applicable for breakdown recovery options. A product which contains only multiple *i*th component is shown in Fig. 3(a). This configuration implies that a manufactured product is fabricated or assembled with multiple components only. An example is a table lamp, which consists of bulb, plastic lamp cover, holder, stands and others. A configuration of complex product, which contains multiple *m*th module and *i*th component is shown in Fig. 3(b). It means that a manufactured product consists of both modules and components. A simple example is a computer, which consists of hard drive, memory chips, optical drives, processor chip, casing and others.

To analyse economic benefit associated with product recovery operations, OEMs are keen on justifying total recovery costs, which include various types of additional processing operations for the returned products. In this context, the formulation of a cost model with product returns is primarily derived to account, operational

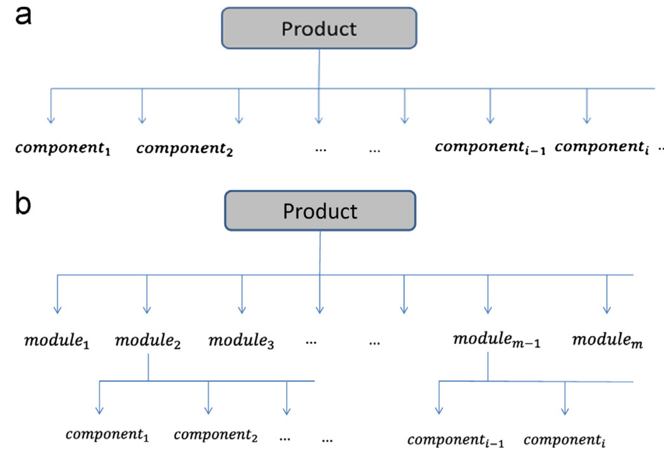

Fig. 3. (a) Product in component level (*decomposition level, d=i*). (b) Product in module and component level (*decomposition level, d=m*).

activities, $o=(1,2,\ldots)$, the number of components/modules in a manufactured product, $i=(1,2,\ldots)$ and collection activity, $n=(1,2,\ldots)$. All relevant notations are given in Table 2. Further, Table 3 presents the important considerations with disposition decision variables for the formulation of a cost model such as product/module/component for recovery. Generally, this proposed model is utilised to estimate approximation of the total recovery cost with the implementation of effective returns management.

Hence, the total cost with recovery, $TC_{REC,d}$ for a manufactured product per product lifecycle with decision parameters is calculated as follows:

$$TC_{REC,i} = \sum_{i=1}^{r}\left[X_{1,i}\left(C_{8,i}+\sum_{o=1}^{3}C_{o,i}\right)+X_{2,i}\left(\sum_{o=3}^{5}C_{o,i}\right)+X_{3,i}\left(\sum_{o=3}^{6}C_{o,i}\right)+X_{4,i}\left(C_{7,i}+\sum_{o=2}^{5}C_{o,i}\right)\right]+\sum_{n=1}^{4}C_{n,\text{collect}} \quad (1)$$

while, the total manufacturing cost, $TC_{VIR,d}$ without recovery for a manufactured product at 1st product lifecycle is:

$$TC_{VIR,i} = \sum_{i=1}^{r}\left[X_{1,i}\left(C_{8,i}+\sum_{o=1}^{3}C_{o,i}\right)\right] \quad (2)$$

Similarly, for a manufactured product in module and component level, the total manufacturing cost with recovery, $TC_{REC,d}$ per product lifecycle is derived.

$$TC_{REC,m} = \sum_{m=1}^{j}\sum_{i=1}^{r}\left[X_{1,i,m}\left(C_{8,i}+\sum_{o=1}^{3}C_{o,i}\right)+X_{2,i,m}\left(\sum_{o=3}^{5}C_{o,i}\right)+X_{3,i,m}\left(\sum_{o=3}^{6}C_{o,i}\right)+X_{4,i,m}\left(C_{7,i}+\sum_{o=2}^{5}C_{o,i}\right)\right]+\sum_{n=1}^{4}C_{n,\text{collect}} \quad (3)$$

For a product in module and component level, the total manufacturing cost without recovery at 1st product lifecycle, $TC_{VIR,d}$ is derived.

$$TC_{VIR,m} = \sum_{m=1}^{j}\sum_{i=1}^{r}\left[X_{1,i,m}\left(C_{8,i}+\sum_{o=1}^{3}C_{o,i}\right)\right] \quad (4)$$

As presented in Table 2, the costs associated with *o*th operational process are expressed in Eqs. (5)–(12). Since, activity of new acquisition for raw material includes procurement and inventory holding costs, the formulation of costs associated with this activity is:

$$C_{1,i} = C_{\text{Procure},1,i}+C_{\text{hold},1,i} \quad (5)$$

Table 2
Cost constraints parameters.

