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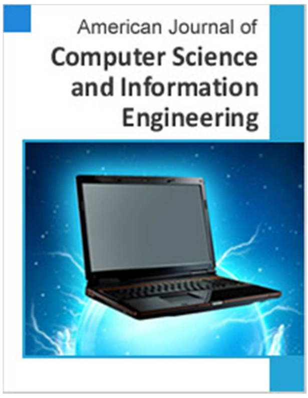

Evaluation of Design Alternatives of End-of-Life Products Under Stochastic Yields in Multiple Periods

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Abstract
Disassembly is an important process that is normally performed before any other product recovery technique is implemented. The End-Of-Life (EOL) products received for product recovery are disassembled to help satisfy all the demands. When the products are received by a product recovery facility, the quality or the conditions of the received EOL products are unknown. This uncertainty leads to stochastic disassembly yields. In this paper, an Advanced-Remanufacturing-To-Order-Disassembly-To-Order system (ARTODTO), which uses heuristic techniques to convert the stochastic disassembly yields into their deterministic equivalents, is proposed. Once the deterministic problem is formulated, multi-criteria decision-making techniques are used to evaluate the design alternatives of EOL products, and to determine the best design or combination of designs to satisfy all the demands, and constraints. In this paper, four criteria are considered for evaluating the design alternatives, viz., total profit, procurement cost, purchase cost, and disposal cost in three periods. A multi-criteria decision making technique known as Goal Programming (GP) is used to solve the problem. An example using Air Conditioners (ACs) is considered to illustrate the implementation of the methodology.

1. Introduction

As government takes more interest in environmental issues, sustainability and reverse supply chains, manufacturers are required to meet rules and regulations for the conservation of the environment and produce green or eco-friendly products [1]. However, rapid technological developments, especially for electronic products, entice consumers to purchase the latest model products, and discard current working products. Therefore, although a product is in good working condition, it is disposed of. This shortens the product's lifecycle, which has a negative impact on the environment [2]. The discarded products are disposed of in landfills, causing pollution and reduction in the number of landfills. Therefore, product recovery must be considered in order to protect the environment and minimize the use of landfills.

To recover products at their EOL phase, the recovery process should be considered at the product design phase [3]. If the product's design is complex, its disassembly at the recovery stage can be difficult because it will be hard to retrieve components from the product, and the chances of damage are increased. However, if the product design facilitates the disassembly or product recovery, then the efficiency of product recovery processes increases. Consequently, product design is one of the most important factors of product recovery [4].

There are different product recovery techniques viz., reuse, remanufacturing, and recycling. Disassembly is also an important process that is performed along with other recovery processes [5]. Disassembly can be destructive or non-destructive. In destructive disassembly, items may be damaged during the process, while in non-destructive disassembly items are not allowed to be damaged. Therefore, non-destructive disassembly is more expensive and labor intensive; thus, it is performed only when the items are to be reused or stored for future. If the items are to be recycled or disposed of, destructive disassembly is performed.

When a product recovery facility receives a variety of EOL products, they are sorted, inspected, and prepared for disassembly. The products are then sent to the disassembly facility where they are disassembled destructively, or non-destructively, into subassemblies/components to fulfill the products, components, and materials demands. However, the uncertainties regarding the quality of the received EOL products and the quantity, and variety of EOL products from different suppliers, complicate the disassembly process and make it difficult to identify the exact number of EOL products needed for disassembly, in order to fulfill all the demands. These uncertainties lead to stochastic disassembly yields, which complicate the problem. In this paper, an ARTODTO system in which different design alternatives of EOL products are purchased from suppliers to satisfy products, components, and materials demands in multiple periods, by implementing the disassembly and remanufacturing processes, is proposed. However, there are numerous uncertainties including the quantity and conditions of the received EOL products, which complicate the process, and makes it difficult to manage the EOL products when fulfilling all the demands [6]. The proposed system enables the management of EOL products through predicting the disassembly yields of these products, which are stochastic in nature. The system uses heuristic methods to convert the stochastic yields into their deterministic equivalents. Since the main input to the system is EOL products, the number of EOL products to be acquired is important, and should be determined such that it satisfies all the demands. The goal of the proposed model is to determine the best suitable design alternative, or combination of design alternatives, to satisfy all the demands and constraints, and also to determine the quantity of EOL products to be acquired. The design alternatives are evaluated based on four criteria viz., total profit, procurement cost, purchase cost, and disposal cost. A numerical example involving ACs is considered to illustrate the proposed model.

2. Literature Review

Disassembly, product design and remanufacturing are some areas related to the topic of interest here. Some relevant literature has been reviewed here.

Gungor and Gupta [7] and Ilgin and Gupta [1] presented state of the art survey papers covering literature available in the area of Environmentally Conscious Manufacturing and Product Recovery (ECMPRO), published through 1998 and 2010 respectively. Together, they classified more than 870 papers (330 and 540 respectively) under four main categories: reverse and closed-loop supply chains, environmentally conscious product design, disassembly and remanufacturing. The relevant areas within these four categories are discussed below.

