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Coping with disassembly yield uncertainty in remanufacturing using sensor embedded products

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Abstract

This paper proposes and investigates the use of embedding sensors in products when designing and manufacturing them to improve the efficiency during their end-of-life (EOL) processing. First, separate design of experiments studies based on orthogonal arrays are carried out for conventional products (CPs) and sensor embedded products (SEPs). In order to calculate the response values for each experiment, detailed discrete event simulation models of both cases are developed considering the precedence relationships among the components together with the routing of different appliance types through the disassembly line. Then, pair-wise t-tests are conducted to compare the two cases based on different performance measures. The results showed that sensor embedded products improve revenue and profit while achieving significant reductions in backorder, disassembly, disposal, holding, testing and transportation costs. While the paper addresses the EOL processing of dish washers and dryers, the approach provided could be extended to any other industrial product.

Keywords: disassembly line, experimental design, sensor embedded products, cost-benefit analysis, discrete event simulation

1. Background

Remanufacturing is an industrial process involving the conversion of used products into like-new condition. This process starts with the collection and transportation of EOL products to a remanufacturing plant where they are disassembled into parts. Following the cleaning and inspection of disassembled parts, repair and replacement operations are performed to deal with defective and worn-out parts. Finally, all parts are re-assembled into a remanufactured product which is expected to function like a new product. In addition to repair and replacement, some parts or modules may also be upgraded while remanufacturing a product.

New and stricter government regulations on EOL product treatment and increasing public awareness towards environmental issues have forced many manufacturers to establish specific facilities for remanufacturing operations. Being the most environment-friendly and profitable product recovery option, remanufacturing has many advantages over other recovery options such as recycling, repairing or refurbishing. In remanufacturing, majority of labor, energy and material values embedded in an EOL product are recovered because the disassembled parts are used as is in the remanufacturing process. On the other hand, in recycling, only the material is recovered because the EOL products are simply shredded in a recycling facility. Remanufactured products provide superior performance due to replacement of worn-out parts and upgrading of some key parts. That is why many manufacturers are willing to give consumers the same warranty provisions as with the new products. Although replacement of some parts may occur during the repair or refurbishment option, there is no upgrading. Therefore repaired or refurbished products may not provide a superior performance and their warranty provisions are inferior to those of the remanufactured or new products.

Although remanufacturing is more sustainable than the traditional way of manufacturing where we only use virgin materials to produce new products, it involves more uncertainty. In a traditional manufacturing system, there are strict requirements to be obeyed by suppliers regarding the quality, quantity and arrival time of components. On the other hand, in remanufacturing, such strict requirements can not be imposed on the quality, quantity

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and arrival time of EOL products. That is why, determination of the condition, type and quantity of a component before actually disassembling it is not possible. This increases the uncertainty associated with the used component yield.

Sensor embedded products which involve sensors embedded into their critical components during the production process can solve this problem by providing information on the condition, type and number of components before actually disassembling them. In this study, we consider the application of SEPs in disassembly of components from EOL appliances for remanufacturing. The impact of SEPs on system performance is analyzed by performing separate experimental design studies based on orthogonal arrays for conventional products (CPs) and SEPs. Detailed discrete event simulation (DES) models of both cases are used to calculate various performance measures under different experimental conditions. Then, the results of pair-wise t-tests comparing the two cases based on different performance measures are presented.

The paper is organized as follows. In Section 2, a review of the issues considered in this study is presented. In Section 3, characteristics of the appliance disassembly line are explained. Section 4 and Section 5 explain the details and results of the design of experiments study, respectively. Finally, some conclusions are presented in Section 6.

2. Literature Review

Heuristics, tools or methodologies developed for manufacturing systems can not directly be applied to remanufacturing systems in most cases due to unique characteristics of remanufacturing process. Hence, researchers developed novel techniques considering different issues in remanufacturing including logistics [1,2], operations and production management [3,4], design for remanufacturing [5-7] and disassembly [8]. A complete and up-to-date overview of these studies can be found in the reviews by [9] and [10]. Being a crucial step in remanufacturing, disassembly has received increasing attention of researchers. Many studies have been presented on different domains of disassembly including sequencing [11,12], scheduling [13], disassembly line [14,15], disassembly line balancing [16,17], disassembly-to-order systems [18] and design for disassembly [19]. Researchers have also addressed the issues related to the disassembly of different type of products e.g., vehicles [20], electronics [21] and consumer appliances [22]. For detailed information on the different aspects of disassembly, we refer the reader to a couple of recent books [23,24].

There is a vast amount of literature on the use of sensor-based technologies on after-sale product condition monitoring. Starting with the study of [25], different methods of data acquisition from products during product usage were presented by the researchers [26-28]. In all of these studies, the main idea is the use of devices with memory to save monitoring data generated during the product usage. Although most of these studies focus on the development of SEP models, only few researchers presented a cost-benefit analysis. [29] analyzed the trade-off between the higher initial manufacturing cost caused by the use of an electronic data log in products and cost savings from the reuse of used motors. [30] improved the cost-benefit analysis of [29] by considering the limited life of a product design. They showed that, in that case, servicing provides more reusable components compared to EOL recovery of parts. [31] investigated the effectiveness of embedding sensors in computers by comparing several performance measures in the two scenarios-with embedded sensors and without embedded sensors. The performance measures considered include average life cycle cost, average maintenance cost, average disassembly cost, and average downtime of a computer. However, they do not provide a quantitative assessment of the impact of SEPs on these performance measures. Moreover, since only one component of a computer (hard disk) was considered, the disassembly setting does not represent the complexity of a disassembly line which is generally used to disassemble EOL computers. By extending [31], [32] analyzed the effect of SEPs on the performance of an EOL computer disassembly line which is used to disassemble three components from EOL computers, namely, memory, hard disk and motherboard. Due to relatively simple structure of an EOL computer, they did not consider the precedence relationships among the components. However, disassembly of a particular component is restricted by one or more components in some products. That is why, these products are disassembled according to a route determined based on the precedence relationships. In this study, we investigate the quantitative impact of SEPs on different performance measures of a disassembly system. The disassembly setting we consider is a disassembly line which is used to disassemble components from EOL dryers and dish washers. We also consider the precedence relationships among the components together with the routing of different EOL product types through the disassembly line.

3. Appliance Disassembly Process

EOL dryers and dish washers (DWs) are disassembled on a five-station disassembly line. Physical configuration of the stations in the disassembly line is given in Figure 1. Figure 2 presents the components disassembled at different stations of the disassembly line together with the disassembly sequence and routing of EOL dryers and dish washers. According to this figure, EOL dryers travel only in downstream direction since the precedence relationships among their components follow the sequencing of

Figure 1 Physical configuration of the stations in the disassembly line.

disassembly process. However, EOL DWs can travel in both upstream and downstream directions depending on which component is to be disassembled next.

There are two common components shared by EOL dryers and dish washers, viz., metal cover and electric motor. Drum is only included in dryers while timer and circuit board are the components that can be disassembled only from EOL dish washers. All disassembled components are demanded except for the metal cover. Table 1 presents the precedence relationships among the components. Disassembly times at stations, demand inter-arrival times for components and EOL product inter-arrival times are all distributed exponentially.

Figures 3 and 4 present disassembly flow charts for conventional and sensor embedded appliance disassembly processes, respectively. Conventional appliances (ones with no sensors) visit all stations. Following the disassembly at each station, components are tested. The testing times are normally distributed with the means and standard deviations presented in Table 1. Sensor embedded appliances visit only the stations which are responsible for the disassembly of functional components and their predecessor components. In addition, no testing is required for this case because of the sensor information available on the condition of the component.

