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Controlling Disassembly Line with Multi-Kanban System

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ABSTRACT

A way to implement the pull system in a disassembly line is to use a multi-kanban model. The model employs several types of kanbans attached to both components and subassemblies. The heart of the system lies in the kanban routing mechanism which allows routing of kanbans in multi-directions based on real time conditions. This mechanism creates minimum amount of residual inventory while satisfying varying demand levels. It also helps regulate the requests for subassembly from upstream workstations when a breakdown occurs at a workstation. This reduces blockage and starvation of subassemblies at workstations other than the broken workstation. In this paper, we discuss the difficulties involved in utilizing the multi-kanban mechanism. We thoroughly investigate several scenarios of the disassembly line setting including a scenario with common products, a scenario with component discriminating demand, a scenario in the presence of products with multiple precedence relationships, and a scenario with workstation breakdowns. These scenarios represent various disassembly environments that a facility may face when dealing with the disassembly of both single and multiple products on a single line. In each scenario, we examine effectiveness of the multi-kanban model using three performance measures, viz., the inventory level, the level of satisfied demand, and the customer waiting time. We compare these results with the ones generated from the same line that employs a traditional push system. Using simulation, we demonstrate that the overall performance of the disassembly line using multi-kanban mechanism outperforms the disassembly line with the traditional push system.

Keywords: JIT, Kanban, Disassembly.

1. INTRODUCTION

The manufacturing of products has become economical and efficient due to improvements in manufacturing technology. This makes higher quality products more affordable. With the result, many products reach their end-of-lives (EOLs) prematurely. Consumers often dispose of their fully functional products in favor of newer models. This is especially true for electronic products. Often, the disposed items end up in a landfill where they cause environmental destruction. On the other hand, many of these products may contain reusable materials and components. In addition, consumers have become more and more aware of the problem. Governments are also taking initiative by passing and enacting legislations. The manufacturers have also jumped on the bandwagon by practicing environmentally conscious manufacturing and design, which they hope will give them a competitive advantage in the market.

Nowadays, many products and components are manufactured from recycled components and materials and these components and materials are usually less expensive and more environmentally friendly. This way, products are faster and cheaper to produce and the quality is usually at par with the products that are produced from virgin resources. The increase in the use of recycled materials and reused components is achieved by escalating the product and materials recovery rates. An important way to do this is via selective disassembly. Selective disassembly helps reduce the cost and time of removing unwanted components and materials from EOL products. Disassembly line is the best way to disassemble products in large quantity. A disassembly line consists of a series of workstations similar to an assembly line. Despite this similarity, there are many characteristics that are unique to the disassembly environment such as

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multiple arrivals of demands, multiple arrivals of EOL products, and fluctuations in inventory levels. These characteristics make a disassembly line more complicated and difficult to control. An appropriate choice of the control mechanism could help increase the efficiency of a disassembly line. One can also achieve this by making the line flexible disassembling multiple EOL products. In an assembly line setting, there are two types of production control systems, viz., push system and pull system. A push system is easy to implement but is not efficient in the disassembly environment, as it tends to generate large amounts of inventory. A pull system produces much less inventory but it is not practical for the disassembly line setting in its current form.

In this paper, we propose a multi-kanban mechanism for the various environments in which a disassembly line operates. The mechanism is designed in a way that the implementation of kanbans helps reduce the inventory build up in the system that is common in a disassembly line with the push system. In addition, the mechanism maintains its ability to service demands at levels that are comparable to the push system. Finally, we show that the mechanism is able to provide excellent results for a smooth operation of the disassembly line in a variety of scenarios, such as a scenarios with common products, component discriminating demand, the presence of products with multiple precedence relationships, and workstation breakdowns. We provide numerical examples to illustrate the methodology and obtain results using simulation. We compare the performance of the pull system with that of the push system.

2. LITERATURE REVIEW

Several studies have recently surfaced that address various aspects of production control mechanism in a disassembly environment. A recent book by Lambert and Gupta [15] is helpful in understanding the general area of disassembly. Korugan and Gupta [12] suggest an adaptive way of implementing kanbans to a single-stage hybrid system. A hybrid system refers to a combination of two distinct lines, viz., a production line and a disassembly line. In a typical assembly environment, Hopp and Spearman [10] give a basic description of kanban control mechanism and its operations in one-card and two-cards environments. Gupta and Al-Turki [5], [6], [7] and Gupta *et al.* [8] propose the concept of the flexible kanban system (FKS) in various environments involving uncertainties. They demonstrated that in such environments, FKS outperforms traditional kanban system (TKS). Other studies are in the area of reverse logistics, environmentally conscious manufacturing, and product recovery. Gungor and Gupta [4] provide a comprehensive survey of issues in environmentally conscious manufacturing, and product recovery. Tibben-Lembke and Rogers [18] discuss the differences between reverse and forward logistics in a retail environment. Within in the area of product recovery, many researches address disassembly and its significant domains such as disassembly sequencing [14], disassembly line [3], [17], disassembly line balancing [2], [3] and disassembly line scheduling [16]. For more information on disassembly and product recovery, see Brennan *et al.* [1], and Gupta and McLean [9]. Lambert [13] suggests the optimal disassembly sequence in electronics disassembly. Udomsawat and Gupta [19] propose an application of pull control mechanism to disassemble appliances.

