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Balancing Inventory Generated from a Disassembly Line: Mathematical Approach

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ABSTRACT

Product recovery is a new trend that many manufacturers practice to minimize the fast depletion of virgin resources and to realize economical benefits from recovering end-of-life (EOL) products. However, the practice of recovering components and materials is challenging as it often requires disassembly. There are many distinctive complications associated with the disassembly process. One of the complications stems from the disassembly line balancing problem (DLBP). DLBP has recently been actively researched in the literature and several heuristic models have been introduced to provide near optimal work contents at each workstation of the disassembly line. However, due to the disparity between demands for parts and their yields, there are many inventory problems that arise during the disassembly line balancing process. In this paper, we identify the issue of unbalanced inventories generated at various workstations of a disassembly line and discuss how to overcome this. A case example involving a personal computer (PC) is considered for discussion. In order to provide a full analysis of the problem, measures of performances are defined. Measures of performances reflect the state of the system and the ability to meet the demand while maintaining consistent flow of parts. We also discuss and compare various issues associated with the assembly systems and the disassembly systems. While it is clear that the inventory issues surrounding the disassembly line offer a new challenge, the understating that we have gained from solving the traditional inventory problems, nevertheless, provide helpful insights in overcoming this new challenge.

Keywords: Disassembly line, Inventory control, End of life products, returned products, Disassembly modeling.

1. INTRODUCTION

In recent years, consumers, large corporations, and government agencies have become more concerned with the environmental issues that are associated with the end-of-life (EOL) products. Many governments in Europe and Japan have already set rules and environmental legislation on how to properly manage the post-use stage of EOL products. However, United States still lags in this practice because such effort is mostly left to the free enterprise [5]. Even so, more and more attention is being given to recycling and recovery of end-of-life (EOL) products [4]. The trend is to allow the use of components and modules multiple times before they are discarded. End-of-life products can be recycled, remanufactured, reused or disposed of. Recycling is focused on the retrieval of the material contents and remanufacturing or reusing calls for the retrieval of components or subassemblies.

In today's fast moving market, many of consumer products are subjected to demanufacturing (disassembly) and remanufacturing [5]. Thus the establishment of disassembly and remanufacturing facilities are necessary to handle the overwhelming number of products retrieved every year. According to a forecast, almost 50 million computers are expected to be discarded every year in U.S. alone. So, for these facilities to be profitable, we have to develop models and techniques to help optimize their operations. Of course, recovery of value from an EOL product can only occur if the components can be easily extracted and subsequently sold at a profit [7]. In U.S. most original equipment manufacturers (OEMs) have no interest in collecting used products and recovering components, in the absence of mandatory take-back

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legislation. This dissuades them from taking ownership of the life-cycles of their products [6]. Some of the factors that encourage such behavior are: i) less vertical integration, ii) significant uncertainties, iii) lack of efficiency of the product recovery process, and iv) questionable profitability from product recovery [5].

Based on the aforementioned argument, an opportunity exists for smaller companies to enter the arena of product recovery by establishing stand alone facilities which, because of their smaller sizes, can operate on smaller scale, assume greater risks and have the flexibility to be "agile" to adapt to different products. However, there are many challenges associated with a disassembly line. Table 1 summarizes some of the differences between an assembly line and a disassembly line [2].

Table 1: Assembly Line vs. Disassembly line

Characteristics	Assembly Line	Disassembly Line
Process Flow	Convergent	Divergent
Condition of components	known	unknown
Inventory Challenges	Low-Moderate	High
Degree of Uncertainty	Low	High
Demand	Last Station	All stations

One of the most challenging issues faced by a disassembly facility is the management of its inventory [6]. The inventory problem stems from the disparity between the demand for disassembled components/materials and the actual line yields. Workstations tend to experience different accumulation rates as well as different depletion rates because of differences in their demands. Such differences create "uncertainties" in inventories and space requirements at the workstations. It is therefore necessary to develop a method to determine appropriate inventory levels, their upper and lower bounds, and ways to handle and maintain work-in-process (WIP) at suitable levels.

Most of inventory related issues addressed in the disassembly literature ignore the uncertain characteristics stemming from the probabilistic returns, the quality of returned items, varying recovery rates, changing demands and the logistical needs to support the disassembly facilities.