2.1. Reverse and Closed Loop Supply Chains

Nagel and Meyer [8] presented a brief study on the end-of-life aspects of environmentally conscious manufacturing along with an overview on the legal responsibility of producers for end-of-life products.

Lee et al. [9] proposed a linear model to optimize a reverse logistics network with multi stages and multi products. The objective was to minimize total shipping cost and fixed opening costs of the disassembly centers and processing centers in reverse logistics. The authors used a hybrid GA to reach near optimal solution. Lee and Dong [10] presented a stochastic approach for the dynamic reverse logistics network design under uncertainty. A two-stage stochastic programming model was developed by which a deterministic model for dynamic reverse logistics network design could be extended to explicitly account for the uncertainties. The proposed method integrated the sample average approximation (SAA) method with a simulated annealing (SA) based heuristic algorithm. According to the authors, the solutions obtained by the proposed stochastic approach were beyond those obtained by the deterministic optimization approach and were closer to being optimal for the true stochastic network design problem.

Reverse Logistics activities may also be employed by outsourcing. In these situations, success of the RL is greatly dependent on the capabilities of the third parties from which the service is outsourced. Cheng and Lee [11] stated the importance and complexity of reverse logistics and presented a systematic approach to select a Third Party Logistics (3PL) provider to outsource the reverse logistic activities. The authors utilized analytical network process (ANP) to investigate the relative importance of reverse logistics service requirements and also to select an appropriate 3PL provider.

Ilgin et al. [12] presented a state of art review paper on the use of MCDM techniques in the field of environmentally conscious manufacturing and product recovery. The authors classified over 190 MCDM studies in environmentally conscious manufacturing and product recovery into three categories: multi-objective optimization, multi-criteria analysis and integration between them.

Garg et al. [13] proposed a CLSC network which consists of four echelons in the forward chain and five echelons in the backward chain. The authors formulated a bi-objective integer nonlinear programming model and solved it using the proposed Interactive Multi-objective Programming Approach Algorithm. The model determines the optimal flow of parts and products in the CLSC network and optimum number of trucks hired by facilities in the forward chain network. Jaggernath [14] presented information and misconception about issues surrounding green supply chain management (GSCM). The author conducted a study by analyzing and critiquing secondary data obtained from numerous sources. The results of the study provided an overview of what GSCM practices entail, strategies successful companies have used to incorporate GSCM practices within the organizations and its impact on the industry. For additional information, see the books by Pochampally, Nukala and Gupta [15] and Gupta [16].

2.2. Environmentally Conscious Product Design

The primary aim of traditional product development is achieving improvements in design with respect to cost, functionality and manufacturability. However, product designers are now considering environmental factors in the designing process. A number of methodologies have been developed to help designers make environmentally friendly design preferences. For example, Cheung et al. [17] proposed and developed a roadmap to facilitate the prediction of disposal costs, which will be used to determine whether the EOL parts are viable to be remanufactured, refurbished or recycled at an early design concept phase. The authors illustrated the proposed roadmap with a defense electronic system case study. Aguiar et al. [3] proposed a diagnostic tool to evaluate product recyclability to be applied during the product design phase for designer decision making. The procedure allows to simulate the product redesign to improve its EOL performance. Kim and Moon [2] introduced a design methodology to develop eco-modular product architecture and access its modularity for product recovery. They proposed a modularity assessment metrics to identify independent interactions between modules and the degrees of similarity within each module. Li et al. [18] presented a state-of- the- art review paper on environmentally conscious product design. They reviewed 120 references on theories, methods, and software tools on environmentally conscious product design published during 2005 to 2015. The references were divided into five categories: product eco-design, design for disassembly, design for recycling, material selection and, eco-design software tools. Design for Disassembly (DfD) is the methodologies directly related to this research study.

Veerakamolmal and Gupta [19] defined Design for Disassembly (DfD) as the ease of disassembly in the design process. Kroll and Hanft [20] presented a method for evaluating ease of disassembly. Veerakamolmal and Gupta [21] introduced a Design for Disassembly Index (DfDI) to measure the design efficiency. A disassembly tree identifies precedence relationships that define the structural constraints of the order in which components can be retrieved. DfDI is calculated by using this disassembly tree. Das et al. [22] estimated the disassembly cost and efforts by calculating a disassembly effort index of seven factors (time, tools, fixture, access, instruct, hazard, and force requirements). Ferrer [23] proposed a framework by developing economic measures of recyclability, disassemblability, and reusability for determining the disassembly and recovery process. Desai and Mital [24] and Mital and Desai [25] proposed a methodology for enhancing the disassemblability of products. They defined disassemblability in terms of exertion of manual force for disassembly, degree of precision required for effective tool placement, weight, size, material and shape of components being disassembled, use of hand tools, etc. Time-based numeric indices are assigned to each design factor. A higher score indicates irregularities in product design from the disassembly perspective. Villalba et al. [26] determined economic feasibility of disassembling a product by using recyclability index of materials.