3. DISSASSEMBLY LINE

A disassembly line consists of a series of workstations working in a sequence to disassemble the end-of-life (EOL) products into subassemblies and/or components. The line is usually faced with numerous problems, the most important of which is the disorderly fluctuation of inventory levels. The fluctuation is a result of two unique characteristics of a disassembly line, viz.. multi-level arrivals of EOL products and multi-level arrivals of demands. EOL product may enter the disassembly line at any of the workstations based on its type. Similarly, depending on what is demanded, the demand could occur at any workstation. These also explain the disruptive fluctuations in the inventory levels in a disassembly line. In this section, we discuss the characteristics and control of a disassembly line.

3.1 Characteristics of Disassembly Line

Mixed Combination and Arrival Pattern of EOL Products. In a disassembly line, an arriving product may consist of different combinations of components from a given set of components. Generally, from a set of N components, the total number of possible combinations of components, $Q_{(N)}$ is given by

$$Q_{(N)} = 2^N - N - 1 \quad (1)$$

For example, a set of 4 components (A, B, C, D) can produce up to 11 possible product combinations (viz., AB, ABC, ABCD, ABD, AC, ACD, AD, BC, BCD, BD, CD). By adding one more component to the set, the number of possible combinations increases to 26. It is therefore clear that the number of combinations increases exponentially with the increase in the number of components. Fortunately, not all combinations exist in reality. Some products, such as PCs, have components that are modularly structured and usually come in various combinations. Household appliances commonly have fewer combinations. This is because they are rarely modified by consumers. Nevertheless, the workstation where a product enters the disassembly line still depends on the type and combination of the components in the product. Thus for example, consider a disassembly line with three workstations. If component A is disassembled at workstation 1, component B is disassembled at workstation 2 and components C and D are disassembled at workstation 3, then a product arriving at the disassembly line consisting of components B, C, and D does not have to go to workstation 1 at all. It could enter the disassembly line directly at workstation 2. Considering the same example, if an arriving product consists of components A, C, and D, it would have to enter workstation 1. However, after getting processed at station 1, it could skip workstation 2 entirely. Furthermore, products with different precedence relationships must be processed through workstations with different sequences. These three situations destabilize the disassembly line by causing an overflow of materials at one workstation while starving some other workstation leading to undesirable fluctuations of inventory in the system. It is therefore crucial to balance the line and manage the materials flow of the line.

Demand Fluctuation and Inventory Management. Among many unique characteristics of a disassembly line, the multilevel arrival of demand is the major reason that makes the disassembly line much more complicated than a typical assembly line. Demand can occur at any workstation of the disassembly line. In most assembly lines, demands arrive only at the last workstation. In an assembly line, even if arrivals of demand were to occur at any workstation, it would have minimal effect on the operation of the line because the product is simply taken off the line to fulfill the demand and does not go forward from there on. On the other hand, a disassembly line generates a significant amount of inventory of components that are in low demand due to the disparity between the number of various components demanded and the number of partially disassembled products. This creates chaos in the system. It, therefore, is necessary to develop a good methodology to control the system and find a way to manage the extra inventory produced as we want to maintain service level of the system. Although, conventional mechanisms such as push system, kanban, base stock and CONWIP have been successfully used in an assembly line setting, they have not been perfected in a disassembly line setting. These mechanisms are not suited for the disassembly environment in their current forms. This, therefore, leads to the need for developing better production control systems for a disassembly line.

3.2 Controlling Disassembly Line

Two types of control mechanisms, viz., *push* and *pull mechanisms* are commonly used in an assembly line setting. Several studies have tried to compare both systems in terms of system efficiency, customer service level, and ease of implementing. The push mechanism relies on a predetermined production schedule based on the expected demand of finished products. Raw materials are pushed through the system in order to meet the future demand. On the other hand, the actual demand triggers the production and causes a flow of materials throughout the pull system. Conclusions from those studies are mixed. In reality, none of the mechanisms dominates in all situations. The push system tends to build up inventory. Therefore, it provides higher levels of customer service in certain production scenarios. Also, it has advantages in terms of experience in implementing it. Pull mechanism, on the other hand, is difficult to implement and relies heavily on consistency of raw materials supplies and agility of the server. Nevertheless, it has an advantage that it does not generate large amounts of inventory. In fact, it controls the inventory very efficiently because it only produces when and where there are needs. This is the key reason that a pull mechanism is more likely to perform better than push mechanism in a disassembly line. One of the most commonly used pull mechanism tools is Kanban. Despite its simplicity and effectiveness in controlling inventory, once implemented in a disassembly line setting, it is burdened by numerous uncertainties. In order to improve its performance, a modification of the mechanism becomes necessary. In the next section, we will discuss many scenarios in the disassembly line environment. We then introduce a multi-kanban mechanism that is designed for implementation in these scenarios.