Notations	Cost constraints parameters
$C_{o,i}$	Cost associated with operational processes, o for ith component, where $o=1,2,\ldots,8$ operational processes
$C_{1,i}$	New acquisition activity costs for ith component
$C_{\text{Procure},1,i}$	New procurement costs for ith component
$C_{\text{hold},1,i}$	Inventory holding costs for ith component
$C_{2,i}$	Manufacturing/forming related activity costs for ith component
$C_{\text{manufacture},2,i}$	Manufacturing and fabricating costs for ith component
$C_{\text{inspect},2,i}$	Inspection costs for ith component
$C_{\text{test},2,i}$	Testing costs for ith component
$C_{\text{hold},2,i}$	Inventory holding costs for ith component
$C_{3,i}$	Assembly related activity costs, which is also expressed as a function of operating time to assemble ith component
$C_{\text{joint},3,i}$	Joint costs for ith component
$C_{\text{assem},3,i}$	Assembly costs for ith component
$C_{\text{resource},3,i}$	Costs of resources required per operating time for ith component assembly activity
$T_{\text{joint},3,i}$	Average time required to complete ith component joint activity
$T_{\text{assem},3,i}$	Average time required to complete ith component assembly activity
$C_{4,i}$	Direct reuse related activity costs for ith component that are incurred by manufacturer
$C_{\text{clean},4,i}$	Cleaning activity costs for ith component
$C_{\text{inspect},4,i}$	Inspection costs for ith component
$C_{\text{test},4,i}$	Testing costs for ith component
$C_{\text{hold},4,i}$	Inventory holding costs for ith component
$C_{5,i}$	Disassembly related costs, which is also expressed as a function of operating time to disassemble ith component
$C_{\text{disjoint},5,i}$	Disjoint activity costs for ith component
$C_{\text{disassem},5,i}$	Disassembly activity costs for ith component
$C_{\text{resource},5,i}$	Costs of resources required per operating time for ith component disassembly activity
$T_{\text{disjoint},5,i}$	Average time required to complete for ith component disjoint activity
$T_{\text{disassem},5,i}$	Average time required to complete for ith component disassembly activity
$C_{6,i}$	Remanufacturing costs associated with inspection, testing, and repairor replacement for ith component
$C_{\text{repair},6,i}$	Repair work activity costs for ith component
$C_{\text{replace},6,i}$	Replace work activity costs for ith component
$C_{\text{inspect.},6,i}$	Inspection costs for ith component
$C_{\text{test},6,i}$	Testing costs for ith component
$\gamma_{6,i}$	$=1$ if ith component is repairable, otherwise it is 0
$\beta_{6,i}$	$=1$ if ith component is replaceable, otherwise it is 0
$C_{\text{hold},6,i}$	Inventory holding costs for ith component
$C_{7,i}$	Recycling related costs including shredding, separation and handling, etc. activity costs with disassembly and without disassembly for ith component
$C_{\text{recycle}_{\text{without}},7,i}$	Shredding, separation, handling, etc. activity costs without disassembly for ith component
$C_{\text{recycle}_{\text{with}},7,i}$	Shredding, separation, handling, etc. activity costs with disassembly for ith component
$\gamma_{7,i}$	$=1$ if ith component is to be disassembled before recycling, otherwise it is 0
$\beta_{7,i}$	$=1$ if ith component is not to be disassembled before recycling otherwise it is 0
$C_{\text{hold},7,i}$	Inventory holding costs for ith component
$C_{8,i}$	Disposal costs for ith component, which is associated with incineration or landfill for hazardous contains and non-hazardous contains
$C_{\text{hazadous},6,i}$	Disposal costs with hazardous contains for ith component
$C_{\text{nonhazadous},6,i}$	Disposal costs with non-hazardous contains for ith component
$\gamma_{8,i}$	$=1$ if ith component contains hazardous material, otherwise it is 0
$\beta_{8,i}$	$=1$ if ith component non-hazardous material, otherwise it is 0
$C_{n,\text{ collect}}$	Cost associated with collection processes, n for returned item where $n=1,2,\ldots,4$ collection processes
$C_{1,\text{collect}}$	Financial related incentives for a whole item incurred by manufacturer
C_{rebate}	Rebate incentive provided
$C_{2,\text{collect}}$	Administration related costs for a whole item incurred by manufacturer for processing paperwork
C_{admin}	General administration costs
$C_{3,\text{collect}}$	Sorting costs, C_{sort} for a whole item incurred by manufacturer
C_{sort}	Initial sorting costs for types of product costs
$C_{4,\text{collect}}$	Transport costs, C_{ship} for a whole item incurred by manufacturer
C_{ship}	Shipping costs for product returns

The manufacturing or forming related activity includes manufacturing, inspection, testing and inventory holding costs. Therefore, the formulation of the manufacturing related activity costs is

$$C_{2,i} = C_{\text{manufacture},2,i} + C_{\text{inspect},2,i} + C_{\text{test},2,i} + C_{\text{hold},2,i} \tag{6}$$

Similarly, assembly related activity includes associated costs of joint and assembly, which is expressed as the multiplication of the required resource costs per time and average operating time to complete assembling operations.

$$C_{3,i} = C_{\text{joint},3,i} + C_{\text{assemble},3,i} = C_{\text{resource},3}(T_{\text{joint},3,i} + T_{\text{assemble},3,i}) \tag{7}$$