Vishwanathan and Allada [27] focused on the importance of product configurations in DFD. They proposed a model called Configuration-Value (CV) model, to evaluate and analyze the effects of configuration on disassembly. This research was extended by Vishwanathan and Allada [28] by developing a model for combinatorial configuration design optimization problem. Kwak et al. [29] developed a concept called "eco-architecture analysis" in which a product is represented as an assembly of EOL modules. By determining the most desirable eco-architecture, optimal EOL strategy can be developed. Chu et al. [30] proposed a CAD based model that can automatically generate a 3D product structure by modifying parts, assembly methods and sequence. A Genetic Algorithm (GA) is employed to determine an optimal product structure.

Chiodo and Billett [31] in their book chapter, proposed a concept of self-disassembly for electronics products. They discussed about the use of Active Disassembly using Smart Materials (ADSM) in the design process, ensuring that at its EOL, the product contains all the necessary information and mechanisms to disassemble itself following a simple generic triggering event such as heat. Shalaby and Saitou [32] presented a unified method to design a high-stiffness reversible locator-snap system that can disengage non-destructively with localized heat. They also presented its application to the external product enclosures of electrical appliances. For additional information, refer to book by Gupta and Lambert [33].

2.3. Disassembly

Disassembly is a widely studied research area. Scholars have categorized the disassembly processes as scheduling ([34], [35], [36]), sequencing ([37], [38]), disassembly line balancing ([39]), disassembly-to-order ([40], [41], [42], [43]), and automated disassembly ([44]). Lambert and Gupta [45] in their book *Disassembly modeling for assembly, maintenance, reuse and recycling* discussed the different aspects of disassembly.

Disassembly-To-Order is one of the relevant category here. Disassembly to order (DTO) systems determine the optimal lot sizes of EOL products to disassemble, to satisfy the component demands from a mix of different product types that have a number of components/modules in common

([46]).

Lambert and Gupta [46] proposed a method called tree network model by modifying the disassembly graph method for a multi-product demand driven disassembly system with commonality and multiplicity. Kongar and Gupta [47] proposed a multi-criteria optimization model of a DTO system, to determine which and how many of the EOL products are to be disassembled to meet the products, components, and materials demands for achieving the goals of maximum total profit, maximum material sales revenue, minimum number of disposed items, minimum number of stored items, minimum cost of disposal, and minimum cost of preparation. Kongar and Gupta [48] extended Kongar and Gupta's [47] method by using fuzzy GP to model the fuzzy aspirations of numerous goals. Gupta et al. [49] used neural networks to solve the DTO problem. Kongar and Gupta [42] proposed a Linear Physical Programming (LPP) model for solving the DTO problem, which can satisfy tangible or intangible financial and environmental performance measures. Kongar and Gupta [50] also developed a multi-objective tabu search algorithm for EOL products disassembly considering the multiple objectives of maximizing total profit, maximizing the resale and recycling percentage, and minimizing the disposal percentage. Imtanavanich and Gupta [51] proposed a multi-criteria DTO system under stochastic yields using GP to determine the optimal number of returned products to disassemble, in order to satisfy the demands for specified number of parts.

Heuristics are developed assuming deterministic disassembly yield. Inderfurth and Langella [40], and Langella [43] proposed two heuristic procedures (one-to-one and one-to-many) to deal with the uncertainties in the disassmebly process by predicting the stochastic disassembly yields. The authors then converted the stochastic disassembly yields into their deterministic equivalents and then solved the deterministic problem in order to get the solution. Imtanavanich and Gupta [52] used the heuristics developed by Inderfurth and Langella [40] to handle the stochastic elements of a DTO system. They also proposed a GP model to determine the number of returned products that satisfy the goals. The authors also generated a DTO plan to satisfy the demand of components while maximizing profit, and minimizing the cost of the system. They used three techniques to solve the problem, viz. genetic algorithm, LPP, and a refining algorithm.

2.4. Remanufacturing

Remanufacturing is an industrial process which converts the worn-out products into like-new conditions ([53]). Andrew-Munot et al. [54] examined the key motivating factors for companies to engage in remanufacturing program, and the major sources for acquiring used-products and subsequent markets for selling remanufactured products. The authors also presented four examples of remanufacturing process of different products to demonstrate the exact number and sequence of remanufacturing processes is dependent on the type of product being remanufactured. For additional information, see the book by Ilgin and Gupta [55].

The uncertainty in the quantity, quality and timing of returned End-Of-Life products complicates the analysis of a remanufacturing system. ([1]). The lack of empirical data about the qualities of returned products was discussed by Klausner and Hendrickson [56]. De Brito and van der Laan [57] pointed out the difficulties in inventory management due to uncertainties in the quality and quantity of EOL products. They showed that information such as forecasts is based on historical data and is never perfectly accurate and impacts the inventory management performance, and the most informed method might not lead to best performance.