4. TYPICAL SCENARIOS IN DISSASSEMBLY LINE ENVIRONMENT

There are situations in the pull-type disassembly environment where the characteristics of product arrivals and departure greatly affect the production efficiency. These situations must be taken into consideration when designing a control mechanism for the disassembly line. Here we consider four most common scenarios for discussion, viz., disassembly line with single product type, disassembly line with component discriminating demand, disassembly line with products having multiple precedence relationships, and disassembly line with workstation breakdowns. In this section, we discuss the difficulties encountered by each scenario in the application of the control mechanism.

4.1 Common Disassembly Line

The most common setup of pull-type disassembly line deals with disassembly of single EOL product and utilizes two or more disassembly workstations. Each workstation disassembles one component at a time, though disassembly of multiple units of the same type of component is not uncommon. Moreover, EOL products sometimes arrive at the line with missing components. Thus, in this type of disassembly line, there are multiple component structures. The scenario also includes a setup disassembly of a family of products that each of them comprise of identical components and has the same precedence relationship. In both cases, demands for these components can arrive at any workstation. These demands do not discriminate against component condition or any other detail factors. That means there is only one type of demand arriving at each workstation. An example of this type of disassembly line is a personal computer (PC) disassembly line. A PC regardless of brand, model, or production year, comprises of similar reusable components such as hard drives, memory, power supply, media drive, and etc. They also have almost identical precedence relationships and often require the same disassemble procedures and tools. Even though many PC disassembly facilities usually employ push-type system, a pull type system can significantly improve efficiency of the line. Pull system achieves this goal by help reducing inventory level and number of disassemblies of unwanted components. Figure 1 shows an example of this type of disassembly line.

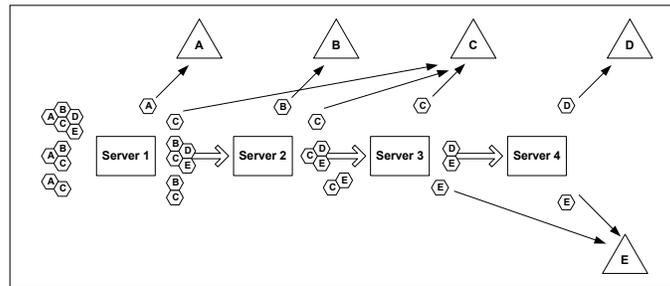


Figure 1. Disassembly Line with Single Product, Multiple Component Structures and Non-Discriminating demand

4.2 Disassembly Line with Component Discriminating Demand

In certain situation, end-of-life products come in different makes, models, and conditions. It requires different end-of-life products to be disassembled in order to retrieve different types of components at different workstations of the disassembly process. Thus, at any workstation of the disassembly line, there are multiple types of demands for multiple types of components resulting from the disassembly process at that workstation. An example of this type of disassembly line is an over-the-counter type facility of automobile dismantling business. In this scenario, common components of a vehicle usually disassemble at the same time regardless of other characteristic such as production year, make and model of the vehicle. However, demand for these components usually discriminate such characteristics. Thus, in each workstation, there are arrivals of demands for different components that can be disassembled from the same or different vehicles. This further complicates the situation by creating selection constraints for vehicles to be disassembled. Many facilities deal with these variations in demand by choosing to serve only certain types of demands or just increase storage space to deal with extra inventory. Most facilities choose to supply component regardless of years, makes and models. For example, alternator can be sold to alternator remanufactured company regardless of years, makes and models. Many body panels are also sold in bulk to insurance company regardless of years, makes and models. Figure 2 shows a workstation with component discriminating demand. The multi-kanban mechanism can be adapted to operate in this situation by splitting component kanban into sublevel component kanbans where they represent individual components. These sublevel component kanbans are located at the same workstation where the components are disassembled.

Distinguishing component kanban into sublevel component kanbans will also assist in product selection because each sublevel component kanban contain specific request that indicates which product will be needed for disassembly.