In considering costs with direct reuse related activity, the estimation of activity costs for cleaning, inspection, testing and inventory holding is:

$$C_{4,i} = C_{\text{clean},4,i} + C_{\text{inspect},4,i} + C_{\text{test},4,i} + C_{\text{hold},4,i} \tag{8}$$

Then, the disassembly related activity usually includes associated costs to complete disassembly operation, which is expressed as the multiplication of resources costs per operating time and average time to complete the disassembly workload. Hence, the estimation of the activity costs is

$$C_{5,i} = C_{\text{disjoint},5,i} + C_{\text{remove},5,i} = C_{\text{resource},5}(T_{\text{disjoint},5,i} + T_{\text{remove},5,i}) \tag{9}$$

As remanufacturing related activity includes associated costs for restoring functionality of an item into 'as-is' original conditions, inspection, testing and inventory holding, the estimation of

Table 3
Disposition decision variables.

Notations	Decision parameters
$X_{1,i}$	$=1$ if ith component is virgin, otherwise it is 0
$X_{1,i,m}$	$=1$ if ith component of mth module of is virgin, otherwise it is 0
$X_{2,i}$	$=1$ if ith component is directly reused, otherwise it is 0
$X_{2,i,m}$	$=1$ if ith component of mth module is directly reused, otherwise it is 0
$X_{3,i}$	$=1$ if ith component is directly remanufactured, otherwise$=0$
$X_{3,i,m}$	$=1$ if ith component of mth module is directly remanufactured, otherwise$=0$
$X_{4,i}$	$=1$ if ith component, i is directly recycled, otherwise$=0$
$X_{4,i,m}$	$=1$ if ith component, i of mth module is directly recycled, otherwise$=0$
i	$=(1,2,\ldots,r)$ components for a product in module and component level or a product in component level, where each component is comprised of a single material only
m	$=(1,2,\ldots,j)$ modules components for a product-module-component based level
d	$=m$ for a product in module and component level, and for a product in component based level

the activity costs is

$$C_{6,i}=\gamma_{6,i}C_{\text{repair},6,i}+\beta_{6,i}C_{\text{replace},6,i}+C_{\text{inspect.},6,i}+C_{\text{test},6,i}+C_{\text{hold},6,i} \tag{10}$$

Recycling related activity costs consists of the reprocessing activity costs with or without disassembly and inventory holding.

$$C_{7,i}=\gamma_{7,i}C_{\text{recycle}_{\text{without}},7,i}+\beta_{7,i}C_{\text{recyle}_{\text{with}},7,i}+C_{\text{hold},7,i} \tag{11}$$

The disposal related activity costs for landfills is generally involved with the waste handling activity with or without hazardous contains. Hence,

$$C_{8,i}=\gamma_{8,i}C_{\text{hazadous},6,i}+\beta_{8,i}C_{\text{nonhazadous},8,i} \tag{12}$$

Subsequently, the derivation of cost models as shown in Eqs. (1) and (3) must be generally satisfied with the disposition decision variables conditions. For the cost model of the product in component level, the condition is met as follows:

$$X_{1,i}+X_{2,i}+X_{3,i}+X_{4,i}=1 \tag{13}$$

Similarly, for the cost model of the product in module and component level, it is:

$$X_{1,i,m}+X_{2,i,m}+X_{3,i,m}+X_{4,i,m}=1 \tag{14}$$

4.2.2. Time model

In conventional manufacturing, the total manufacturing lead-time is expressed as the summation of three elements, such as setup related activity time, T^{sup} operation related activity time, T^{op} and non-operation related activity time, T^{nop} [45]. However, operational activity with recovery options for a manufactured product consists of virgin operation activity and recoverable operation activity, quality inspection, testing and assembly or disassembly related activities. All these activities are involved with various setup time, operation time, and non-operation time. Therefore, the manufacturing lead-time, MLT_{REC} with recovery is derived and operational processes of $g=1,2,\ldots$ as shown in Table 4.

$$MLT_{REC,i}=\sum_{i=1}^{r}\left[X_{1,i}\left(T_{7,i}+\sum_{g=1}^{2}T_{g,i}\right)+X_{2,i}\left(\sum_{g=2}^{4}T_{g,i}\right)+X_{3,i}\left(\sum_{g=2}^{5}T_{g,i}\right)+X_{4,i}\left(T_{6,i}+\sum_{g=1}^{4}T_{g,i}\right)\right] \tag{15}$$

Then, the total manufacturing lead-time without recovery, $MLT_{VIR,d}$, is

$$MLT_{VIR,i}=\sum_{i=1}^{r}\left[X_{1,i}\left(T_{7,i}+\sum_{g=1}^{2}T_{g,i}\right)\right] \tag{16}$$