3. Problem Statement

The ARTODTO system takes back a wide variety of EOL products from suppliers in order to fulfill the products, components, and materials demands. Figure 1 displays a flowchart of an ARTODTO system. The purchased EOL products are sent to a collection facility for inspection, sorting, cleaning, and preparation for disassembly. Once the EOL products are prepared for disassembly, they are sent to the disassembly facility. Depending on the final use and condition of the component, the type of disassembly process is determined. Components that are demanded for reuse, remanufacturing and/or storage (i.e. functional components) are disassembled using non-destructive disassembly, while components that are demanded for recycling and/or disposal (i.e. non-functional components), are disassembled using destructive disassembly.

The components yields from destructive and non-destructive disassembly processes are stochastic due to the uncertainty regarding the conditions of the received EOL products. The components from the non-destructive disassembly are inspected for good and bad components. Good non-destructive components are used to satisfy the demands of remanufactured and reused components, while bad non-destructive components are sent to the recycling process. If the demands cannot be met using the disassembled components, additional components are procured from outside suppliers, as the demand shortage is not allowed. If the number of good non-destructive components exceeds the reuse and remanufacturing demands, excess components are stored for future use. Components from destructive disassembly are inspected for recyclable and non-recyclable components. Recyclable components from destructive disassembly along with the bad components of non-destructive disassembly are sent to the recycling facility. Finally, the non-recyclable components from destructive disassembly are disposed of.

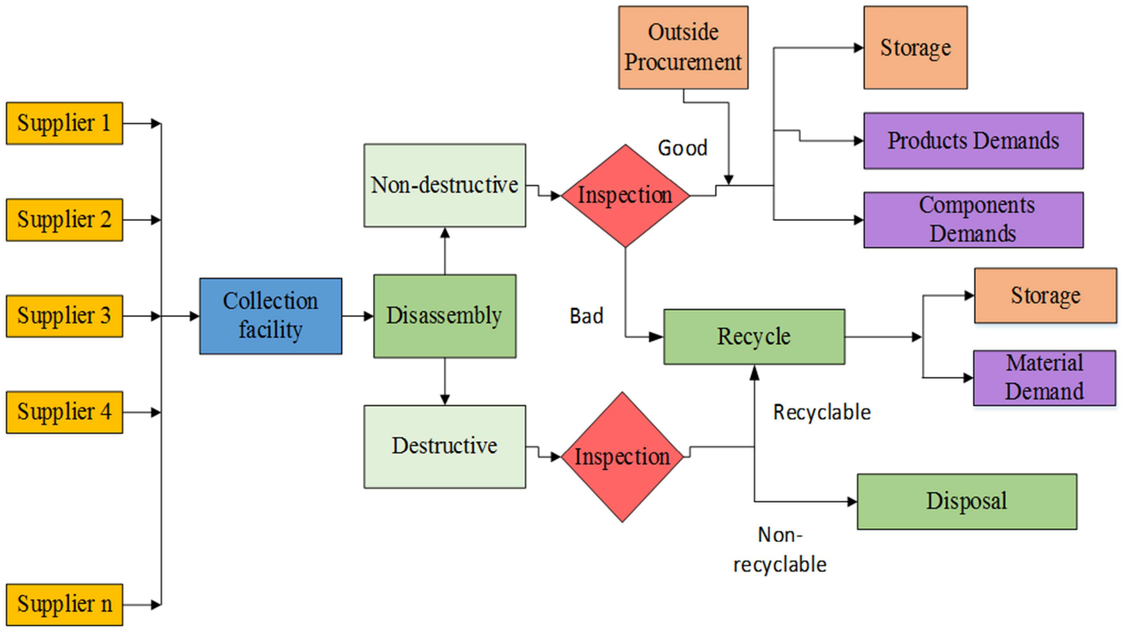

Figure 1. *Advanced-Remanufacturing-to-Order-Disassembly-to-Order System under Stochastic Yields.*

The received EOL products are available in various design alternatives depending on the customer's demands, manufacturer, model, version, use etc. Some of the factors affected by the different product designs are:

1. Size and shape of the product – The size and shape of the alternatives can be different.
2. Location of use – An alternative can be specific to the location or function of the use.
3. Ease of disassembly – The assembly or arrangement of components in different alternatives can be different affecting the retrieval of components from the products.
4. Time for disassembly – The time for disassembly can differ depending on the design alternative.
5. Labor skills and costs – The alternative which is difficult to disassemble may require more skilled labor than the alternative which is easy to disassemble, in which case the labor cost will also be different.

To account for these factors, a disassembly factor is introduced which is defined as follows:

$$f = \frac{number\ of\ assemblies\ to\ disassemble}{total\ number\ of\ assemblies} \quad (1)$$

An assembly will be disassembled if it contains one or more target components or if it contains lower level assemblies that contain target components [17]. The disassembly factor can be utilized to determine the EOL performance of various design alternatives by using it in the disassembly cost calculations of components.