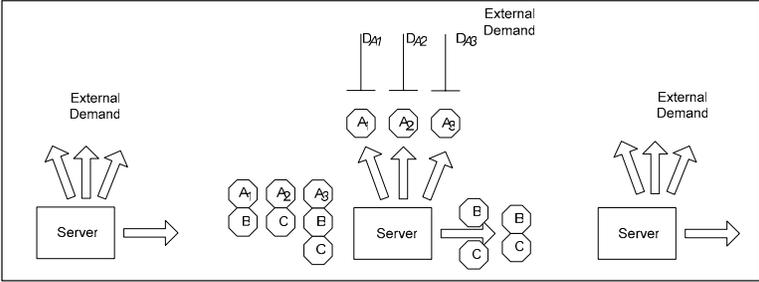


Figure 2. Disassembly Line with Component Discriminating Demand

4.3 Disassembly Line with Presence of Product with Multiple Precedence Relationships

This special case of disassembly line occurs when EOL products contain similar components yet different precedence relationships. Thus, in order to remove target components from the EOL products, each EOL product must be routed according to its own disassembly sequence. To facilitate the control of this type of disassembly line using pull system, we categorize EOL products into two types. The first common type is the product that its precedence relationship of components follows the sequencing of disassembly process. This type of product is disassembled and travels in downstream direction only. The second type of product is more complicated because its precedence relationship of components does not follow the sequencing of disassembly process. Hence, it can travel in both upstream and downstream direction depending on which component is to be disassembled next. An example of this type of disassembly line is an appliance disassembly line. Because household appliances share similar materials and reusable components, they can be disassembled together in the same disassembly system. These appliances also require similar disassembly process and disassembly tools. A disassembly facility can benefit from disassembling multiple types of appliances in two ways. One is the reduction of uncertainty of supply fluctuation. The facility can have constant feed of end-of-life products. Another benefit is the variety of components and material retrieved from the end-of-life appliances. An example of a group of appliances that share similar components and require similar disassembly processes are refrigerator, washer, dryer, and conventional and microwave oven. These appliances contain reusable components such as electric motors, control circuit, thermostatic switches, and etc. They also contain many recyclable materials such as steel and aluminum frame and body components, aluminum radiator, and copper piping. Figure 3 shows an example of appliance disassembly line [19].

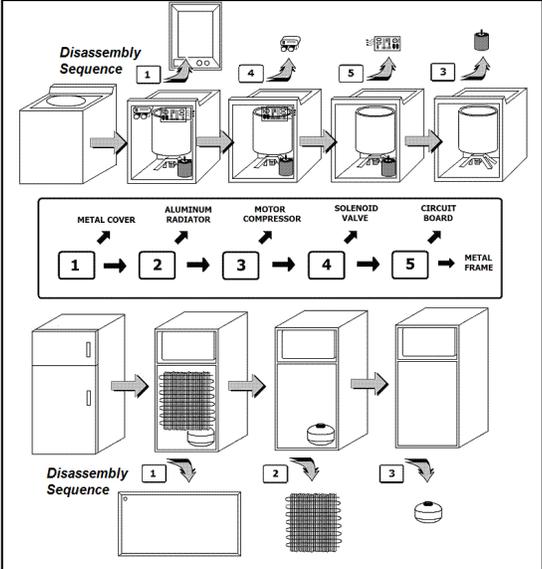


Figure 3. Disassembly Line with Presence of Product with Multiple Precedence Relationships

4.4 Disassembly Line with Workstation Breakdowns

Another important scenario is when breakdowns occur in a disassembly environment. Disassembly line that implements push system compensates blocking and starving by carrying large amount of inventory. This works very well with components that have low storage cost, low disassembly cost, long shelf life and stable demand. However, for many EOL products, dealing with breakdowns by carrying large amount of inventory is not always the best option. Thus, pull system offers tremendous benefits by means of selective disassembly. By disassembling components at right amount, right time and right place, the pull system reduces piling up of unwanted components. Two common types of breakdowns are studied in this paper, viz. sudden breakdown and scheduled breakdown.

5. MULTI-KANBAN MODEL FOR DISASSEMBLY LINE

In this section, we describe the multi-Kanban mechanism. The mechanism proposed here employs many different types of Kanbans that correspond to various components and subassemblies in the system. The Kanbans are used mainly to control the inventory level of the system by initiating and terminating the disassembly process at workstations. Modeling a disassembly line using pull type system offers three major advantages over push type system. First, pull system carries minimal inventory because it only allows disassembly to be initiated when there is an actual demand for components. As a result, the facility does not have to carry large amount of inventories and can save on inventory carrying cost and disassembly cost of unwanted components. Second, the pull system using multi-kanban can help in keeping track of inventory, which is very useful in giving out a quote to a customer. Last, the multi-kanban mechanism proposed here relies on routing rules that direct kanbans to workstations that result in residuals that are needed most. This way, customer satisfaction will be retained while the kanban routing takes care of fluctuations in demands of various components.

5.1 Base Model for a Common Disassembly Line

5.1.1 Material Types

There are two basic types of materials in the system, viz., *components* and *subassemblies*. A component is a single item that cannot be further disassembled. It is placed in the component buffer waiting to be retrieved via a customer demand. On the other hand, a subassembly is something that can still be disassembled. Subassembly is composed of at least two components. Both types of materials can be further distinguished as regular or overflow items. Regular items are what customers or downstream workstations demand. In order to fulfill the demand, a server must disassemble the demanded component or subassembly. The residual item from this disassembly process that does not fulfill any request is called overflow item. Because the disassembly process is initiated by a single kanban, the overflow item will not have a kanban attached to it. However, the overflow item is routed in the same way as the regular item. The only difference between them is that the overflow item is given priority of being retrieved after it arrives at its buffer. It should be noted that, as long as there is an overflow item in the buffer, its demand would not initiate any further disassembly process. This will help the system eliminate any extra inventory first that is caused due to unbalanced demands.