For a product in module and component level, the development of the total manufacturing lead-time, $MLT_{REC,d}$, with recovery is

$$MLT_{REC,m}=\sum_{m=1}^{j}\sum_{i=1}^{r}\left[X_{1,i,m}\left(T_{7,i}+\sum_{g=1}^{2}T_{g,i}\right)+X_{2,i,m}\left(\sum_{g=2}^{4}T_{g,i}\right)+X_{3,i,m}\left(\sum_{g=2}^{5}T_{g,i}\right)+X_{4,i,m}\left(T_{6,i}+\sum_{g=1}^{4}T_{g,i}\right)\right] \tag{17}$$

while, for a product in module and component level, the total manufacturing lead-time without recovery, $MLT_{VIR,d}$, is

$$MLT_{VIR,m}=\sum_{m=1}^{j}\sum_{i=1}^{r}\left[X_{1,i,m}^{Virgin}\left(T_{7,i}+\sum_{g=1}^{2}T_{g,i}\right)\right] \tag{18}$$

since, the approximation of lead-time for manufacturing related activity includes an activity of performing setup, manufacturing and inspection and testing. Therefore, the estimation of the lead-time is

$$T_{1,i}=T_{\text{setup},1,i}+T_{\text{manufacture},1,i}+T_{\text{inspect},1,i}+T_{\text{test},1,i} \tag{19}$$

Further, the approximation of lead-time for assembly related activity includes setup, assembly operation, inspection, and testing.

$$T_{2,i}=T_{\text{setup},2,i}+T_{\text{joint},2,i}+T_{\text{inspect},2,i}+T_{\text{test},2,i} \tag{20}$$

As reuse related activity time involves the job execution of setup, cleaning, processing, inspecting, and testing.

$$T_{3,i}=T_{\text{setup},3,i}+T_{\text{clean},3,i}+T_{\text{inspect},3,i}+T_{\text{test},3,i} \tag{21}$$

The approximation of lead-time for disassembly related activity consists of setup, disassembly operation, inspection, and testing. So that, the estimation of the lead-time for disassembly is

$$T_{4,i}=T_{\text{setup},4,i}+T_{\text{disjoint},4,i}+T_{\text{inspect},4,i}+T_{\text{test},4,i} \tag{22}$$

Similarly, remanufacturing related activity is required to execute setup related activity for restoring functionality of items into “as-is” conditions through repair or replacement activity as well as doing inspection and testing. Therefore,

$$T_{5,i}=T_{\text{setup},5,i}+\alpha_{5,i}T_{\text{repair},5,i}+\varphi_{5,i}T_{\text{replace},5,i}+T_{\text{inspect.},5,i}+T_{\text{test},5,i} \tag{23}$$

For recycling related activity, the approximation of lead-time is calculated based on the jobs execution for setup, reprocessing, inspecting and testing. The estimation of lead-time is

$$T_{6,i}=T_{\text{setup},6,i}+\alpha_{6,i}T_{\text{recycle}_{\text{without}},6,i}+\varphi_{6,i}T_{\text{recyle}_{\text{with}},6,i}+T_{\text{inspect},6,i}+T_{\text{test},6,i} \tag{24}$$

Lastly, disposal related activity lead-time consists of setup, operation activity for handling hazardous or non-hazardous contains, inspection and testing. Therefore,

$$T_{7,i}=T_{\text{setup},7,i}+\alpha_{7,i}T_{\text{hazadous},7,i}+\varphi_{7,i}T_{\text{nonhazadous},7,i}+T_{\text{inspect},7,i}+T_{\text{test},7,i} \tag{25}$$

Table 4
Manufacturing lead time constraint parameters.