4. Mathematical Formulation Using Goal Programming (GP)

The design alternatives are evaluated based on four goals. The mathematical formulation is as follows:

4.1. Goals

The four goals considered in this formulation in order of priorities are total profit, total outside procurement cost, total product purchase cost and total disposal cost. Note that η_s and ρ_s represent the negative and the positive deviations from goal *s* respectively.

i) The first goal is to maximize the total profit. The aspiration level of total profit is set to TP^*. This goal can be formulated as follows:

$$\min \quad \eta_1 \quad (2)$$

$$TP + \eta_1 - \rho_1 = TP^* \quad (3)$$

ii) The second goal is to minimize the total outside procurement cost, to have a value no more than its limitation value of $TOPC^*$. This goal can be formulated as follows:

$$\min \quad \rho_2 \quad (4)$$

$$TOPC + \eta_2 - \rho_2 = TOPC^* \quad (5)$$

iii) The third goal is to minimize the total product purchase cost, to have a value no more than its limitation value of $TPRC^*$. This goal can be formulated as follows:

$$\min \quad \rho_3 \quad (6)$$

$$TPRC + \eta_3 - \rho_3 = TPRC^* \quad (7)$$

iv) The fourth goal is to minimize the total disposal cost, to have a value no more than its limitation value of TDISPC*. This goal can be formulated as follows:

$$\min \quad \rho_4 \tag{8}$$

$$TDISPC + \eta_4 - \rho_4 = TDISPC^* \tag{9}$$

where:

TP is total profit that is derived from of resale revenue (*RSR*), material value (*MV*), stored value (*SV*), total disassembly cost (*TDISSC*), total disposal cost (*TDISPC*), total holding cost (*THOLC*), total outside procurement cost (*TOPC*), total recycling cost (*TRECC*), total remanufacturing cost (*TREMC*), and total product purchase cost (*TPRC*). It is represented as follows:

$$TP = RSR + MV + SV - TDISSC - TDISPC - THOLC - TOPC - TRECC - TREMC - TPRC \tag{10}$$

RSR is the resale revenue gained by reusing the good non-destructively disassembled components. It is obtained by the multiplication of the number of reused components (i.e. the demand for reused components) and the component resale value.

$$RSR = drec_j * rv_j \tag{11}$$

MV is the material value gained by recycling the bad non-destructively disassembled components and the destructively disassembled components. It is the multiplication of the amount of material recycled and the material value.

$$MV = (qbrc_j + qddc_j) * mv_j \tag{12}$$

SV is the stored value gained by storing the extra reusable components, and good recycled material. It is the multiplication of the amount of stored components and the stored value of the components, and the amount of stored material and the stored value of materials.

$$SV = qsc_j * scv_j \tag{13}$$

TDISSC is the total disassembly cost which is divided into two parts; destructive disassembly cost and non-destructive disassembly cost. The first part of destructive disassembly is the multiplication of the disassembly factor of a component in a design alternative, labor cost, and disassembly time for destructive disassembly. The second part of non-destructive disassembly is the multiplication of the disassembly factor of a component in a design alternative, labor cost, and disassembly time for non-destructive disassembly.

$$TDISSC = (f_{tj} * lcdd_j * tdd_j) + (f_{tj} * lcndd_j * tndd_j) \tag{14}$$

TDISPC is the total disposal cost which is divided into three parts; disposal cost of products, disposal cost of components, and disposal cost of materials. The first part is the multiplication of the total amount of disposed products, and the disposal cost of products. The second part is the multiplication of the disposed components, and the disposal cost of components. The third part is the multiplication of the disposed materials, and the disposal cost of materials.

$$TDISPC = qdispp_i * cdp_i + qdisc_j * cdc_j + qdispm_j * cdmj \tag{15}$$

THOLC is the total holding cost, which is divided, into two parts: the holding cost of components, and the holding cost of products. The first part is the multiplication of the amount of stored components, and the holding cost of components. The second part is the multiplication of the amount of stored materials, and the holding cost of materials.

$$THOLC = qsc_j * chc_j + qsm_j * chm_j \tag{16}$$

TOPC is the total outside procurement cost, which is the multiplication of the amount of components procured from outside, and the outside procurement cost of the components.

$$TOPC = qopc_j * cpc_j \tag{17}$$

TRECC is total recycling cost which is the multiplication of the amount of materials recycled, and the recycling cost of the materials.

$$TRECC = qrecm_j * crc_j \tag{18}$$

TREMC is the total remanufacturing cost which consists of two processes: the disassembly of broken or lifetime deficit components, and the assembly of the required components. Therefore, it is the multiplication of the amount of products remanufactured, and the sum of non-destructive disassembly and assembly costs.

$$TREMC = qremp_i * ((f_{tj} * lcndd_j * tndd_j) + ca_j) \tag{19}$$

TPRC is the total product purchase cost which is the multiplication of the amount of EOL products taken back from suppliers, and the purchased products cost.