Excess products, subassemblies and components are disposed of using a small truck with a load volume of 475 cubic feet. Whenever the total volume of the excess product, subassembly and component inventories become equal to the truck volume, the truck is sent to a recycling facility. Any product, subassembly or component inventory which is greater than *maximum inventory level* is assumed to be excess. Component volumes are given in Table 1. The volumes of EOL DWs and EOL dryers are taken as 20 cubic feet and 22 cubic feet, respectively. A multi kanban system (MKS) developed by [33] is used to control the disassembly line.

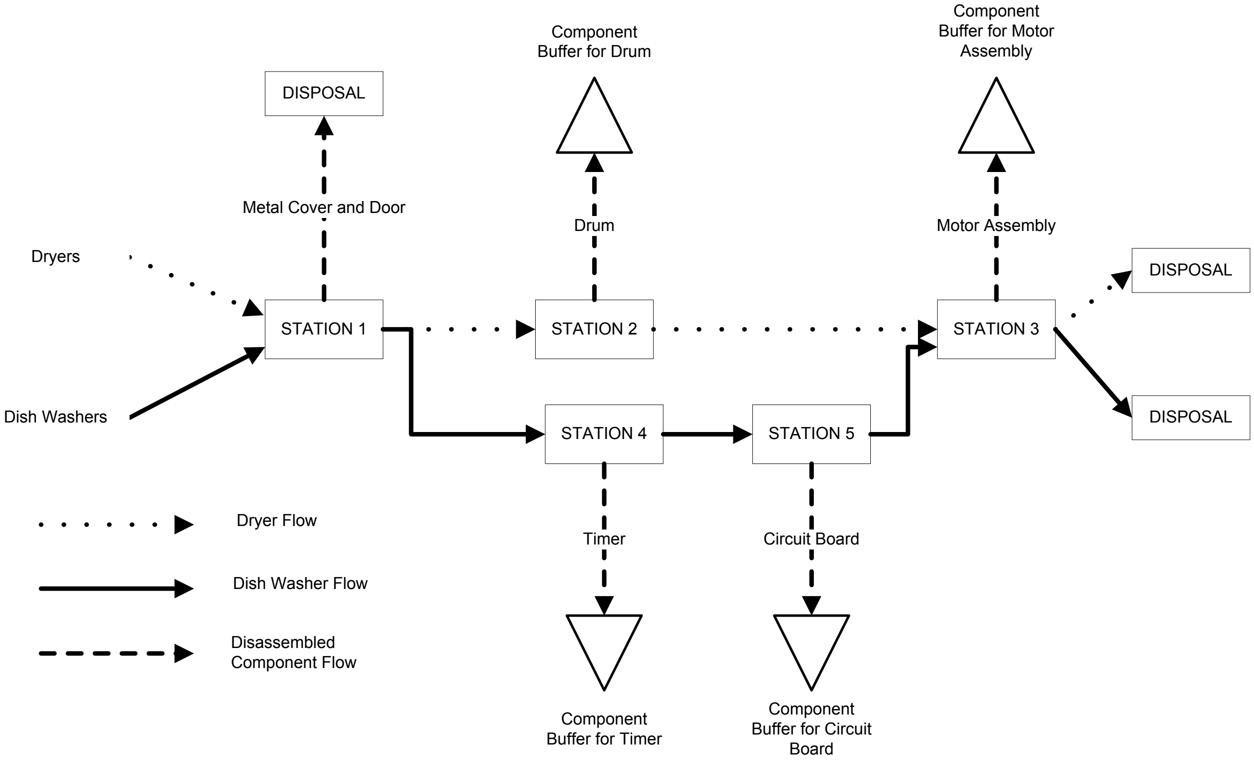


Figure 2 Sequence of appliance flows on the disassembly line.

Table 1 Specifications for DW and Dryer Components

Component Name	Code	Precedence Relationship		Testing Time (minutes)		Volume (cft)	Weight (lbs)
		DW	Dryer	Mean	Std. Dev.		
DW Metal Cover	A	-	-	-	-	0.720	*
Dryer Metal Cover	B	-	-	-	-	0.800	*
Drum	C	-	B	6	1.5	5.000	*
Motor Assembly	D	A, E, F	B, C	12	2	0.150	*
Timer	E	A	-	2.5	0.5	0.020	1
Circuit Board	F	A, E	-	6	1	0.030	1

*DW Metal Cover, Dryer Metal Cover, Drum and Motor Assembly weights are factors in the design of experiments study. For the weight ranges defined for these components, see Table 2.

4. Design of Experiments Study

In this section, we compare SEPs against CPs under different experimental conditions. The factors and factor levels considered in the experiments are given in Table 2. In this table, weights and prices of components have been estimated based on an online web search of various DW and dryer component sellers in USA. Further online web search was performed of various recyclers throughout the USA in order to estimate the steel scrap revenue per pound, disposal cost per pound, disposal cost increase factor for EOL products and scrap revenue decrease factor for EOL products. User and service manuals of various DW and dryer manufacturers were employed while estimating the mean disassembly and testing times of components together with small component weight factor. Maximum inventory level was estimated by making some trial simulation runs with different maximum inventory level values and investigating the changes in the number of products and components waiting in queues and various cost parameters. All the remaining parameter values (viz., non-functional and missing component probabilities, mean demand rates for components, mean arrival rates of products, backorder cost rate, holding cost rate, testing cost per minute and disassembly cost per minute) were estimated based on the values used in the literature.

A full factorial design with 39 factors requires an extensive number of experiments (viz., 4.05E+18). Therefore, experiments were performed using orthogonal Arrays (OAs) [34] which allow for the determination of main effects by running a minimum number of experiments. Specifically, L_{81} OA was chosen since it requires 81 experiments while accommodating 40 factors with three levels [35]. DES models for both cases were developed using Arena 11 [36] to determine profit value together with various cost and revenue parameters for each experiment. Animations of the simulation models were built for verification purposes. In addition, models' output results were checked for reasonableness. Dynamic plots and counters providing dynamic visual feedback were used to validate the simulation models. The replication time for each DES model was 60480 minutes, the equivalent of six months with one eight hour shift per day. DES models were replicated 10 times for each OA experiment.

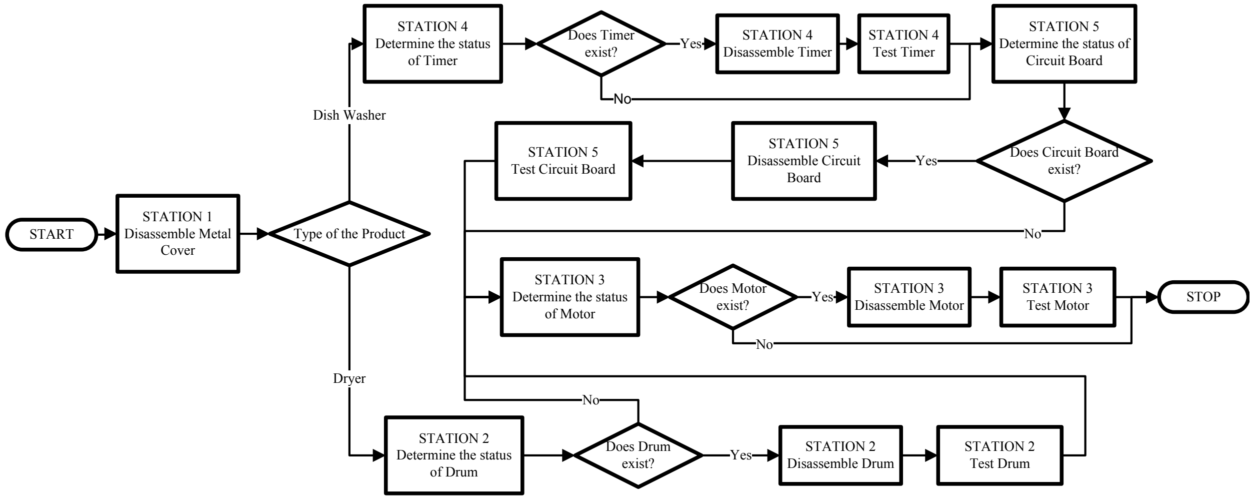


Figure 3 Disassembly flow chart for conventional products.