Notations	Time constraints parameters
$T_{g,i}$	Lead-time involved with setup time, operation time and non-operation time for each operational process, $g=1,2,\ldots7$ for ith component
$T_{1,i}$	Lead-time for manufacturing setup activity related time, operation activity of manufacturing/forming time, and non-operation activity time of testing and inspection for ith component
$T_{\text{setup},1,i}$	Manufacturing setup activity time for ith component
$T_{\text{manufacturing},1,i}$	Manufacturing/forming activity time for ith component
$T_{\text{test},1,i}$	Testing activity time for ith component
$T_{\text{inspect},1,i}$	Inspection activity time for ith component
$T_{2,i}$	Lead-time for assembly setup activity related time, joint or assembly activity time, and non-operation time of testing and inspection, for ith component
$T_{\text{setup},2,i}$	Assembly setup activity time for ith component
$T_{\text{joint},2,i}$	Joint activity time for ith component
$T_{\text{assem},2,i}$	Assembly activity time for ith component
$T_{\text{test},2,i}$	Testing activity time for ith component
$T_{\text{inspect},2,i}$	Inspection activity time for ith component
$T_{3,i}$	Lead-time for direct reuse including setup activity related time, cleaning/processing activity time and non-operation time of testing, and inspection for ith component
$T_{\text{setup},3,i}$	Direct reuse setup activity time for ith component
$T_{\text{clean},3,i}$	Cleaning/processing activity time for ith component
$T_{\text{test},3,i}$	Testing activity time for ith component
$T_{\text{inspect},3,i}$	Inspection activity time for ith component
$T_{4,i}$	Lead-time for disassembly including setup activity related time, joint and assembly activity times and non-operation time of testing and inspection for ith component
$T_{\text{setup},4,i}$	Disassembly setup activity time for ith component
$T_{\text{disjoint},4,i}$	Disjoint activity time for ith component
$T_{\text{disassem},4,i}$	Disassembly activity time for ith component
$T_{\text{test},4,i}$	Testing activity time for ith component
$T_{\text{inspect},4,i}$	Inspection activity time for ith component
$T_{5,i}$	Lead-time for remanufacturing setup activity related repair activity and replacement activity and non-operation time of testing, and inspection for ith component
$T_{\text{setup},5,i}$	Remanufacturing setup activity time for ith component
$T_{\text{repair},5,i}$	Repair activity time for ith component
$T_{\text{replace},5,i}$	Replacement activity time for ith component
$\alpha_{5,i}$	$=1$ if ith component is required to be repaired otherwise it is 0
$\varphi_{5,i}$	$=1$ if ith component is not to be replaced otherwise it is 0
$T_{\text{test},5,i}$	Testing activity time for ith component
$T_{\text{inspect},5,i}$	Inspection activity time for ith component
$T_{6,i}$	Lead-time for recycling setup related activity time, operation time with disassembly, and without disassembly, for shredding, separating, and sorting activities and non-operation time of testing, and inspection, for ith component
$T_{\text{setup},6,i}$	Recycling setup activity time for ith component
$T_{\text{recycle}_{\text{with}},6,i}$	Recycling with disassembly activity time for ith component
$T_{\text{recycle}_{\text{without}},6,i}$	Recycling without disassembly activity time for ith component
$\alpha_{6,i}$	$=1$ if ith component is disassembled otherwise it is 0
$\varphi_{6,i}$	$=1$ if ith component is not disassembled otherwise it is 0
$T_{\text{test},6,i}$	Testing activity time for ith component
$T_{\text{inspect},6,i}$	Inspection activity time for ith component
$T_{7,i}$	Lead-time for disposal processing setup activity time, operation time for hazardous contains and non-hazardous contains, and non-operation time of testing, and inspection for ith component
$T_{\text{setup},7,i}$	Disposal setup activity time for ith component
$T_{\text{hazadous},7,i}$	Disposal of hazardous materials activity time for ith component
$T_{\text{nonhazadous},7,i}$	Disposal of non-hazardous materials activity time for ith component
$\alpha_{7,i}$	$=1$ if ith component has hazardous materials, otherwise it is 0
$\varphi_{7,i}$	$=1$ if ith component is non-hazardous materials, otherwise it is 0
$T_{\text{test},7,i}$	Testing activity time for ith component
$T_{\text{inspect},7,i}$	Inspection activity time for ith component

The derivation of time models for either a product in component level or a product in module and component level as derived in Eqs. (15) and (17) must generally satisfy the disposition decision variables conditions as proposed in Eqs. (13) and (14).

4.2.3. Waste model

In this study, the total waste minimisation with recovery WM_{REC} is mathematically defined as the ratio of recoverable content for a manufactured product and derived in Eq. (26).

$$WM_{REC}=\frac{Z_2+Z_3+Z_4}{Z_1+Z_2+Z_3+Z_4} \tag{26}$$

where Z_1 is the 'virgin' weight proportion for a product; Z_2 is the recoverable content of 'reuse' weight proportion for a product; Z_3 is the recoverable content of 'remanufacture' weight proportion for a product; Z_4 is the recoverable content of 'recycle' weight proportion for a product.

The total waste minimisation with recovery is then derived for a product in component level in Eqs. (28) and (29) and a product in module and component level in Eqs. (30) and (31).

$$WM_{REC,d}=\frac{W_{REC,d}}{W_{TOL,d}} \tag{27}$$

If $d=i$, for a product in component level, the approximation of total weight proportion for a manufactured product is

$$W_{TOL,i}=\sum_{i=1}^{r}[X_{1,i}(Z_{1,i})+X_{2,i}(Z_{2,i})+X_{3,i}(Z_{3,i})+X_{4,i}(Z_{4,i})] \tag{28}$$

Table 5
Quality constraints parameters.

Notations	Quality constraints parameters
N	$N=1$ (virgin); 2 (reuse); 3 (remanufacture) and 4 (recycle)
$b_{N,i}$	Weibull shape parameter for ith component
l	Maximum allowable lifecycle before wear-out, which is applicable for either reused or remanufactured ith component, where $l=(1,2,..n)$
$\theta_{N,i}$	Characteristic life for ith component
$\delta_{1,i}$	Average operating hours before virgin ith component is taken back
$\delta_{2,i}$	Average operating hours before reused ith component is taken back
$\delta_{3,i}$	Average operating hours before remanufactured ith component is taken back
$\delta_{4,i}$	Average operating hours before recycled ith component is taken back