$$TPRC = qpurp_i * cpp_i \tag{20}$$

4.2. Constraints

The total number of products *i* to be disassembled has to be equal to the total number of EOL products *i* purchased, multiplied by the stochastic good condition percentage of products *i*. Therefore,

$$qdissp_i = qpurp_i * sgp_i \tag{21}$$

The total number of disassembled components should be equal to the number of disassembled products, multiplied by the multiplicity of that component in the product.

$$qdissc_j = qdissp_i * m_{ij} \tag{22}$$

The total number of non-destructively disassembled components should be less than or equal to the total number of disassembled products, multiplied by the multiplicity and disassembly yields of the component in that product.

$$qnddc_j \le qdissp_i * m_{ij} * sdy_{ij} \quad (23)$$

The total number of destructively disassembled components is equal to the subtraction of the total number of non-destructively disassembled components from the total number of disassembled components.

$$qddc_j = qdissc_j - qnddc_j \quad (24)$$

The total number of components disassembled for reuse cannot exceed the total number of non-destructively disassembled components.

$$qrec_j \le qnddc_j \quad (25)$$

The quantity of functional components that can be reused is equal to the multiplication of the number of component j sent for reuse, and its stochastic reusable percentage.

$$qgrc_j = qrc_j * srp_j \quad (26)$$

The quantity of non-functional components j that cannot be reused and will eventually be recycled is equal to the subtraction of functional components from the quantity of components disassembled for reuse.

$$qbrc_j = qrc_j - qgrc_j \quad (27)$$

The demand for reusable components is fulfilled by good reusable components obtained from non-destructively disassembled components, and components procured from outside.

$$drec_j = qgrc_j + qopc_j \quad (28)$$

The components are procured from outside when the demand cannot be met using the good reuse components. Hence, the number of procured components is the maximum value between the subtraction of the number of reusable components from the demand of reusable components, and zero.

$$qopc_j = Max\{(drec_j - qgrc_j), 0\} \quad (29)$$

The recycling process does not usually recover all the materials from components. Therefore, the total number of recycled components is equal to the demand of recycled components divided by the recyclable percentage.

$$qrecc_j = drecc_j / srec_j \quad (30)$$

The total number of recycled components cannot exceed the sum of the bad reuse components, and the total number of destructively disassembled components.

$$qrecc_j \le qbrc_j + qddc_j \quad (31)$$

The quantity of recycled components that exceeds the recycling demands is sent to disposal. Therefore, the quantity of recycled components sent to recycling is the maximum value between the subtraction of the quantity of components recycled from the sum of non-functional components that cannot be reused, and the quantity of destructively disassembled components, and zero.

$$qredc_j = Max\{[(qbrc_j + qddc_j) - qrecc_j], 0\} \quad (32)$$

The total weight of recycled material is equal to the multiplication of the number of recycled components, the weight of the component, and its stochastic recyclable percentage.

$$wrecm_j = qrecc_j * wc_j * srec_j \quad (33)$$

The total number of stored components is the subtraction of reused components from the sum of components stored in the previous period and total number of non-destructively disassembled components.

$$qsc_j = qosc_j + qnddc_j - qrc_j \quad (34)$$

The total number of disposed products is the subtraction of the total number of disassembled products from the total number of purchased products.

$$qdispp_i = qpurp_i - qdissp_i \quad (35)$$

The total number of disposing components is equal to the subtraction of the number of recycled components from the sum of the bad reuse components, and destructively disassembled components.

$$qdispc_j = qbrc_j + qddc_j - qrecc_j \quad (36)$$

The total number of disposing materials is the multiplication of the amount of recycled components, weight of the components, and the non-recyclable percentage.

$$qdispm_j = qdispc_j * wc_j * (1 - srec_j) \quad (37)$$

5. Numerical Example

To illustrate the formulated model, an example is presented in this section. The ARTODTO system receives EOL ACs from four different suppliers. There are four types of air conditioners with their own unique features; however, they all have the same function of providing cool air and they all share the following eight components: evaporator, control box, blower, air guide, motor, condenser, fan, and compressor. The different types of air conditioners are window AC, split AC, packaged AC, and central AC.

Table 1 through Table 7 display the input data to solve the formulated model.

Table 1. *Component reuse demand and component recycling demand.*

Component	Reuse Demand	Recycling Demand
	Period 1/2/3	**Period 1/2/3**
Evaporator	250/150/160	180/150/100
Control Box	300/250/210	200/100/0
Blower	280/150/100	220/210/200
Air Guide	100/50/70	180/160/140
Motor	185/100/120	150/140/130
Condenser	120/130/140	160/180/195
Fan	230/250/210	200/260/240
Compressor	350/360/365	260/210/180

Table 2. *Product demands, product purchase cost and product disposal cost.*

Product	Demands	Purchase Cost ($)	Disposal Cost ($)
	Period 1/2/3		
Windows AC	10/10/12	100	2
Split AC	10/80/8	300	2
Packaged AC	8/40/2	800	2
Central AC	5/0/0	500	2