5.1.2 Kanban Types

Corresponding to material types, there are two basic types of kanbans in the system, viz., *component kanbans* and *subassembly kanbans*. A component kanban is attached to a disassembled component that is placed in the component buffer of the workstation where it is disassembled. Similarly, a disassembly kanban is attached to a residual subassembly that is placed in the subassembly buffer of the workstation where it was separated from the component. A component placed in a component buffer can be retrieved by an external demand. When authorized, a subassembly placed in the subassembly buffer is routed for disassembly to the next workstation based on its disassembly sequence.

At the first workstation, EOL products arrive only from outside sources. However, at any other workstation i , where $1 < i \leq N-1$, there are two possible types of arrivals. The first type is a subassembly that arrives from an upstream workstation, called internal subassembly. There is always a subassembly kanban attached to an internal subassembly. The second type is a product (or subassembly) that arrives from outside sources, called external subassembly. There is no kanban attached to an external subassembly. This is also true of the products arriving from external sources to the first workstation. As long as there is an external product or subassembly available at an input buffer, the system will process it first before processing any available internal subassembly. This will avoid unnecessary pulling of an internal subassembly from an upstream workstation. Thus, the number of kanbans attached to internal subassemblies will remain constant throughout the process. Figure 4 illustrates the kanbans and materials flow in a typical disassembly line.

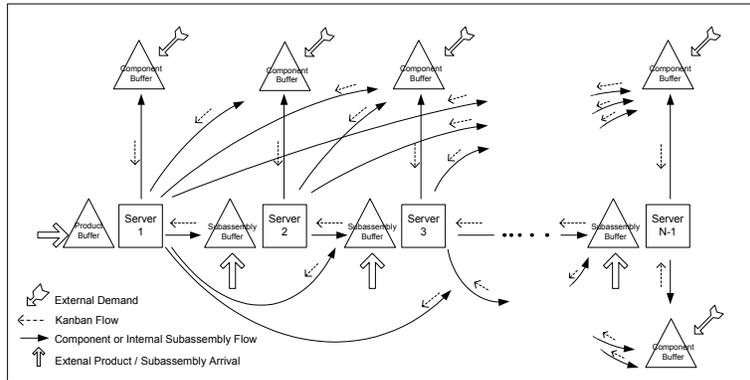


Figure 4. Kanbans and Materials Flows in a Disassembly Line

5.1.3 Kanban Routing Mechanisms

Consider workstation j , where $1 \leq j \leq N-1$. When a demand for component j arrives at the component buffer of workstation j , one unit of component j is retrieved and the component kanban j attached to it is routed to the most desirable workstation. The procedure for determining the most desirable workstation to route component kanban j is given below. (Note that this procedure is not applicable to component kanbans $N-1$ and N . In both cases the kanbans are routed to the input buffer of the last workstation).

A component kanban originating from workstation j will be routed to a workstation i , where $1 \leq i < j$, or workstation j depending on the availability and the desirability of the subassembly that contains component j . Routing component kanban j to workstation i , where $1 \leq i \leq (j-1)$, will result in an immediate separation of component j from component i . Thus, the only subassembly located at the input buffer of workstation i that would be useful is a subassembly that contains only components i and j . If this type of subassembly exists in the input buffer of workstation i , then workstation i is qualified. Similarly, if there is at least one subassembly in the input buffer of workstation j , then workstation j is qualified.

Next, we need to select the most desirable workstation to route component kanban j to, among the qualified ones, such that, if chosen, will cause the least amount of extra inventory in the system. Choosing workstation i will increase the inventory level of component i by an additional unit. Thus, the best workstation i is the one that is most starving for its component. By checking the backorder level for demand i , we could determine the most starving workstation. If there is a tie, select the most downstream workstation. Choosing workstation j will create a residual subassembly that will be further disassembled at downstream workstations. If workstation j is chosen, then a proper subassembly must be chosen to disassemble. For example, if a backorder exists at the component buffer of workstation k , where $j < k \leq (N-1)$, then, if available, we might try to disassemble a subassembly that contains only components i and k . If more than one workstation qualify as starving workstations, then the one that is most starving among them is chosen. If there is a tie, then the most downstream workstation is selected.

We can now compare the starving levels of workstations i and j . If the highest starving level of workstation i is greater than or equal to the starving level of workstation j then we will route the component kanban j to workstation i , otherwise, we will route it to workstation j . Note that whenever an external subassembly is available, it will always be chosen first. Internal subassemblies will only be used when no external subassembly of the desired kind is available. Subassembly kanbans are routed in a fashion similar to component kanbans.