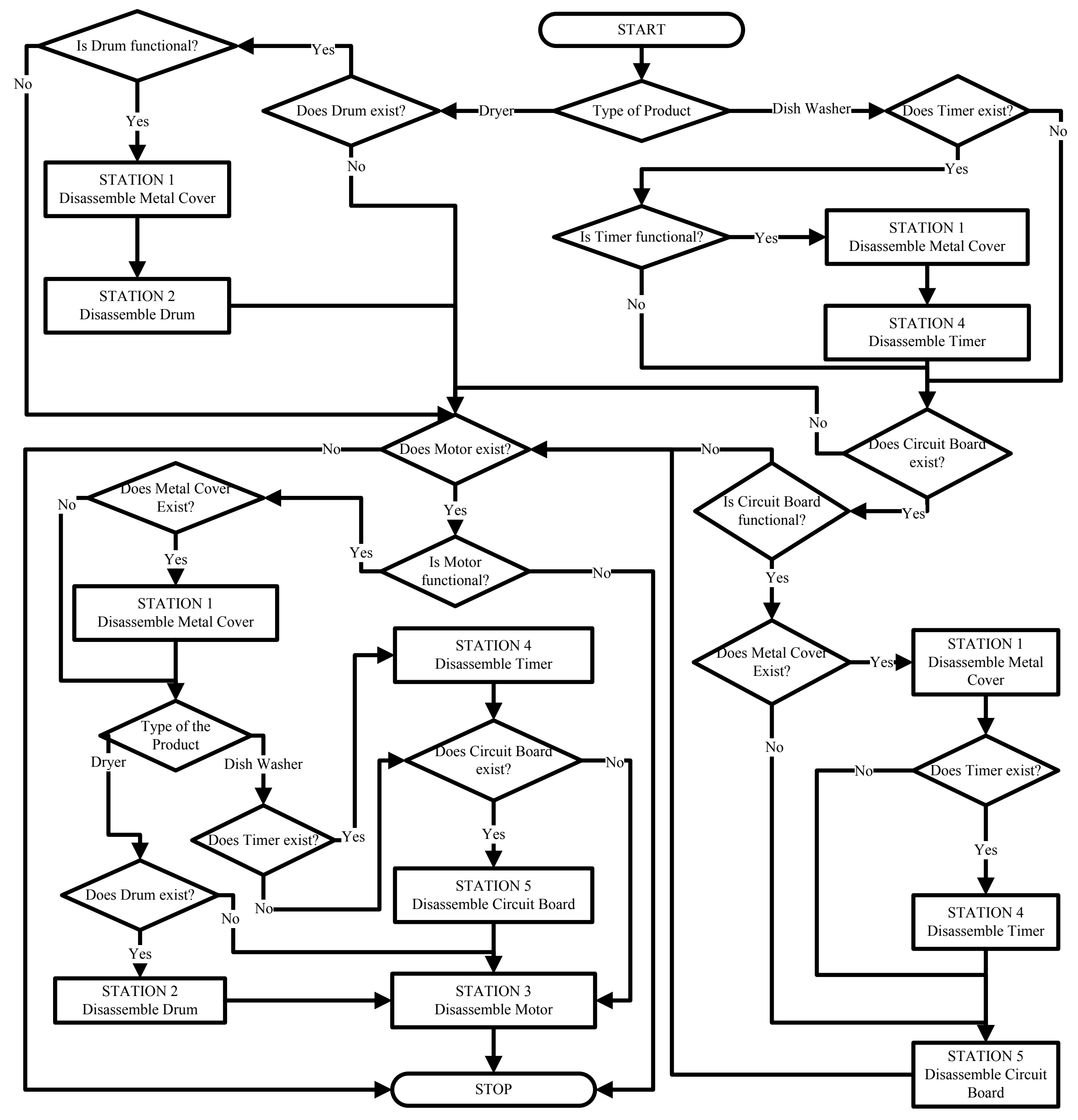


Figure 4 Disassembly flow chart for sensor embedded products.

Flow chart for the demand process is given in Figure 5. Figures 6 and 7 present the flow charts for the disassembly processes initiated by component kanbans for the CPs at the stations other than the last station and at the last station, respectively. Figures 8 and 9 present the flow charts of the disassembly processes initiated by component kanbans for the SEPs at the stations other than the last station and at the last station, respectively. Flow charts for the disassembly processes initiated by subassembly kanbans for CPs and SEPs are depicted in Figures 10 and 11, respectively.

The following equation presents the formula used in the DES models for the calculation of profit value.

$$Profit = \overbrace{(SR + CR + SCR)}^{\text{Total Revenue}} - \overbrace{(HC + BC + DC + DPC + TC + TPC)}^{\text{Total Cost}} \quad (1)$$

Table 2 Factor levels

Number	Factor	Levels		
		1	2	3
1	Disposal cost increase factor for EOL products	0.06	0.12	0.18
2	Scrap revenue decrease factor for EOL products	0.06	0.12	0.18
3	Mean demand rate for Drum *(components per hour)*	8	12	16
4	Mean demand rate for Motor Assembly *(components per hour)*	8	12	16
5	Mean demand rate for Timer *(components per hour)*	8	12	16
6	Mean demand rate for Circuit Board *(components per hour)*	8	12	16
7	Mean arrival rate of EOL DWs *(products per hour)*	8	16	24
8	Mean arrival rate of EOL Dryers *(products per hour)*	8	16	24
9	Mean disassembly time for station 1 *(minutes)*	0.40	0.80	1.20
10	Mean disassembly time for station 2 *(minutes)*	0.75	1	1.25
11	Mean disassembly time for station 3 *(minutes)*	0.75	1	1.25
12	Mean disassembly time for station 4 *(minutes)*	0.75	1	1.25
13	Mean disassembly time for station 5 *(minutes)*	0.75	1	1.25
14	Backorder cost rate	0.40	0.60	0.80
15	Disassembly cost per minute *($)*	0.75	1.5	2.25
16	Testing cost per minute *($)*	0.50	0.60	0.70
17	Holding cost rate	0.20	0.30	0.40
18	Weight for Metal Cover of DW *(pounds)*	4	8	12
19	Weight for Metal Cover of Dryer *(pounds)*	5	10	15
20	Weight for Drum *(pounds)*	6	12	18
21	Weight for Motor Assembly *(pounds)*	5	10	15
22	Weight of other steel components of DW *(pounds)*	70	90	110
23	Weight of other steel components of Dryer *(pounds)*	80	100	120
24	Price for Drum *($)*	30	50	70
25	Price for Motor Assembly *($)*	40	60	80
26	Price for Timer *($)*	20	40	60
27	Price for Circuit Board *($)*	25	50	75
28	Disposal cost per pound *($)*	0.40	0.50	0.60
29	Steel scrap revenue per pound *($)*	0.20	0.25	0.30
30	Maximum inventory level	6	12	18
31	Small component weight factor	0.05	0.10	0.15
32	Probability of a non-functional Drum	0.12	0.24	0.36
33	Probability of a non-functional Motor Assembly	0.12	0.24	0.36
34	Probability of a non-functional Timer	0.12	0.24	0.36
35	Probability of a non-functional Circuit Board	0.12	0.24	0.36
36	Probability of a missing Drum	0.06	0.12	0.18
37	Probability of a missing Motor Assembly	0.06	0.12	0.18
38	Probability of a missing Timer	0.06	0.12	0.18
39	Probability of a missing Circuit Board	0.06	0.12	0.18

The different cost and revenue components used in the equation 1 can be defined as follows:

- SR : The total revenue generated by the component sales during the simulated time period (STP).
- CR : The total revenue generated by the collection of EOL products during the STP.
- SCR : The total revenue generated by selling scrap components during the STP.
- HC : The total holding cost of components, EOL products and subassemblies during the STP.
- BC : The total backorder cost of components during the STP.
- DC : The total disassembly cost during the STP.
- DPC : The total disposal cost of components, EOL products and subassemblies during the STP.
- TC : The total testing cost during the STP.
- TPC : The total transportation cost during the STP.