Table 3. *Component yields from each AC type.*

	Window AC	Split AC	Packaged AC	Central AC
	Period 1/2/3	**Period 1/2/3**	**Period 1/2/3**	**Period 1/2/3**
Evaporator	0.35/0.87/0.96	0.47/0.79/0.88	0.28/0.90/0.98	0.78/0.74/0.78
Control Box	0.42/0.85/0.86	0.84/0.85/0.98	0.23/0.85/0.97	0.00/0.76/0.90
Blower	0.51/0.86/0.97	0.34/0.86/0.97	0.50/0.89/0.99	0.26/0.77/0.85
Air Guide	0.57/0.85/0.98	0.17/0.65/0.72	0.00/0.75/0.86	0.28/0.68/0.78
Motor	0.00/0.85/0.93	0.52/0.77/0.87	0.62/0.62/0.96	0.21/0.69/0.85
Condenser	0.70/0.64/0.72	0.59/0.78/0.99	0.74/0.57/0.85	0.51/0.45/0.98
Fan	0.75/0.77/0.87	0.00/0.46/0.82	0.72/0.86/0.79	0.65/0.57/0.65
Compressor	0.82/0.88/0.92	0.68/0.70/0.92	0.63/0.87/0.77	0.82/0.59/0.87

Table 4. *Labor rates and times of components of ACs.*

Component	Labor Rate (Destructive Disassembly) ($/hr.)	Labor Rate (Non-Destructive Disassembly) ($/hr.)	Disassembly Time (Destructive Disassembly) (hr.)	Disassembly Time (Non-Destructive Disassembly) (hr.)
Evaporator	10	15	0.2	0.3
Control Box	10	15	0.2	0.3
Blower	10	15	0.2	0.3
Air Guide	10	15	0.2	0.3
Motor	10	15	0.2	0.3
Condenser	10	15	0.2	0.3
Fan	10	15	0.2	0.3
Compressor	10	15	0.2	0.3

Table 5. *Disassembly factors for windows, split, packaged and central ACs.*

	Windows AC	Split AC	Packaged AC	Central AC
Evaporator	0.17	0.20	0.17	0.17
Control Box	0.17	0.20	0.17	0.17
Blower	0.50	0.60	0.50	0.50
Air Guide	0.50	0.80	0.50	0.50
Motor	0.50	0.50	0.50	0.50
Condenser	0.17	0.50	0.17	0.17
Fan	0.50	1.00	0.50	0.50
Compressor	0.17	0.50	0.17	0.17

Table 6. *Resale component price, material price, stored component value and holding cost.*

Component	Resale Component Price ($)	Material Price ($)	Stored Component Value ($)	Holding Cost ($)
Evaporator	93.67	13.00	60.00	12.00
Control Box	15.00	2.20	20.00	6.00
Blower	8.37	5.00	6.00	3.00
Air Guide	11.25	5.00	8.00	3.00
Motor	54.25	2.20	50.00	10.00
Condenser	52.00	13.00	30.00	15.00
Fan	6.84	2.20	7.00	2.00
Compressor	104.81	13.00	45.00	10.00

Table 7. *Component disposal cost, outside procurement cost and material disposal cost.*

Component	Component Disposal Cost ($)	Outside Procurement Cost ($)	Material Disposal Cost ($)
Evaporator	0.60	187.34	0.40
Control Box	0.40	35.00	0.20
Blower	0.70	16.74	0.50
Air Guide	0.40	22.50	0.30
Motor	0.60	108.49	0.40
Condenser	0.70	103.99	0.40
Fan	0.60	13.68	0.40
Compressor	0.70	209.61	0.50

6. Results Using Goal Programming

The model was solved using LINGO 11.0.

6.1. Results for Period 1

The results are displayed in Table 8 and Table 9.

Table 8. *Aspiration levels and values of goals for period 1.*

Goals	Aspiration Level	Step 1	Step 2	Step 3	Step 4
Total profit	100,000.00	118,156.30	100,000.00	100,000.00	100,000.00
Total Outside Procurement cost	3,700.00	3,821.00	3,715.75	3,715.75	3,715.75
Total Product Purchase cost	80,000.00	86,000.00	84,000.00	80,000.00	80,000.00
Total Disposal cost	0.00	825.54	651.15	504.21	445.18

Table 9. *Number of Purchased EOL products for period 1.*

Purchased products for Windows AC	81
Purchased products for Split AC	210
Purchased products for Packaged AC	8
Purchased products for Central AC	5

The results show that the model achieved the aspiration levels for total profit and total product purchase cost, but underachieved the goals of total outside procurement cost and total disposal cost.

6.2. Results for Period 2

The results are displayed in Table 10 and Table 11.

Table 10. *Aspiration levels and values of goals for period 2.*

Goals	Aspiration Level	Step 1	Step 2	Step 3	Step 4
Total profit	120,000.00	135,185.25	120,000.00	120,000.00	120,000.00
Total Outside Procurement cost	2,800.00	2,852.50	2,782.54	2,800.00	2,800.00
Total Product Purchase cost	85,000.00	87,800.00	86,300.00	85,000.00	85,000.00
Total Disposal cost	0.00	625.14	513.47	318.61	284.00

Table 11. *Number of Purchased EOL products for period 2.*

Purchased products for Windows AC	120
Purchased products for Split AC	185
Purchased products for Packaged AC	12
Purchased products for Central AC	15

The results show that the model achieved the aspiration levels for total profit, total outside procurement cost and total product purchase cost but underachieved the goal of total disposal cost.