5.1.4 Selection of Products

Because we allow multiple combinations of products, the worker may have several options when selecting the product for disassembly. If the authorization of disassembly is initiated by the subassembly kanban (j_x) , which can occur only at workstation i , where $1 \leq i < j$, the workers will have no option but to select the subassembly that results in immediate separation of subassembly (j_x) , viz., subassembly (ij_x) . If the authorization of disassembly is initiated by component kanban j at workstation i , where $1 \leq i < j$, the worker will have to remove subassembly (ij) from the product buffer with

no other options because the only subassembly that results in immediate separation of component j is the subassembly (ij). However, if the component kanban j arrives at workstation j , there are multiple options because every subassembly located in the product buffer contains component j and always results in immediate separation of component j . In this case, we determine whether or not the residual that is created by the disassembly will result in overflow of inventory. We choose the subassembly (j_x) where x is the most desirable residual ranking based on the request of subassembly kanban x at workstation j (existing kanban x at the workstation j) or current inventory level of subassembly (component) x , respectively.

5.1.5 Determining the Kanban Level

The kanban level plays an important role in the multi-kanban mechanism as it maintains a proper flow of components and subassemblies at a desired level throughout the system. It can be determined by considering product arrival rate, demand arrival rate and disassembly time. The number of kanbans for both the *component kanban*, k_i and the *subassembly kanban*, k_j^* can be computed, at any point in the disassembly line, using the following general expressions:

$$k_i = \max(1, R_i / F_i) \quad (2)$$

$$k_j^* = \max(1, R_j^* / F_j^*) \quad (3)$$

where R_i is the *request rate* of component i , F_i is the *furnish rate* of component i , R_j^* is the *request rate* of subassembly j , and of F_j^* is the *furnish rate* subassembly j . These request rates and furnish rates can be calculated as follows:

$$R_i = d_i, \text{ for } 1 \leq i \leq N \quad (4)$$

$$F_i = \sum_{w=1}^i s_{(i,w)}, \text{ for } 1 \leq i \leq N \quad (5)$$

$$R_j^* = s_i, \text{ } i \text{ is the next component to be disassembled in the sequence} \quad (6)$$

$$F_j^* = a_j^* + \sum_{w=1}^{m-1} s_{(i,w)}, \text{ } i \text{ is the latest component disassembled in the sequence} \quad (7)$$

Where d_i is the demand arrival rate of component i , $s_{(i,w)}$ is the disassembly rate of component i at workstation w , s_j is the disassembly rate of subassembly j , a_j^* is the arrival rate of subassembly j (from external source), m is the current workstation index, N is the maximum number of component, and $N-1$ is the maximum number of workstation. For the case of *component kanban*, which is requested only from a single source, request rate is equal to the customer demand arrival rate. However, because the component kanban arrives from several sources in the system, the furnish rate is the summation of arrival rates from all possible sources. For the case of *subassembly kanban*, the furnish rate is influenced by both the disassembly rate and the external subassembly arrival rate. Thus, we take all external and internal arrival rates of subassemblies at the buffer into account. Similarly, the two requesting sources, viz., the demand for target component and the demand for residual subassembly affect the request rate. The number of kanbans is determined at the beginning of the disassembly process. It is clear that demand, supplies, disassembly time, and product structure, all affect the computation of the number of kanbans.

5.2 Multi-Kanban Model for Disassembly Line with Component Discriminating Demand

In order to cope with multiple components being disassembled at a single workstation, we distinguish components into component groups. Components in the same component group are disassembled at the same workstation. The kanban routing rules for this type of disassembly line are as follow.

Consider workstation j , $1 \leq j \leq N-1$, where N is the maximum number of component groups, $N-1$ is the maximum number of workstations, and sublevel kanban is k , $k=1, 2, \dots, Q$, where Q is the maximum number of sublevel components in component group j . When a demand for the k^{th} sublevel component of component group j , called j_k , arrives at the component buffer of workstation j , one unit of component j_k is retrieved and the component kanban j_k attached to it is routed to the most desirable workstation. The procedure for determining the most desirable workstation to route

component kanban j_k is as follows. (Note that this procedure is not applicable to component kanbans for the first component group, $N=1$. In this case the kanbans are routed to the input buffer of the first workstation). A component kanban originating from workstation j will be routed to a workstation i , where $1 \leq i < j$, or workstation j depending on the availability and the desirability of the subassembly that contains component j_k . Routing component kanban j_k to workstation i , where $1 \leq i \leq (j-1)$, will result in an immediate separation of component j_k from component i_r , $r=1, 2, \dots, Q$, given that there exist product $j_k i_r$ at workstation i . Thus, the only subassembly located at the input buffer of workstation i that would be useful is a subassembly that contains only components i_r and j_k . If this type of subassembly exists in the input buffer of workstation i , then workstation i is qualified. Similarly, if there is at least one subassembly in the input buffer of workstation j , then workstation j is qualified. Next, we need to select the most desirable workstation to route component kanban j_k to, among the qualified ones, such that, if chosen, will cause the least amount of extra inventory in the system. Choosing workstation i will increase the inventory level of component i_r by an additional unit. Thus, the best workstation i is the one that is most starving for its component i_r . By checking the backorder level for demand of i_r , we could determine the most starving workstation. If there is a tie, select the most downstream workstation. If there is a tie inside workstation i , select the one with most available subassembly $j_k i_r$. Choosing workstation j will create a residual subassembly that will be further disassembled at downstream workstations. If workstation j is chosen, then a proper subassembly must be chosen to disassemble. For example, if a backorder exists at the component buffer of workstation l , where $j < l \leq (N-1)$, then, if available, we might try to disassemble a subassembly that contains only components l_r and j_k . If two or more workstations qualify as starving workstations, then the one that is most starving among them is chosen. If there is a tie, then the most downstream workstation is selected. If there is a tie inside a workstation, we break it the same way as a tie inside upstream workstation. We can now compare the starving levels of workstations i and j according to the same procedure described in section 5.1.3. The number of kanbans in component discriminating demand environment is determined in similar fashion to the non-discriminating demand environment. The rules of selecting products also remain unchanged for this type of disassembly line.