The approximation of recoverable weight proportion for a manufactured product by reprocessing operation is estimated as the summation of reuse, remanufacturing and recycling proportion. Then:

$$W_{REC,i} = \sum_{i=1}^{r} [X_{2,i}(Z_{2,i}) + X_{3,i}(Z_{3,i}) + X_{4,i}(Z_{4,i})] \tag{29}$$

similarly, $d=m$ for a product in module and component level, the approximation of total weight proportion for a manufactured product is

$$W_{TOL,\,m} = \sum_{m}^{j} \sum_{i=1}^{r} [X_{1,i,m}(Z_{1,i}) + X_{2,i,m}(Z_{2,i}) + X_{3,i,m}(Z_{3,i}) + X_{4,i,m}(Z_{4,i})] \tag{30}$$

The approximation of recoverable weight proportion for a manufactured product by reprocessing operation is estimated as the summation of reuse, remanufacturing and recycling proportion.

$$W_{REC,m} = \sum_{m}^{j} \sum_{i=1}^{r} [X_{2,i,m}(Z_{2,i}) + X_{3,i,m}(Z_{3,i}) + X_{4,i,m}(Z_{4,i})] \tag{31}$$

For the waste model of either a product in component level or a product in module and component level, the decision condition must meet Eqs. (13) and (14).

4.2.4. Quality model

A component in a product is subject to the variety of the potential failure modes within a certain timeframe and depends on the wear-out life. Even if, in practice, the remaining technology cycle and attainable economic value for a manufactured product in an existing market are satisfied, the quality in terms of reliability characteristics for a manufactured product is still subject to the influential factors of its characteristic life, failure phase and average usage lifespan, when any reused, remanufactured, recycled or virgin modules and components are being utilised in a manufactured product. Reliability theory [28] is used for the estimation of the total reliability, R of a system, which is expressed as the multiplication of each subsystem of the reliability in a series configuration.

$$R = \prod e^{-(t/\theta)^{b}} \tag{32}$$

where θ is the characteristic life that will fail theoretically; t is the operating age during the system lifecycle; b is the Weibull shape parameter,

For a product in component level, the total system reliability with recovery, $QR_{REC,d}$, is:

$$QR_{REC,i} = \prod_{i=1}^{r} \Big[X_{1,i}(e^{-(\delta_{1,i}/\theta_{1,i})^{b_{1,i}}}) + X_{2,i}(e^{-(l\times\delta_{2,i}/\theta_{2,i})^{b_{2,i}}}) + X_{3,i}(e^{-(l\times\delta_{3,i}/\theta_{3,i})^{b_{3,i}}}) + X_{4,i}(e^{-(\delta_{4}/\theta_{4,i})^{b_{4,i}}}) \Big] \tag{33}$$

similarly, for a product in module and component level, the total system reliability with recovery, $QR_{REC,d}$, is

$$QR_{REC,m} = \prod_{m}^{j} \prod_{i=1}^{r} \Big[X_{1,i,m}(e^{-(\delta_{1,i}/\theta_{1,i})^{b_{1,i}}}) + X_{2,i,m}(e^{-(l\times\delta_{2,i}/\theta_{2,i})^{b_{2,i}}}) + X_{3,i,m}(e^{-(l\times\delta_{3,i}/\theta_{3,i})^{b_{3,i}}}) + X_{4,i,m}(e^{-(\delta_{4}/\theta_{4,i})^{b_{4,i}}}) \Big] \tag{34}$$

Table 5 shows the quality constraints parameters of the system reliability for a manufactured product in component level as derived in Eq. (33) and in module and component level in Eq. (34). OEMs need to maintain its component/module practical lifespan and the product's overall system reliability by monitoring its maximum allowable lifecycle, l for ith component before reaching wear-out life during its operating usage.

4.3. Phase 3: Optimising performance measurement models

The primary motivation of this *DFSS-optimise* stage is to satisfy hypothetical propositions of a manufactured product with recovery (*REC*) and a manufactured product without recovery or a totally virgin manufactured product (*VIR*). If the outcome of the proposed hypothetical propositions in terms of cost, time, waste and quality is met, an organisational strategy is considered aligning the objectives of landfill waste minimisation of the product disposal as well as the system reliability for a manufactured product with recovery against manufacturer' goals or other environmental legislative requirements (*SET*).

To account for these considerations, the performance assessment guideline is developed to quantitatively justify a primary market's demand: whether or not recovery operations for a manufactured product are advantageous and beneficial in terms of cost, time, waste and quality measures. The hypothetical propositions of a manufactured product with or without recovery are summarised in Table 6 as a guideline.

Similarly, an alternative product (*ALT*) for a secondary market is considered by utilising obsolete item/product/component. Two hypothetical propositions are proposed to quantitatively compare and decide whether or not the proposal for improvement is feasible for minimising landfill waste due to product disposal and obsolete as shown in Table 6.

These hypothetical propositions can be then classified and simplified as the elements of economic performance indicators (*ECOI*), which consist of total recovery cost and manufacturing lead-time with recovery, and the elements of environmental performance indicators (*ENVI*), which consists of waste minimisation for landfill due to product disposal and quality characteristic in terms of reliability for the purpose of the trade-off benchmark. To consider optimising returns management process based on a trade-off assessment, a guideline of the economic and environmental performance indicators are required to be met individually and are formulated in Eqs. (35)–(38):

(i) A benchmark of economic performance indicator is the ratio of the performance measure, which is $ECOI \geq 1$. Therefore, $ECOI_{TC}$ for performance measure of TC with recovery;

Table 6
Hypothetical proportions for a manufactured product with or without recovery.