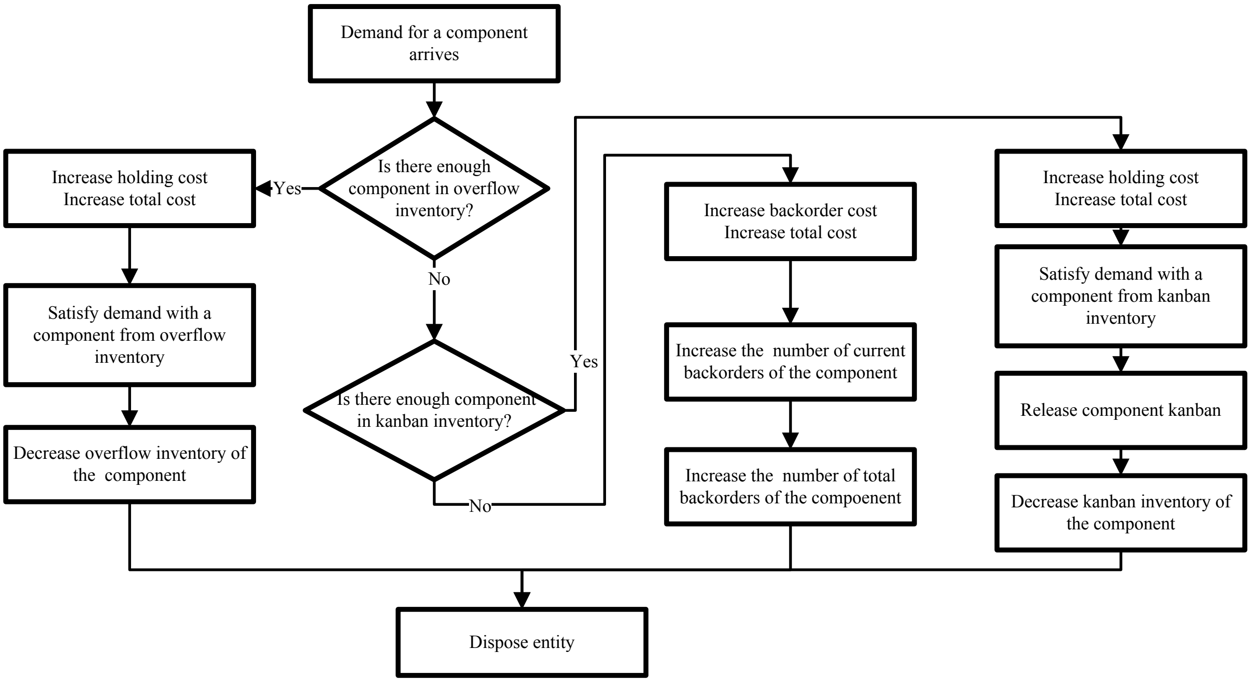


Figure 5 Operations performed upon the arrival of demand for a component.

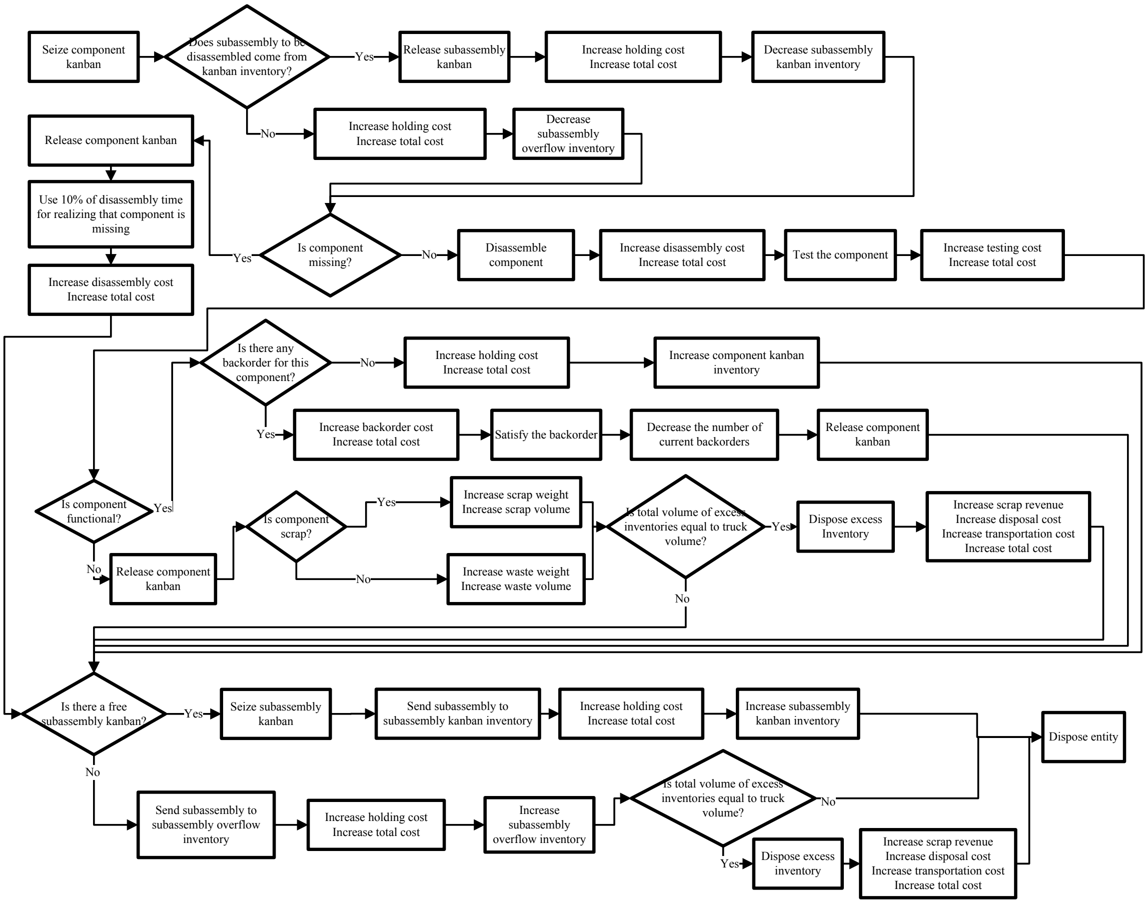


Figure 6 Disassembly operations authorized by a component kanban at stations other than the last station for the case of CPs.