In this paper, we address the problem of balancing the inventories generated at each workstation of a disassembly line. This research addresses the balancing issue and suggests how to manage excess inventories and minimize their impact on the performance of the disassembly line and maximize its profitability. The objective is to find the right balances such that the demands are satisfied and the costs are minimized. An example consisting of a simple PC is considered to illustrate the approach.

2. BASIC TERMINOLOGY

The following is a list of some of the terminology used in this paper.

Demand — Demand (D) is the actual quantity of a particular component needed during a specific time period.

Forecast — Forecast (F) is a process of estimating future demand values of a particular component during a specific time period based on historical data.

Deviation — Deviation (DEV) is the actual disparity in quantity between demand and the line yield.

Workstation — A workstation (WS) is a segment of a disassembly line where a certain amount of work (a set of tasks) is performed. A WS can be a machine, a human worker, or combination of both. The work content of a WS (set of assigned tasks) is referred to as the workstation load. The time necessary to complete the workstation load is the workstation time [3].

Safety Stock Safety Stock (SS) is the quantity of inventory used to make up for any deviation between the actual demand and the line yield.

3. PROBLEM DEFENITION

Because of the differences in flow rates (in and out), disassembled components and materials could pile up at workstations. At some workstations, this may not interfere with the work at the workstation because of the components' size and/or quick turn over. At other workstations, the accumulation of inventory could block the workstation. The unexpected behavior of product returns and/or sudden changes in demand levels could lead to excess or shortage in inventory levels. The challenge is to manage the inventory of disassembled components so as to satisfy the demands and carry a minimal amount of components or materials on hand at all times.

The inventory problem discussed here is unique because it only focuses on the effect of inventory accumulation at workstations, which is different from the inventory that is stored at the warehouse facility. The goal is to keep optimum amounts of inventories at workstations.

Disassembly line inventory problem is defined as follows: A disassembly line is designed to disassemble one type of product that has *n* components. Disassembly task times, cycle time, precedence relationships and demands are known. However, there is uncertainty associated with the quantity and the quality of recovered components and/or subassemblies. The objective is to balance the inventory generated at each workstation by siphoning off the components/materials disassembled by providing a proper flow to demand sources, thus minimizing the disparity between the actual demand and line yield (deviation) and/or optimizing some measure of performance. Figure 1 shows an example of a disassembly line with components recovered at different rates.

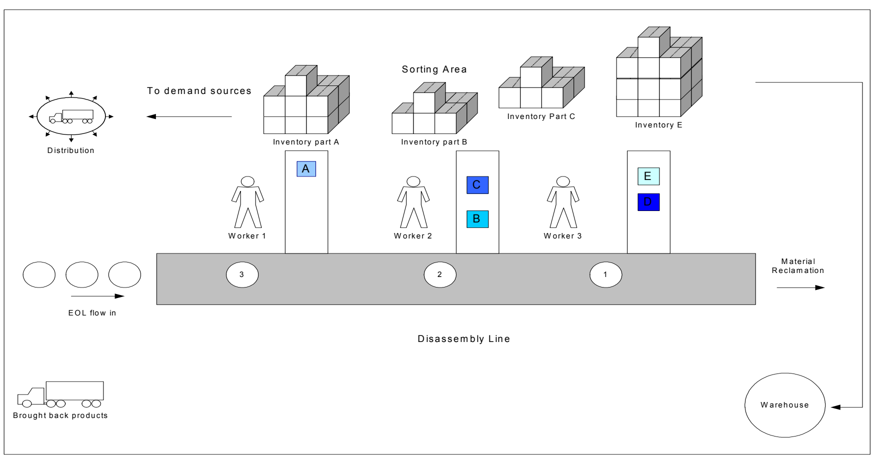

Figure 1. Disassembly line diagram with product recovery, WS=3, and *n=5*

4. DISASSEMBLY INVENTORY MODEL WITH RESTRICTION

In a disassembly line, workstations are where disassembly operations take place. Each product is routed through all the workstations for different disassembly operations. Each workstation is allowed a predefined cycle time before the product is sent to the downstream workstation. At a workstation, the disassembly operation is performed to extract component(s) from the product. Each disassembled component that passes the inspection is sent to the component inventory (storage bin), from where they are sent to the demand source. All damaged components are sent to the materials inventory (storage bin) to be recycled. The residual, that could also include hazardous materials, is disposed of. See figure 2 for a schematic diagram of the process.