If 'Hypothetical proposition' is met		Then
Condition 1	**Condition 2**	
$TC_{REC} > TC_{VIR}$ and $MLT_{REC} > MLT_{VIR}$ $TC_{ALT} < TC_{VIR}$ and $MLT_{ALT} > MLT_{VIR}$	$WM_{REC} \cong WM_{SET}$ or $WM_{ALT} \cong WM_{SET}$ and $QR_{REC} \cong QR_{SET}$ or $QR_{ALT} \cong QR_{SET}$	If the propositional condition is satisfied, a strategy for recovery settings is not practically feasible for maximising economic benefit and minimising environmental effect
$TC_{REC} > TC_{VIR}$ and $MLT_{REC} < MLT_{VIR}$ $TC_{ALT} < TC_{VIR}$ and $MLT_{ALT} < MLT_{VIR}$		If the propositional condition is satisfied, a strategy for recovery settings is practically feasible for maximising economic benefit and minimising environmental effect

$$ECOI_{TC} = \frac{TC_{VIR}}{TC_{REC}} \geq 1, \quad \text{or} \quad ECOI_{TC} = \frac{TC_{VIR}}{TC_{ALT}} \tag{35}$$

Further, $ECOI_{MLT}$ for performance measure of MLT with recovery is

$$ECOI_{MLT} = \frac{MLT_{VIR}}{MLT_{REC}} \geq 1, \quad \text{or} \quad ECOI_{MLT} = \frac{MLT_{VIR}}{MLT_{ALT}} \geq 1 \tag{36}$$

(ii) A benchmark of environmental performance indicator is the ratio of the performance measure, which is $ENVI \cong 1$. Therefore, $ENVI_{WM}$ for performance measure of WM with recovery is

$$ENVI_{WM} = \frac{WM_{REC}}{WM_{SET}} \cong 1 \quad \text{or} \quad ENVI_{WM} = \frac{WM_{REC}}{WM_{SET}} \cong 1 \tag{37}$$

Further, $ENVI_{QR}$ for performance measure of QR with recovery is

$$ENVI_{QR} = \frac{QR_{REC}}{QR_{SET}} \cong 1 \quad \text{or} \quad ENVI_{QR} = \frac{QR_{ALT}}{QR_{SET}} \cong 1 \tag{38}$$

4.4. Phase 4: Validating performance measurement models using PUV estimation

Practically, each performance indicator of $ECOI$ and $ENVI$ is required to satisfy the proposed benchmark individually as discussed in Eqs. (35)–(38) to increase economic benefits and reduce environmental impacts of a manufactured product. However, the development of performance measurement with an integrated estimation to account performance attributes of cost, time, waste and quality is still lacking. Hence, an overall of quantitative estimation of PUV_{REC} to assess the performance of sustainable manufacturing is recommended in this study. This assessment is done by evaluating the recoverable content of a manufactured product, in terms of the economic benefit and environmental protection as shown in Eq. (39). This assessment is also expressed as a function of total recovery costs, manufacturing lead-time, waste minimisation and quality in terms of system reliability for a manufactured product.

$$PUV_{REC} = f(ECOI_{TC}, ECOI_{MLT}, ENVI_{WM}, ENVI_{QR}) \tag{39}$$

Alternatively, PUV_{REC} can also be approximately calculated based on the summation of area under the curves by the representation diagram of the trade-off measures, which is illustrated in Fig. 4.

$$PUV_{REC} = \left(\frac{1}{2} \times \frac{TC_{VIR}}{TC_{REC}} \times \frac{QR_{REC}}{QR_{SET}}\right) + \left(\frac{1}{2} \times \frac{TC_{VIR}}{TC_{REC}} \times \frac{WM_{REC}}{WM_{SET}}\right) + \left(\frac{1}{2} \times \frac{MLT_{VIR}}{MLT_{REC}} \times \frac{QR_{REC}}{QR_{SET}}\right) + \left(\frac{1}{2} \times \frac{MLT_{VIR}}{MLT_{REC}} \times \frac{WM_{REC}}{WM_{SET}}\right) \tag{40}$$

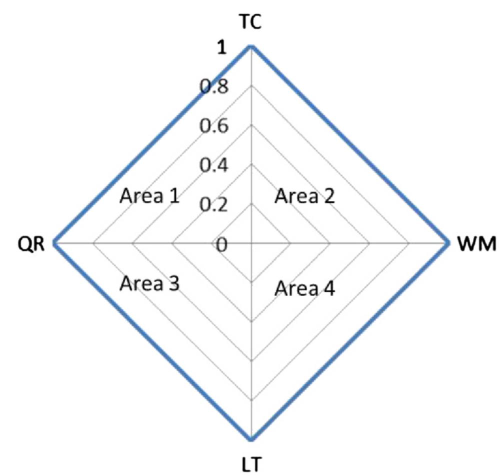

Fig. 4. Representation diagram of trade-off measures for the returns management.