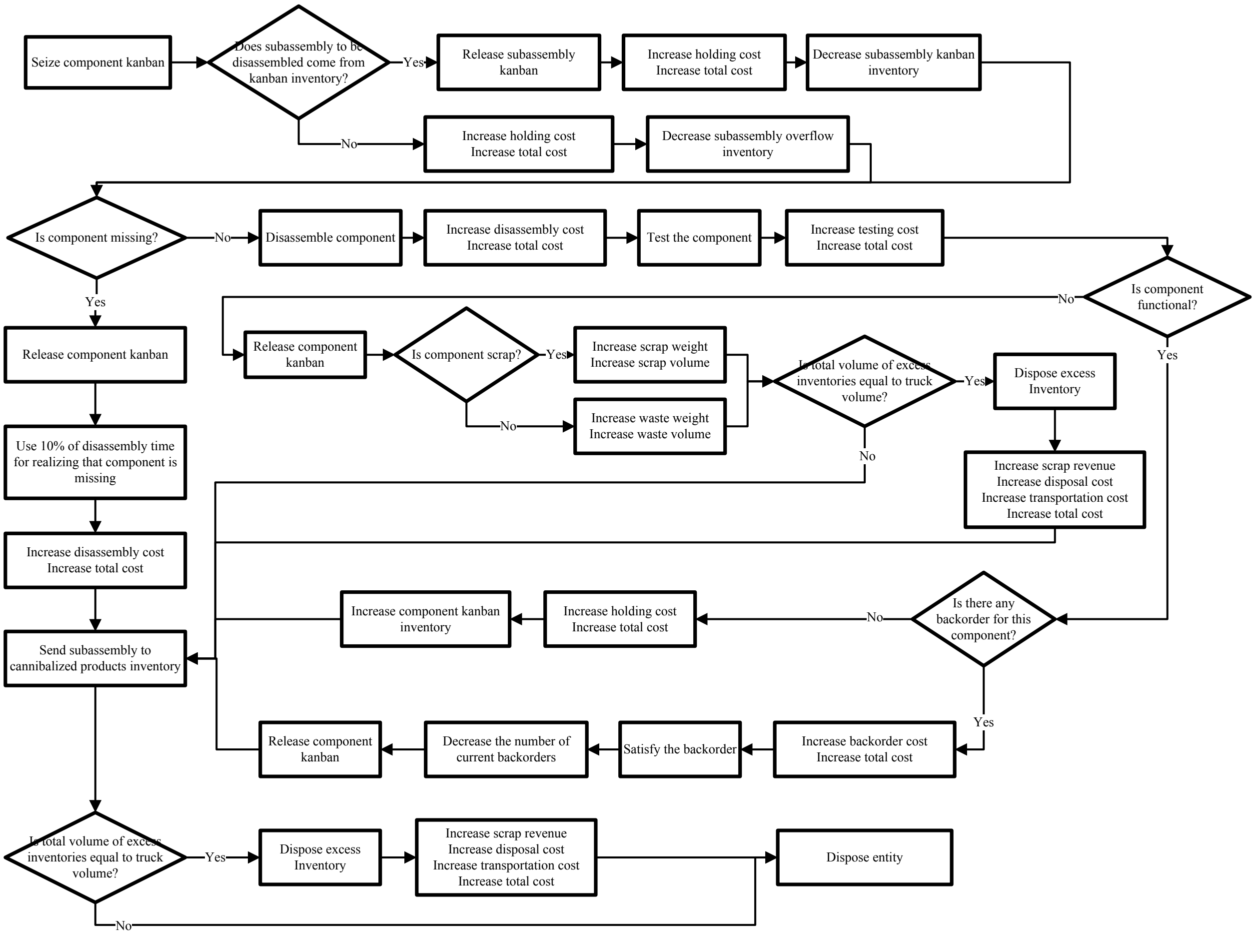


Figure 7 Disassembly operations authorized by a component kanban at the last station for the case of CPs.

In each DW, metal cover, door and other steel components (i.e., side and bottom steel plates) are sold as steel scrap. Metal cover, door, drum (if it is disposed due to excess inventory) and other steel components (i.e., side and bottom steel plates) are sold as steel scrap in each dryer. If the motor assembly of a dryer is disposed due to excess inventory, it is considered as a waste component. If timer, circuit board or motor assembly of a DW is disposed, it is considered as a waste component. In order to determine the total weight of small components such as screws, cables, total weight of the main components of a DW or a dryer is multiplied by a *small component weight factor*. These small components are considered as waste components.

It should be noted that there is no demand for metal cover and other steel components. That is why, there is no price determined for these components. Since holding cost is calculated based on the price of a component, holding cost for these components is not calculated. However, there is a demand and an associated price for drum. Consequently, the holding cost for drum is calculated based on its price.

Disposal cost of a waste component (D_c) is calculated using the following expression:

$$D_c = (W_c) * (dcp) \tag{2}$$

where W_c is the weight of the component in pounds and *dcp* is the disposal cost per pound. Disposal cost for subassemblies and products (D_s) are calculated as follows:

$$D_s = (W_s) * (dcp) * (dcif) \tag{3}$$

where W_s is the total weight of waste components in subassembly or product, *dcp* is the disposal cost per pound and *dcif* is the disposal cost increase factor. This factor is employed in order to consider the fact that disposal of subassemblies and products create higher nuisance than components since they may involve multiple and/or hazardous materials.

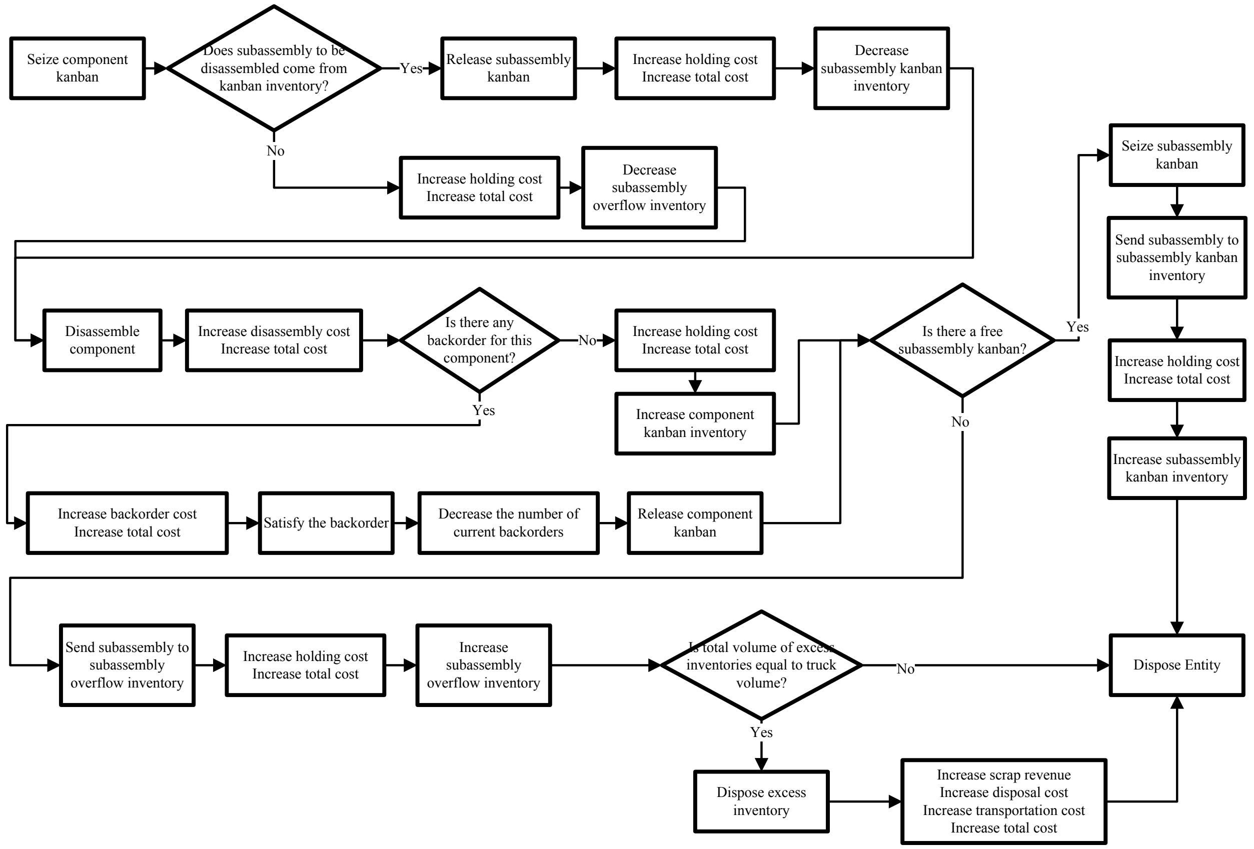


Figure 8 Disassembly operations authorized by a component kanban at stations other than the last station for the case of SEPs.