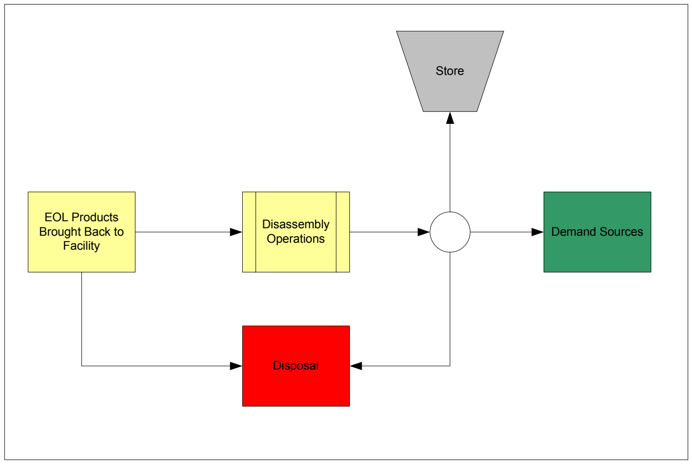

Figure 2. Process flow in disassembly facility

The characteristics of the product to be disassembled play a role in planning for inventory. For example, the size and shape of the component(s), and the amount of space available in the sorting areas of workstations on the disassembly line may influence the inventory policy. Here, we develop a simple model to balance the inventories at different workstations.

The available space at each workstation (storage bin) is a limited resource. The space is expressed in cubic units designated as, *W*, and each component disassembled on the line consumes a certain amount of space, *w* [1]. The recycled inventory is neglected at this stage. The space relationship can be written as follow:

$$\sum_{D=1}^{D} w_i \leq W \qquad i = 1, 2, \ldots n \tag{1}$$

where *D* (which is equal to the total number of products disassembled) is the demand per unit time, *n* is total number of components/subassemblies in a product, and *i* is the component type. Obviously, it is not profitable to disassemble the number of EOL products that is less than the break even point, and the disassembly of extra units could result in extra expense such as extra disassembly and carrying costs.

By assuming that each workstation has limited bin space that can carry a maximum of I^* components, where I_i^* is the maximum inventory of type *i* at the workstation, then

$$I_i^* w_i \leq W \tag{2}$$

which means that the maximum possible inventory of each component type *i* is as follows:

$$I_i^* \leq W / w_i \tag{3}$$

At any time during the disassembly operations, we can calculate the consumed space, the available space, and the accumulation rates of the different components. Based on that, the decision maker can balance the inventory at the workstations so that the work is not interrupted due to limited space, and demand source starvation does not occur. The objective is to balance the space consumption so that

$$Iw_1 \approx Iw_2 \approx Iw_3 \approx \ldots Iw_n \tag{4}$$

The model for the inventory balancing problem considered in this paper consists of two phases. The first phase is to balance the current inventory at the bin, and the second phase is to correct any shortages or excess inventory at the workstations. Details of the model are as follows.

Phase 1:

1) Assign the value w_i to all *n* components, expressed in cubic units, of the product disassembled. Each product has a total of *n* components/subassemblies.

2) Assign a value *W*, bin storage capacity expressed in cubic units, to all workstations. A total of *M* workstations exist on the disassembly line. For simplicity we assumed the values of *W* are equal at all workstations.

3) At time $t = 0$, set initial inventory bins of all components/subassemblies and recyclables equal to zero, i.e., INV_A=0, INV_B=0, INV_C=0….etc.

4) At equal time intervals (that is equal to the cycle time *C*), update the inventory of the bins by 1 unit, i.e., INV_A=INV_A+1, INV_B=INV_B+1, INV_C=INV_C+1…etc.

5) Perform a periodic review to examine the inventory levels at the storage bins, I_i, at constant time intervals equal to *nC* for all components/subassemblies.

6) Compare I_i, inventory levels at the storage bins, for $i = 1, 2, ..., n$, with current demand D_i for $i = 1, 2, ..., n$. If $I_i \leq D_i$, then no action is needed at this stage. Otherwise, if I_i is greater than D_i, then phase 2 of the model should be applied.

Phase 2:

1) Select the largest $I_i * w_i$ value and calculate the excess number of components on hand in order to match it to the second largest $I_i * w_i$ value. The values of excess inventory of each component type should be recorded.