6.3. Results for Period 3

The results are displayed in Table 12 and Table 13.

Table 12. *Aspiration levels and values of goals for period 3.*

Goals	Aspiration Level	Step 1	Step 2	Step 3	Step 4
Total profit	200,000.00	200,116.84	200,000.00	200,000.00	200,000.00
Total Outside Procurement cost	3,000.00	3,176.47	2,995.14	3,000.00	3,000.00
Total Product Purchase cost	95,000.00	96,900.00	96,100.00	95,000.00	95,000.00
Total Disposal cost	0.00	742.54	643.61	589.43	476.25

Table 13. *Number of Purchased EOL products for period 3.*

Purchased products for Windows AC	135
Purchased products for Split AC	220
Purchased products for Packaged AC	10
Purchased products for Central AC	15

The results show that the model achieved the aspiration levels for total profit, total outside procurement cost and total product purchase cost but underachieved the goal of total disposal cost.

7. Conclusion

Product design has a significant impact on product recovery at the products' EOL stage. A complex product design will lead to higher recovery costs due to the difficulty in the disassembly process. Therefore, it is crucial to consider recovery processes during the product design phase. There are various methodologies developed to help designers in developing products which favor the recovery processes such as Design for X (DfX), life cycle assessment, and material selection.

In this paper, an ARTODTO system in which EOL products are purchased from different suppliers, to satisfy all the demands in three periods, was proposed. Different suppliers provided different design alternatives of the products. The model evaluated the design alternatives of the EOL products, to determine the best combination of designs for disassembly and remanufacturing. The model also optimized the purchase of EOL products from suppliers, while achieving the desired levels of multiple criteria, and determined the number of products of each design alternative to be purchased by the system, in order to meet all the demands.

Nomenclature

Variable/ Parameter	Description
MV	Material Value;
RSR	Resale Revenue;
SV	Stored value;
TDISPC	Total disposal cost;
TDISSC	Total disassembly cost;
THOLC	Total holding cost;
TOPC	Total outside procurement cost;
TP	Total profit;
TPRC	Total product purchase cost;
TRECC	Total recycling cost;
TREMC	Total remanufacturing cost;
ca_j	Assembly cost per unit of component j;
cdc_j	Disposal cost for component j;
cdm_j	Disposal cost for material of component j;
cdp_i	Disposal cost for product i;
chc_j	Holding cost per unit of component j;
chm_j	Holding cost per unit of material of component j;
cpc_j	Outside procurement cost per unit of component j;
cpp_i	Purchase cost per unit of product i;
crc_j	Recycling cost per unit of material of component j;
$drec_j$	Demand for reuse component j;
$drecc_j$	Demand for recycled component j;
f_{tj}	Disassembly factor of component j in design alternative t;
$lcdd_j$	Labor cost for destructive disassembly of component j;
$lcndd_j$	Labor cost for non-destructive disassembly of component j;
m_{ij}	Multiplicity of component j in EOL product i;
mv_j	Value of material of component j;
$qbrc_j$	Quantity of bad non-destructively disassembled component j;

Variable/ Parameter	Description
$qddc_j$	Quantity of destructively disassembled component j;
$qdispc_j$	Quantity of component j disposed of;
$qdispm_j$	Quantity of material of component j disposed of;
$qdispp_i$	Quantity of product i disposed of;
$qdissc_j$	Quantity of disassembled component j;
$qdissp_i$	Quantity of product i disassembled;
$qgrc_j$	Quantity of good non-destructively disassembled component j;
$qnddc_j$	Quantity of non-destructively disassembled component j;
$qopc_j$	Quantity of component j procured from outside;
$qpurp_i$	Quantity of product i purchased;
qrc_j	Quantity of reused component j;
$qrecc_j$	Quantity of recycled material of component j;
$qrecm_j$	Quantity of recycled material of component j;
$qredc_j$	Quantity of recycled component j that is disposed of;
$qremp_i$	Quantity of remanufactured product i;
qsc_j	Quantity of stored component j;
qsm_j	Quantity of stored material of component j;
rv_j	Resale value of component j;
scv_j	Stored value of component j;
sdy_{ij}	Stochastic disassembly yield of component j in product i;
sgp_i	Stochastic good condition percentage of product i;
smv_j	Stored value of material of component j;
$srec_j$	Stochastic recyclable percentage of component j;
srp_j	Stochastic reusable percentage of component j;
tdd_j	Time for destructive disassembly of component j;
$tndd_j$	Time for non-destructive disassembly of component j;
wc_j	Weight of component j;
$wrecm_j$	Weight of recycled material of component j;

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