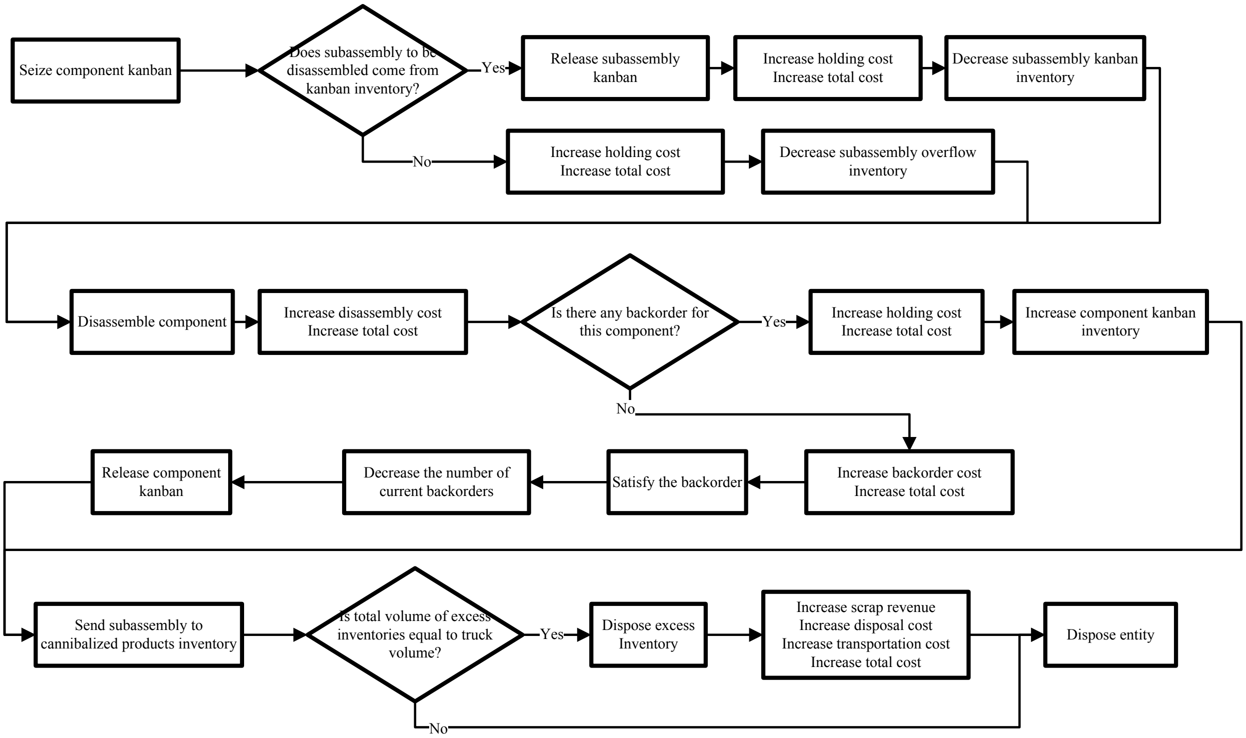


Figure 9 Disassembly operations authorized by a component kanban at the last station for the case of SEPs.

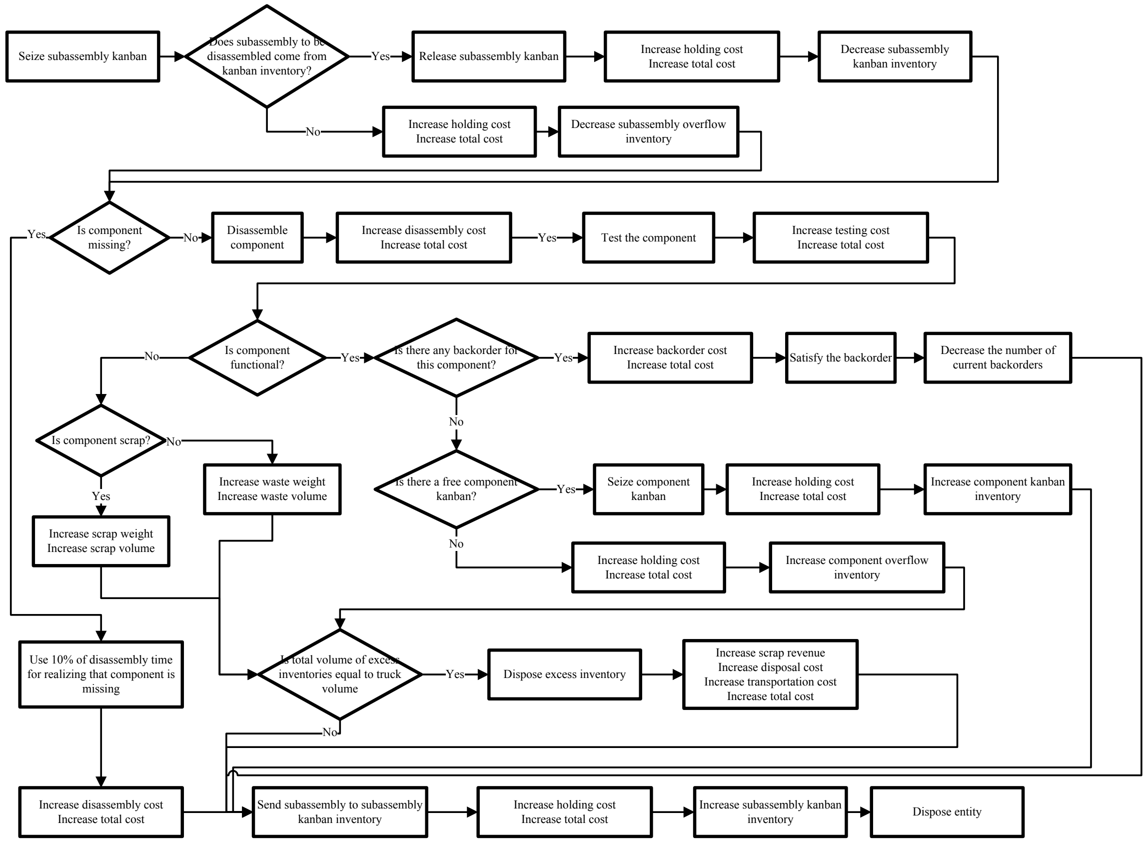


Figure 10 Disassembly operations authorized by a subassembly kanban for the case of CPs.