2) We have four options to exercise depending on the inventory policy that is being used, after satisfying the required safety stock: i) sell all extra units to a third party remanufacturing facility at discounted prices, ii) send all excess units to recyclable inventory regardless of their conditions, iii) dispose of all components at a predefined disposal cost, and iv) carry it in inventory at a predetermined holding cost.

The objective is to find the right balance of quantity to be assigned to each option above so that profit is maximized, and space allocation is optimized at all workstations. The objective function can be formulated as follow

$$Max = \sum_{i=1}^{n} i_i r_i I_{DP} + R\sum_{i=1}^{n} \psi I_{REC} + C\sum_{i=1}^{n} I_{DIS} + \sum_{i=1}^{n} hI_{OHI} \qquad (5)$$

where i_i is the discounted percentage, r_i is the net revenue per component sold, ψ is the unit to volume mapping conversion, *h* is the holding cost per component, *C* is the cost of disposal per component, I_{DP} is the components sold at discounted price, I_{REC} is the components sent for recycling, I_{DIS} is the components to be sent to disposal, and I_{OHI} on hand inventory to be carried to the next cycle. The constraints are yet to be set to determine the optimal quantity for each option.

5. NUMERICAL EXAMPLE

In this example, we will study the disassembly operations of a hypothetical product module of a PC that contains three components: A, B, and C. Each component is disassembled at a separate workstation along the disassembly line. Thus the line has a total of 3 workstations to perform the disassembly operations, in addition to an entry workstation where initial inspection is performed.

The assumptions made are as follows:

1. Single-product model with static deterministic inventory
2. Constant demand rate D (units/unit time)
3. Infinite supply of EOL products at a constant rate
4. Units disassembled are added to inventory one at a time
5. Cycle time is constant and known for the disassembly operations.

Each workstation has a space limitation. That means each workstation has a storage bin that can carry inventory up to a certain point before blockage occurs. For simplicity, we assume equal storage bin capacity for all workstations.

Table 2: Space limitation, component size, and Max Inventory allowed

Size/WS	WS_1	WS_2	WS_3
W_i	100	100	100
w_i	0.1	0.5	0.25
I_i*	1000	200	400

Table 2 gives the relevant data, where W_i is the space available at each workstation, w_i is size of component *i*, and I_i^* is the maximum inventory allowed of each component type. The demand of each component is assumed to be deterministic and known. The five-day demand forecast is shown in table 3.

Table 3: Five-Day demand forecast for parts A, B, and C

Day/Demand	Part A Demand	Part B Demand	Part C Demand
Day 1	680	110	510
Day 2	850	155	460
Day 3	660	150	150
Day 4	900	400	375
Day 5	440	200	220

At the end of each working day, we can calculate the available inventory of each component type.

The idea is to minimize the space occupied at the workstations so that not only the demand is satisfied at each workstation, the utilization of resources are also similar at each workstation. The handling of excess inventory and the validation of the model used will be investigated in future research using the proposed formula presented here, equation number (5). A simulation model will need to be developed to investigate the inventory build up and the amount recycled. We plan to investigate the model based on both the current market prices and the remaining value of components. This example is assumed to be valid only for a stand alone disassembly facility rather than an existing manufacturing or remanufacturing facility.

6. RESULTS AND DISCUSSION

As the process of disassembly progresses, the inventory bins at workstations start to fill up with different components at different rates. The demands of these components vary from one day to the next, resulting in variations of on hand inventories of various components, and hence variations in utilization rates. For this example, we assumed constant demand rates during the five-day period, and we recorded the utilization rates of storage bins at the end of each of the five days. The on hand inventory of each part type at the end of each day is given in table 4.

Table 4: On hand inventory at hypothetical times (end of day)

Day	I_A	I_B	I_C
t=1	700	120	220
t=2	550	150	160
t=3	850	70	280
t=4	900	80	160
t=5	550	50	140

We can calculate the utilization rate of each bin using the following formula

$$U = I_i * w_i \text{, where } i = 1,2,3 \quad (6)$$

The utilization rates are given in table 5.

Table 5: Utilization rates of inventory bins

Day	$I*w_1$	$I*w_2$	$I*w_3$
t=1	70	60	55
t=2	55	75	40
t=3	85	35	70
t=4	90	40	40
t=5	55	25	35

At the end of each day, we calculated the deviation between the on hand inventory and the demand as shown in table 6. The positive numbers indicate that we have an excess inventory on hand, while negative numbers indicate shortages which result due to unsatisfied demands.