5.3 Multi-Kanban Model for Disassembly Line with Presence of Product with Multiple Precedence Relationships

We expanded the original multi-kanban model explained in section 5.1 to further cope with a disassembly which EOL products with multiple precedence relationships are present. Many key elements of the model remain unchanged. However, difference in precedence relationships of components in different products causes variation in disassembly sequences. Thus, the kanban routing mechanism is modified so that it can be deployed on this type of disassembly line. The first common type is the product that its precedence relationship of components follows the sequencing of disassembly process. This type of product is disassembled and travels in downstream direction only. Thus, the rules for routing kanban for this type of product remain unchanged. The second type of product is more complicated because its precedence relationship of components does not follow the sequencing of disassembly process. Hence, it can travel in both upstream and down stream direction depending on which component is to be disassembled next. We need to determine all possible routes. There are upstream and down stream route. The kanban, in this case, may be routed to one of downstream workstations (workstation k , where $j < k \leq (N-1)$) depending on whether it meets the criteria. We select the best destination using the same criteria as the regular products that are routed in the only downstream direction. In other words, there are more choices to be select from when allowing multiple precedence relationships in to the system. The selection criteria remain the same regardless of kanban routing direction.

5.4 Multi-Kanban Model for Disassembly with Workstation Breakdowns

When sudden breakdowns occurs among servers, instead of sitting still and rely on component or subassembly inventory, the mechanism copes with the situation by route the kanban from the starving buffer to other candidate workstations. The comparison criteria remain unchanged. However, the breakdown workstation is excluded and does not qualify as a candidate. That is, the mechanism takes advantage of having multiple candidates and ability to request part from other workstations that still operating. For workstation that is blocked by the breakdown workstation, the mechanism still accepts it as a candidate. However, in the situation that subassemblies those are in need are abundant, it is most likely for that workstation to prevail as the most desirable workstation because the mechanism considers it as a workstation that has high tendency to generate residual subassembly that is highly requested. Figure 5 demonstrates the example of blocking workstation and starving buffers. Solid arrows show a sample of how a starving buffer C being supplied by two workstations (1 and 2) upward of the blocking workstation (3). Also, in this case, candidates for component kanban B can be either workstation 1 or 2. The mechanism weighs the priority between the demand of residual parts at each workstation, viz. component A at workstation 1, and subassembly DEF or component C at workstation 2.

When there is a scheduled breakdown or maintenance of a server, the mechanism copes with such situation in two stages. At the first stage, the mechanism calculates amount of extra components will be demanded at the starving workstation during the maintenance. The mechanism takes into consideration of disassembly rate, demanding rate, and current inventory level of that component. Also at this step, the mechanism calculates amount of extra subassemblies will be disassembled and routed to the blocking workstation. Again, it takes into account of disassembly rate, demanding rate, and current inventory level of that subassembly. Then, at a required amount of time prior to the maintenance, the mechanism enters preventive maintenance mode. In this mode, all the calculated extra demand and supply are added to the actual rate of demand and supply from external source. The second stage involves routing the kanban from the starving buffer to other candidate workstations according to rate of demand and supply assign by the first stage. The comparison criteria are similar to the sudden breakdown situation.

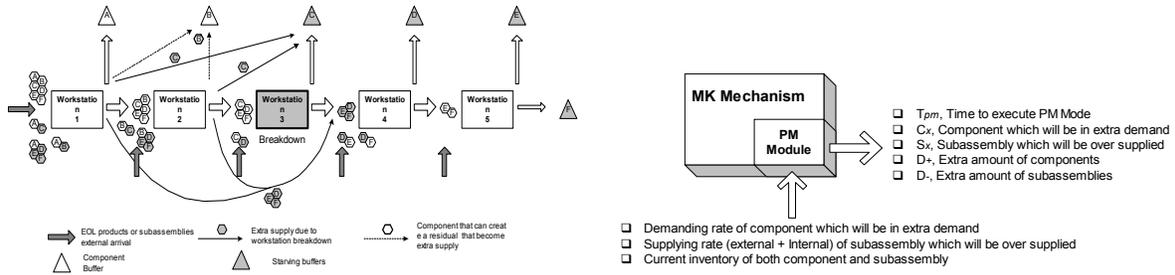


Figure 5. Coping with the Sudden Breakdown (left) and the Preventive Maintenance (right)