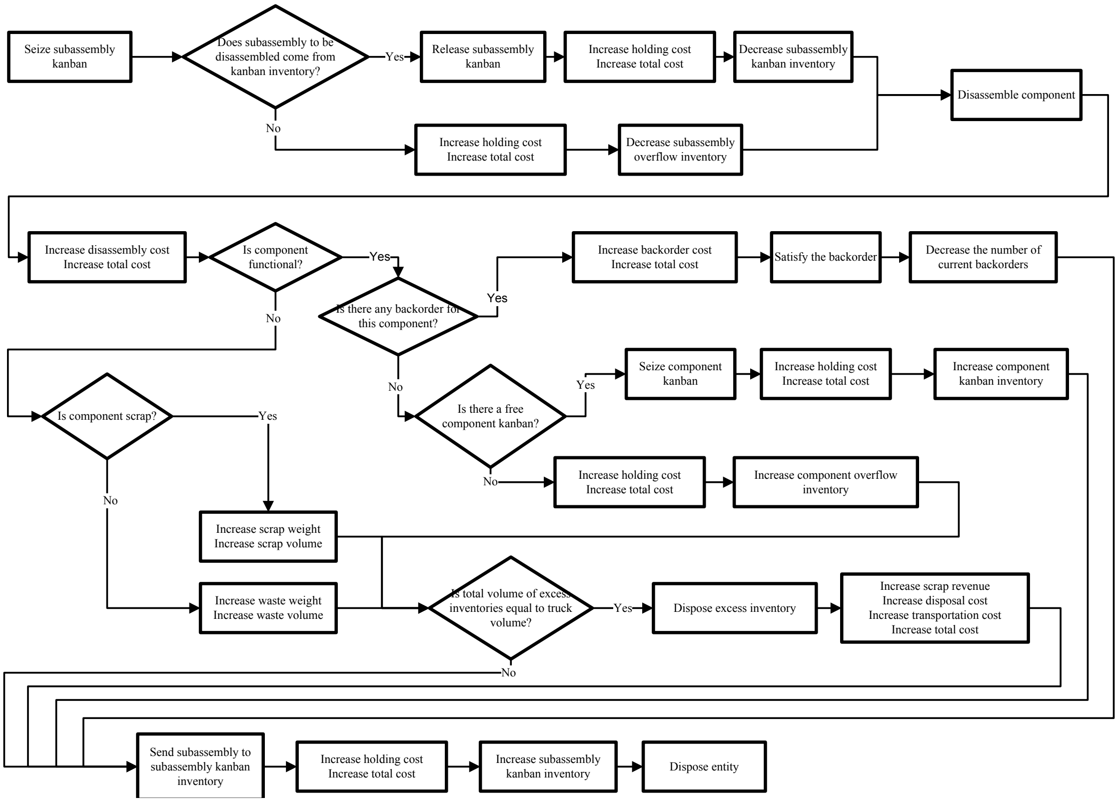


Figure 11 Disassembly operations authorized by a subassembly kanban for the case of SEPs.

Scrap revenue for a steel component (R_c) is calculated as follows:

$$R_c = \ (W_c) * (ssr) \tag{4}$$

where W_c is the weight of the component in pounds and *ssr* is the steel scrap revenue per pound. Scrap revenue for subassemblies and products (R_s) are calculated as follows:

$$R_s = \ (W_s) * \left(srp\right) * \left(srdf\right) \tag{5}$$

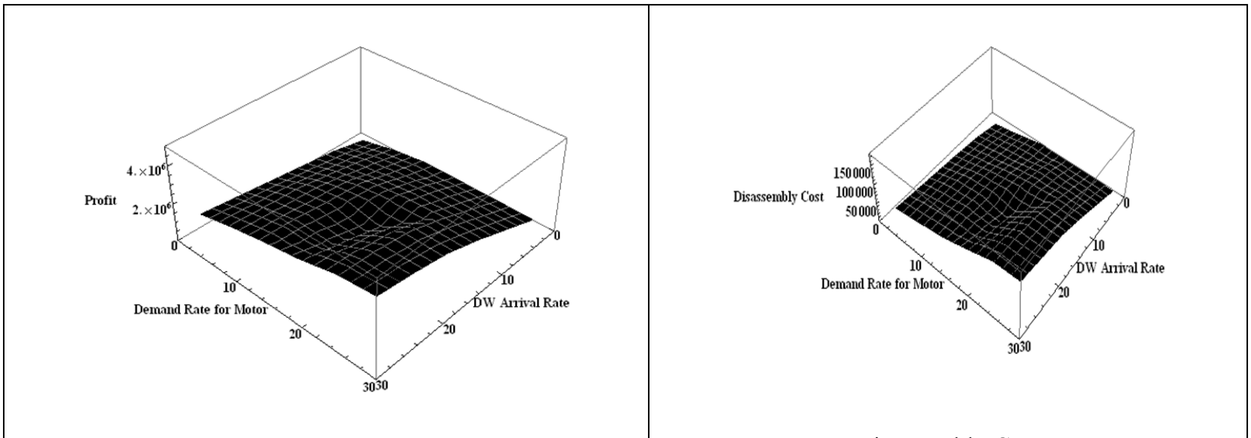
where W_s is the total weight of steel components in subassembly or product, *srp* is the steel scrap revenue per pound and *srdf* is the scrap revenue decrease factor. This factor is employed in order to consider the additional costs associated with further material separation operations that might have to be performed on products or subassemblies before disposal.

While estimating the testing cost for SEPs, the time required to retrieve information from the sensors prior to disassembly is assumed to be 20 seconds and 15 seconds for DWs and dryers, respectively. In the calculation of transportation cost, the operating cost associated with each trip of the truck is assumed to be $55. The collection fee for EOL DWs and EOL dryers is $10.

5. Results

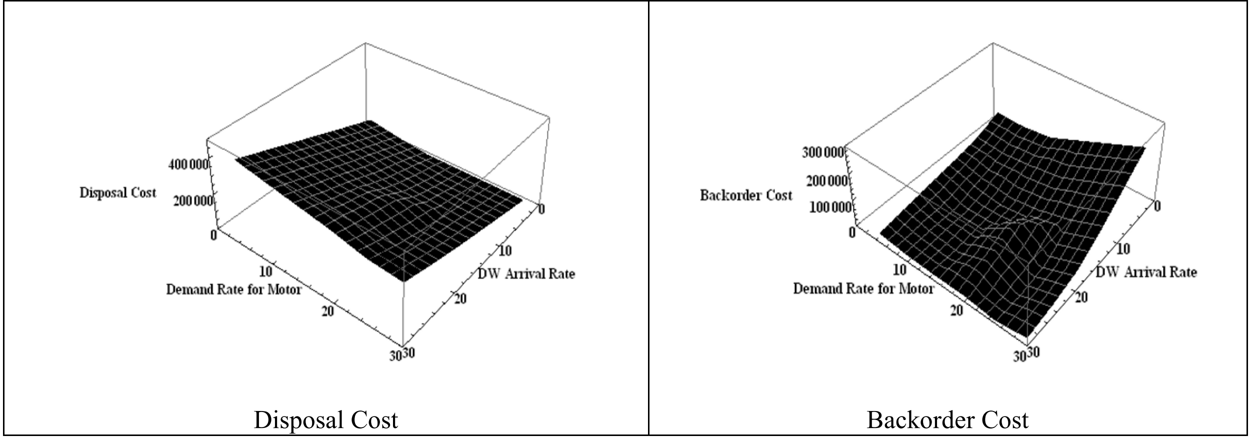
Three dimensional graphs given in Figures 12 and 13 present the values of four performance measures (viz., profit, disassembly cost, disposal cost, backorder cost) against the different levels of two factors (i.e., demand rate for motor and DW arrival rate) for SEPs and CPs, respectively. By visually comparing the graphs in Figures 12 and 13, we can easily see that SEPs result in higher profit values while having lower backorder, disposal and disassembly costs. However, there is a need for statistical comparison in order to have a quantitative assessment of the impact of SEPs on disassembly line performance measures.

That is why, design of experiments scheme presented in Section 4 was run for SEPs and CPs. Then, pair-wise t-tests were carried out for each performance measure. Table 3 presents the 95% confidence interval, t-value



Profit

Disassembly Cost



Disposal Cost

Backorder Cost

Figure 12 **Plots of changes in four performance measures against different levels of two factors for sensor embedded products**.