Table 6: Deviation between demand and on hand inventory

Day/DEV	DEV Part A	DEV Part B	DEV Part C
t=1	20	10	-290
t=2	-300	-5	-300
t=3	190	-80	130
t=4	0	-320	-215
t=5	110	-150	-80

Next, we evaluate each inventory bin's status individually and use the procedure proposed earlier to balance it.

Day 1: We only have excess inventories for parts A and B. Part C has a shortage of 290 units. In order to balance the inventory utilization of Part A to match the utilization of part B inventory, we perform a simple calculation to find out the minimum number of units required to match the utilization rates. The calculation is as follow

Minimum number of units required= $\frac{70-60}{0.10} = \frac{10}{0.10} = 100$ units of part A

However, we only have 20 units on hand. Thus, we will apply equation (5), after satisfying the safety stock requirement, to maximize the profit by finding the optimum distribution of extra units among the different options we have, sold at discounted prices, send it to recycled, disposed of at a cost, or carry it on hand with extra carrying cost.

Day 2: All components are experiencing shortages, and therefore there is no inventory to be balanced.

Day 3: We have a shortage of 80 units for part B, and excess inventories for parts A and C. In order to match the utilization of A and B's inventories, we calculate the optimum number of units to distribute among the different options discussed previously while describing the second phase of the model.

The optimum number of units can be calculated as follow:

Minimum number of units required= $\frac{85-70}{0.10} = \frac{15}{0.10} = 150$ units of part A

Since there are a total of 190 units on hand, we keep 40 units of A on hand and exercise one of the four options to process the extra 150 units.

Day 4: We have no inventory for part A, and shortages for parts B and C. Therefore, no action is required.

Day 5: We have excess inventory for part A only. We will match the utilization rates of part A and C inventories.

Minimum number of units required= $\frac{55-35}{0.10} = \frac{20}{0.10} = 200$ units of part A

Since there are only 110 units on hand, we exercise one of the four options to process these 110 units as described in the second phase in the model.

The model suggested above seems to be reasonable. However, other techniques may be possible in such situations. For example, it may be possible to handle the excess inventory based on the value remaining and by the value of its contents rather than by the quantity available or marker price.

7. OTHER APPROACHES

It may be profitable for the disassembly facilities to hold on to the relatively newer components by paying the holding costs if their perceived marginal profits are higher than what one would realize from one of the four options described in the second phase of the model. The effect of wear and tear should be examined and included in the decision making process to determine quality of the components.

As proposed by Gunter [5], other possibilities include the use of cut-off values and end-of-use values (the satisfaction remaining) in decision making process.

The minimum functional value (the minimum cut-off value) represents the value of the materials in the component. Thus, if the functional value is any lower, it is more economical to recycle the materials of the component rather than hold it in inventory or sell it to a remanufacturing facilities [5]. In other words, the minimum latent value (summation of individual component functional values) must be greater than the summation of the minimum allowable functional value of each part. Mathematically, it can be expressed as follows:

$$V_L \geq \sum_{i=1}^{n} Cut-off_i^{\min} \tag{7}$$

The end-of use value can be used to determine the cut-off values. As a product is used, its value is consumed. The wear and tear of components causes the total value of the product to decrease rapidly, and catastrophic part failure leads to precipitous drop in the product's value [5]. The value remaining in a product can be related to the satisfaction remaining as follows:

$$V(t) = \int_{t}^{t_F} s(\tau)d\tau \tag{8}$$

where t is the current time and t_F is the time of product failure.

8. CONCLUSIONS

In this paper, we discussed the problem of balancing the inventory generated at various workstations of a so-called "balanced" disassembly line. Because of the disparity between the demand and the line yield, complications may arise during the disassembly operations causing the accumulation of parts at different rates [2]. So far, this issue has not been raised in the literature. We proposed a simple heuristic model to find out the right "balance" such that the space utilizations of the inventory bins are similar. Any excess units could be sold at discounted prices, sent for recycling, disposed of, or in some cases, held on in inventory. While, at this time, it is not clear how to overcome all the problems at once, the knowledge of traditional inventory systems should provide helpful hints on how to address or avoid many of them. Future research will investigate other aspects of the line and their effects on the inventory balancing.

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