6. LINE DESCRIPTION AND ASSUMPTIONS

We consider 4 disassembly lines for 5 different scenarios. The input location for end-of-life products depends on its configuration and precedence relationship. The input location for a product is the most upstream workstation that disassembles the first component, according to its precedence relationship, from that product. Only one component or component group is disassembled at a given workstation except when there are only two components left to be disassembled. It may take different amount of time to disassemble different components. At each workstation, there are two types of output buffers, viz., component buffer and subassembly buffer. The component disassembled at a workstation, s_i , is placed in the *component buffer*, B_i . The rest of the subassembly is routed to the *subassembly buffer*, B_i corresponding to the next component to be disassembled. The subassembly buffer becomes the input buffer for the subsequent workstation to further disassemble the subassembly according to its disassembly sequence. There are multiple sources of demands. A demand can occur at any workstation. The demand at a given workstation is always for the component that is disassembled at that workstation. Regardless of the configuration, a product must be disassembled in a predefined sequence from the first component to the last component. When a particular component is demanded, it is retrieved from the output component buffer, B_i , of the workstation where it is disassembled. If there is no component available at the component buffer, the demand waits there in the form of a backorder. In studying the example model using simulation, the following assumptions were made: (a) customer backorder is allowed, (b) external demand is for component only and can arrive at any workstation, (c) components must be disassembled according to their precedence relationships one type at a time until the last component in disassembly sequence is disassembled, and (d) products may enter the line at any workstation along the line depending on its configuration.

7. NUMERICAL EXAMPLES AND CONCLUSIONS

Numerical examples of various scenarios of disassembly line are used to illustrate the application of the multi-kanban concept.

- Scenario 1. A common disassembly line with 4 workstations and one EOL product consists of 5 components. The product can arrive with missing components.
- Scenario 2. A disassembly line with 4 workstations and one EOL product consists of 5 components. The product can arrive with missing components. Demand is discriminating against 3 distinctiveness of each component. That means each component is classified into 3 sub groups.

- Scenario 3. A disassembly line with 5 workstations and 3 EOL products consist of 6 shared components. These products have different precedence relationships. Therefore, there are 3 different disassembly sequences.
- Scenario 4a. A common disassembly line with 4 workstations and one EOL product consists of 5 components. The product can arrive with missing components. Sudden breakdown is allowed.
- Scenario 4b. A common disassembly line with 4 workstations and one EOL product consists of 5 components. The product can arrive with missing components. Scheduled breakdown is allowed.

We used ARENA® software [11] to simulate the model. We ran two sets of experiments for each scenario representing the push system and the multi-kanban system. For each experiment, we collected the data over a 5 day period. In the push system, all arriving products are processed continuously in the order of their arrival. The demand is fulfilled as soon as the components are available. In the multi-kanban pull control system, we utilize smart-routing for kanbans in both upstream and downstream directions (as explained in the Kanban Routing Mechanism subsection) in order to reduce the inventory built up caused by disparity in demands among components. We also utilize product selection method (as explained in the Selection of Products subsection). In these experiments, statistics on the following three performance measures were collected: system's ability to satisfy the demand, average inventory level, and average customer waiting time.

Table 1. Performance Measures

Scenario	Satisfied Demand		Average Inventory		Average Waiting Time	
	Traditional Push System	Multi-Kanban Pull System	Traditional Push System	Multi-Kanban Pull System	Traditional Push System	Multi-Kanban Pull System
1	623	615	54	20	4.8	5.1
2	270	265	36	25	2.3	2.4
3	165	169	49	26	6.7	6.4
4a	301	297	72	51	12.1	11.9
4b	421	416	65	49	8.5	8.6

It is clear from table 1 that regardless of disassembly scenarios in the experiment, the multi-kanban mechanism significantly reduces average inventory while maintaining the components' demands fulfillment rates and customer's waiting time. In the push environment, the system builds up inventory in order to fulfill customers' demands. The large amount of inventory helps coping fluctuation in demands. Alternatively, the multi-kanban mechanism responds to fluctuation among demands by routing the kanbans to the most suitable workstation. For the example considered, the system was able to reduce the inventory level by the maximum of 63% in scenario 1 and at least 25% in scenario 4b while fulfilling customers' demands comparable to push system. Despite serious complications in a disassembly line, this paper demonstrated that a pull system could be adapted to perform well in controlling disassembly line. With the help of the examples, it was shown that the proposed multi-kanban mechanism could be implemented effectively. The multi-kanban mechanism allows the system to meet the customers' demands and stabilizes the fluctuations in the system's inventory levels. To achieve this, the mechanism relies on real time routing adjustment of kanban.

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