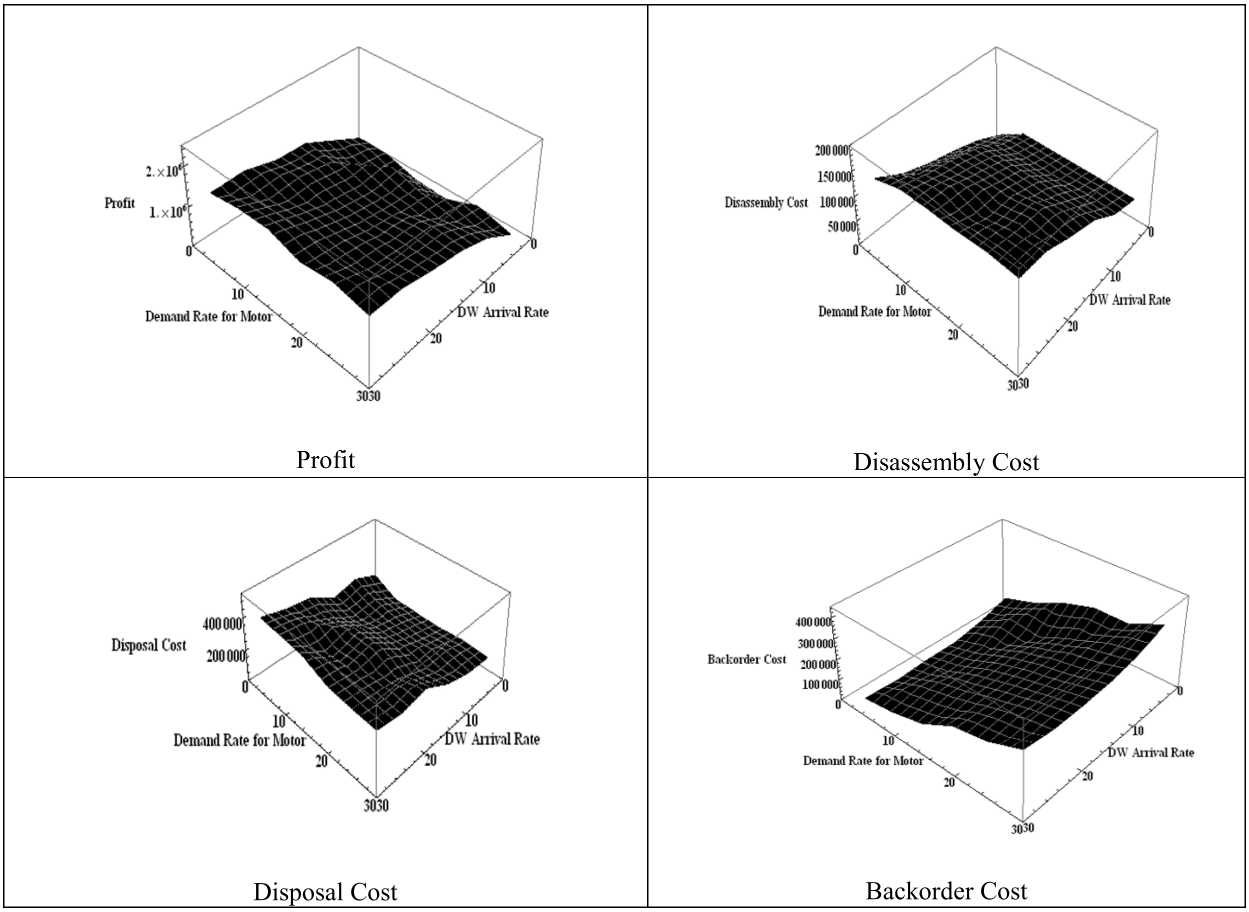


Figure 13 **Plots of changes in four performance measures against different levels of two factors for conventional products**.

and p-value for each test. According to this table, SEPs achieve statistically significant savings in holding, backorder, disassembly, disposal, testing and transportation costs. Moreover, there are statistically significant improvements in total revenue and profit for the case of SEPs.

In order to determine the average value provided by the sensors embedded in an EOL product, we first take the difference in profit values for SEPs and CPs for each experiment. By dividing this difference by the total number of EOL products collected, the value of sensors in an EOL product is determined for that experiment. Then, average value of sensors in an EOL product across all experiments is calculated by dividing the sum of individual experiment values by the total number of experiments. These calculation steps are presented in

Table 3 Pairwise t-test results for the comparison of SEPs against CPs.

Performance Measure	95% Confidence Interval on Mean Difference (Sensor -No Sensor)	t-value	p-value
Holding Cost	(-247.5, -180.7)	-12.76	0.000
Backorder Cost	(-94213, -71263)	-14.35	0.000
Disassembly Cost	(-45516, -35950)	-16.95	0.000
Disposal Cost	(-93485, -60931)	-9.44	0.000
Test Cost	(-118577, -108416)	-44.45	0.000
Transportation Cost	(-33331, -30669)	-47.85	0.000
Total Cost	(-370178, -322602)	-28.98	0.000
Total Revenue	(479013, 614665)	16.04	0.000
Profit	(810575, 975883)	21.51	0.000

Table 4 Use of experimental design study results to determine the average value of sensors

(1) Experiment	(2) Profit (SEPs)	(3) Profit (CPs)	(4) Difference in Profit ((2)-(3))	(5) Total Number of EOL Products Collected	(6) Value of Sensors in an EOL Product ((4)/(5))
1	892765.57	689984.74	202780.84	16161.60	12.55
2	1478995.73	1048313.37	430682.35	16173.60	26.63
3	1476935.85	1055570.37	421365.48	16185.60	26.03
4	2050911.70	1350521.63	700390.07	32327.60	21.67
5	3063884.18	2798715.87	265168.31	32339.60	8.20
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
80	1801372.32	1370260.27	431112.05	24271.20	17.76
81	1748333.24	1315398.01	432935.24	24247.20	17.86
Average	**2259563.26**	**1366333.99**	**893229.27**	**32320.83**	**28.64**

Table 4. According to Table 4, average value of sensors in an EOL product across all experiments is $28.64. This value can be useful in the determination of the cost associated with embedding sensors in products. In other words, as long as this cost is less than $28.64, embedding sensors in products is a profitable business decision. In this study, the value of sensors was determined by considering only EOL processing. It must be noted that if we had considered the additional benefits of sensors during the working lives of the products such as during maintenance, the value of sensors would have been further enhanced.

6. Conclusions

As a result of stricter environmental regulations, increasing public awareness toward environmental issues and economic reasons, remanufacturing has become a viable alternative to the traditional way of manufacturing products using new parts and/or components. In remanufacturing, used components and/or parts disassembled from EOL products as well as new parts/components are used during the manufacturing process. Due to missing and/or non-functional components, the number of parts that can be recovered from an EOL product is highly uncertain. In this study, we analyzed the use of sensors embedded in EOL products in determination of the condition of components prior to disassembly. First, separate design of experiments studies based on orthogonal arrays were carried out for CPs and SEPs. Then, pair-wise t-tests were conducted to compare the two cases based on different performance measures. According to the test results, SEPs not only decreased various costs (viz., disassembly, disposal, testing, backorder, transportation, holding) but also increased revenue and profit. The range of monetary resources that could be invested in SEPs was also determined based on the improvements achieved by SEPs on profit for different experiments.

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Authors' contributions
MAI reviewed the literature on the use of sensor-based technologies on after-sale product condition monitoring and developed the simulation models. He carried out the orthogonal arrays- based statistical experiments. SMG defined the research subject and directed the research from the start to the end. He provided important advices throughout the study and helped in editing the manuscript. KN provided information in the disassembly of dish washers and dryers and helped in writing and revising the manuscript and preparing the figures. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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