However, PUV_{REC} is subject to the trade-off performance benchmark of

$$PUV_{REC} \geq 2 \tag{41}$$

5. Numerical example

Two case scenario of recovery configuration "A" and "B" are used for comparison of two product lifecycles, where in first product lifecycle, all virgin materials and normal manufacturing processes are assumed. The reasons for demonstrating these both recovery configuration options are to show the differences of recovery configuration options, which could impact an overall PUV_{REC} level for a manufactured product in terms of cost, time, waste and quality at the second product lifecycle. Each recovery configuration of 'A' and 'B' consists of 20 components. Therefore, the PUV_{REC} level for product 'A' configuration option is calculated based on 5 reused, 4 remanufactured, 6 recycled and 5 new components, while the PUV_{REC} level of product B configuration is estimated based on 4 recycled, 8 reused, 6 components, and 2 new components. Table 7 presents a summary of the numerical case of product configurations of 'A' and 'B' for allowing component reuse, remanufacture and recycle by quantitatively assessing each performance attribute.

In this typical scenario, the product 'B' configuration is most desirable solution for a primary market as PUV_{REC} is more than 2. However, the result obtained is by no means perfect, but demonstrates that the performance measurement using DFSS methodology is practically feasible for designing returns management with recovery options.

Fig. 5 illustrates the trade-off representation diagram of cost, time, waste and quality measures. In this example, trade-offs

Table 7
A summary of simulated scenario.

Configuration	Virgin	Product 'A'	Product 'B'
Virgin ($X_{1,i}$)	20	5	2
Reuse ($X_{2,i,}$)	0	5	8
Reman ($X_{3,i}$)	0	4	6
Recycle ($X_{4,i}$)	0	6	4
Cost (TC)	\$885	\$760	\$820
Time (MLT)	1.54 h	1.75 h	1.32 h
Waste (WM)	0	0.75	0.90
Quality (QR)	0.96	0.92	0.91
PUV_{REC}	n/a	1.74	2.03

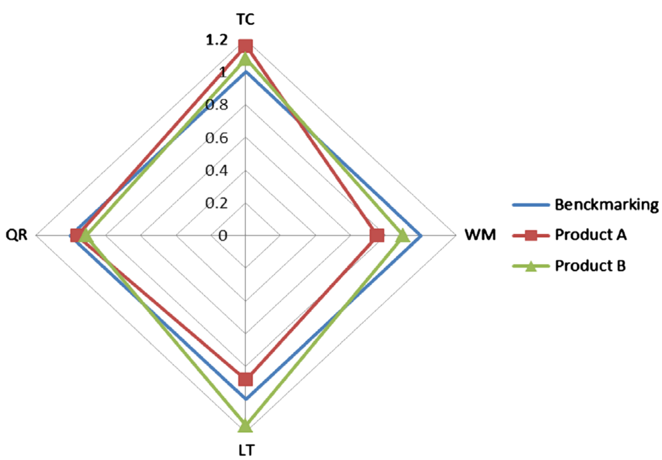

Fig. 5. Trade-off representation diagram of PUV_{REC}, for product 'A' and 'B'.

quantification among these measures has also been proven that product 'B' option is highly recommended solution based on the estimation of PUV. In comparison with both configurations, the total recovery cost of product 'B' is significantly higher than product 'A' but the estimation of the landfill reduction for product 'B', which is approximately 90% in recoverable content when comparing with product 'A' of approximately 75% in recoverable content. In this case, the option of a product 'B' has utilised more recoverable components than the option of a product 'A'.

In terms of the quality measure, the reliability is about 92% for product 'A' and 91% for product 'B'. Further, the manufacturing lead-time for a product 'B' is 1.32 h, which is much lower than the product 'A', which is 1.75 h and a virgin manufactured product of 1.54 h. Therefore, the estimation of PUV_{REC}, is highly recommended to account all these four attributes to overcome over-estimation of the PUV_{REC} for each recovery configuration of a manufactured product.

Product recovery configurations can be developed in accordance with the product designer's recommendation as well as to meet technical specifications, such as wear-out life, technology cycle, design lifecycle, functionality of the returned items, quality of the returned items and others. As recommended by Ross and Ishii [28], all these specifications can generally alter the end-of-life strategy in designing a returns management process. Nevertheless, the proposed performance measurement system offer some understanding and insights on the integrated estimation of PUV_{REC} for thoroughly assessing a returns management process.

6. Conclusion

This paper has proposed an integrated estimation of PUV_{REC} to aid decision makers for assessing performance level of product returns and recovery operations. A strategy for sustainable manufacturing is also presented by understanding 3R approach towards environmental friendly practices with economic benefits. Further, this paper proposed a trade-off representation diagram for benchmarking a performance measurement system, which has not done in any previous research. This proposed performance measurement system can be used to evaluate the four performance attributes simultaneously in a reverse supply chain.

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