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Disassembly Planning and Costing Through Petri Net Approach

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DISASSEMBLY PLANNING AND COSTING THROUGH PETRI NET APPROACH

by

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M.E. May 2003, NC University

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ABSTRACT

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Old Dominion University, 2008
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In the current consumer oriented environment, many new products appear in the market almost on a daily basis. Lured by advertisements and tempted by new product features, customers are constantly purchasing newer products. Acquiring newer products for often leads to throwing out older ones, but it is a totally different story for manufacturers. They need to consider the best way to reuse a product both for economic purposes and for environmental protection. Considerations for them often include: how to minimize total disassembly cost, how to achieve the lowest total disassembly time at each processing step, and how to sort valuable parts from hazardous parts as early as possible during the disassembly procedure.

In this paper, we use a Disassembly Petri-Net (DPN) to generate the Disassembly Process Plan (DPP). This plan is a sequence of disassembly tasks from the initial stage of the whole product to the final stage where each part is separated from the other parts. This disassembly plan is very valuable for product recycling or remanufacturing. Prior to having the DPN, we apply an algorithm to generate a Disassembly Precedence Matrix (DPM) helped by the construction steps involved in SolidWorks^{TM}, a solid model software used to create the part in the first place. From the DPN, we find all feasible paths and generate the corresponding costs of disassembly based upon tool changes, changes in direction of the movement and individual part characteristics (e.g. hazardous

components and recycle component). Cost data was extracted from previously published studies by Boothroyd et al. to obtain the handling time and disassembly time. Afterwards, we developed the optimal or near-optimal DPP for the best time and cost based disassembly options.

In summary, this paper presents a systematic method to disassemble a part into its individual components and provides a cost figure for doing so. This is in contrast with many studies reported in the literature in that they concentrate either on a measure of disassembly complexity, or even if cost is presumably the driving force, their costs are arbitrary costs based on pre-selected values for such things as tool change penalty, disassembly direction change penalty or penalty for delaying removal of hazardous materials. In this paper, we are using disassembly times based on experimental work and/or industrial experience. Given the correct labor rate, our cost evaluation indeed yields a realistic cost value.

This thesis is dedicated to my parents and my wife

ACKNOWLEDGMENTS

When I first came to the U.S. I felt everything was wonderful; all kinds of luxury cars on the street was my first impression. After one month we left from San Diego to Norfolk. This was my first study in the U.S.. Courses were very tough that next year; April 9, 2006 I was baptized. Let God lead me to go through graduate student life. I always believe "with man this is impossible, but with God all things are possible."(Matthew 19:26)

Do not be anxious about anything, but in everything, by prayer and petition, with thanksgiving, present your requests to God. And the peace of God, which transcends all understanding, will guard your hearts and your mind in Christ Jesus. (Philippians 4:6)

Thanks to God for putting Dr. Bao, Dr. Hou, Dr. Huang, Dr. Yuan, Shoanne, Billy and Migo around me to help me finish the Master's Degree.

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CHAPTER 1

INTRODUCTION

The concept of environmental protection has gradually been established during the last five decades in reaction to growth in consumption and depletion of natural resources. This concept has become more and more important not only because of state and federal regulations, but also because people are aware of the effects of industrial pollution on the environment, such as global warming and climate change. Why do we have so much waste now? Why did the problems not show up 20 years ago? The reason is not hard to understand. For instance, in the past if you dumped a television, what you dumped was only a television. Now when you dump a television, you have also dumped the remote control and the batteries as well. In addition, you might consider discarding the television stand, a set of audio equipment and other accessories. There are many other products that have a similar critical impact, such as multi-functional printers and so on. Besides, in the past, merchandise was discarded when consumers were not able to fix it or because the required parts could not be found. Nowadays, consumers do not maintain their merchandise as cautiously as in previous generations. Consumers purchase their merchandise more frequently to keep up with the current fashion. For the reasons mentioned above, the roots of many crucial environmental problems are obviously diverse.

Disassembly is considered to be key to solving these crucial problems because this technique can sort all kinds of components and retrieve the valuable parts from the wasted products. Many disassembly operations are performed to:

* This thesis follows ASME format

1. Sort the parts based on their flammability characteristics
2. Remove the hazardous parts
3. Recover the valuable parts
4. Reuse the subassembly parts to reduce cost
5. Meet state and federal laws. One such law is the Resource Conservation and Recovery Act (RCRA), enacted in 1976

In this thesis, a solid model software to visualize the assembled part is a first step to figure out the approximate number of components at a glance. Then an algorithm is applied to generate a Disassembly Precedence Matrix (DPM). Next, relationships among the components are identified to generate a Disassembly Petri-Net (DPN) from this DPM. Once the DPN exists, the Disassembly Process Plan(DPP) can be produced. Many aspects in DPP need to be considered in order to get the optimal or near optimal best time and cost based on various disassembly options. In many if not all disassembly options, obstructions are encountered. Therefore, some other parts must be removed before proceeding along a disassembly pathway. Additionally, as many parts as possible should be removed at the same time. Each part may require a different tool for removal. The best way is to remove all of the parts or most of the parts with the same tool. This work can save on cost and time and prevent switching tools too frequently. Removing valuable parts and hazardous parts as early as possible is desirable for disassembly processes because the more valuable the parts you get out early, the more benefits the company gains. If a disassembly line in a company can obtain 10 valuable parts per hour and other companies' disassembly lines can only obtain 8 valuable parts per hour from the same product, then obviously the benefit to the former company is larger than that to the latter company. Moreover, in order to reduce employees' exposure to dangerous disassembly processes involving hazardous parts, it is best to disassemble the hazardous parts as early as possible. These concepts are like LEGO bricks when you want to change an original model to another model. Disassembly priorities, orientation and changing tools must be considered. These are the important factors before a disassembly process is executed. Besides, handling time and disassembly time for each disassembly step must be added following these considerations:

First, handling times depend on each part's physical characteristics such as size, stiffness strength, buckling and so on.

Second, disassembly times depend on, difficulty of separation, location reachability, vision restriction, and hazardous penalty.

After a product is disassembled, the following groups of parts can be identified: recycled parts, hazardous parts, sub-disassembly parts and discarded parts. For the discarded parts, some may go to incineration plants and others to landfills. Through this processing, our environment can be adequately preserved. The sub-disassembly and recycled parts can be reused in other products or other purposes to cut down product costs and enhance the company's benefits. The hazardous parts should be dealt with through adequate procedures to minimize their impact on the environment.

In conclusion, most people now realize that it is important to preserve the environment and natural resources for themselves and their offspring. The disassembly process is one of the best approaches to facilitate this goal. Do you still consider the end-of-life product as a waste? If you can engineer waste in the right way, you will make good money from garbage.

This thesis is on the modeling of the disassembly process. After this introduction, chapter 2 provides an in-depth literature survey. This is followed by a discussion in chapter 3 of the research methodology adopted in this thesis. Chapter 4 presents four case studies to illustrate the research methodology introduced in chapter 3. Finally, chapter 5 offers some concluding remarks and a summary of this thesis.

CHAPTER 2

LITERATURE CITED

The disassembly process is a pre-requisite to the reduction of the waste that has been gradually accumulating over the decades. During the disassembly process, we are concerned about the optimal or near optimal way to bring economic benefits to manufacturers or producers and minimizing the impact on the environment.

Gungor and Gupta presented a methodology to evaluate different disassembly strategies so that the best one can be chosen. [1] Disassembly evaluation methodology allows the evaluator to choose the best disassembly process among several alternatives. Total time of disassembly (TTD) gives a measure of the efficiency of a given disassembly sequence of a product. There are some factors that affect the TTD, such as direction of disassembly changes and types of joints. There are four things we need to know in order to calculate the total time of disassembly for alternative disassembly sequences of a product: disassembly sequence of the product, disassembly time of each component of the product, disassembly directions, and joint types of the product's components. Since it is not an easy task to identify all possible disassembly sequences of complex products, the authors proposed a disassembly sequence generation heuristic that gives a near optimum disassembly sequence for a product. This heuristic requires two types of information in order to define the difficulty level for removal of the components; one is the precedence relationships of components of the product under consideration, and the other is the average difficulty rating for each part of the product.

Villalba, Segarra, Chimenos and Espiell presented a way to determine if it is economically feasible to disassemble a product using the recyclability index of materials (R). [2] First, a percentage of the product that is composed with materials with a high R is calculated. This gives an estimate of how much of the product can be recycled theoretically. Second, a profit-to-loss margin is obtained to determine whether it is economically feasible with that percentage of materials with a high R. If the margin is positive, the product is economical to recycle. If it is negative, then some actions have to be taken in order to make the margin become positive.

Zussman, Kriwet and Seliger introduced a quantitative assessment tool that can help the designer decide whether a product is suitable for recycling or not. [3] There are two important aspects to be considered: First, there is a necessity to combine multiple design objectives. Second, the uncertainty regarding future recycling conditions such as the price for raw materials, the refinement of process technologies and development of regulations must be assessed. These aspects have been successfully dealt with by integrating probabilistic design methods into the concept of utility theory. An AND/OR graph was used to represent all technically feasible disassembly processes. Based on the AND/OR graph concept, a new recovery graph was developed by including the recycling options for every component, and the problem of identifying the optimal recycling strategy was transformed into a graph search problem.

Various books have discussed the following topics: disassembly precedence graph; disassembly tree; state diagrams (connection-oriented & component-oriented); AND/OR graphs; and Carpenter's Approach to describe disassembly process representation. A brief discussion of these topics follows.

2.1 Disassembly precedence graph [4]

The process can be broken into many steps. While you go from one step to another step, you need to consider the removing order, e.g., move task A prior to move task B. The precedence relationships can be graphically described in the form of a precedence diagram, which was developed in the mid-1950s. The disassembly precedence graph is shown in figure 1. From the figure, we can very clearly see that if you want to go through the whole process you have two choices: ABCDE or ABDCE. Also, we would know that task C and task D must be done prior to task E. In this disassembly sequence, we will remove one single component at a time. If we meet a subassembly, we will temporarily consider it as a single part. Even for a simple precedence graph, the number of the sequence might be very high. The drawback of the disassembly graph is when we want to describe a specific product. The disassembly graph cannot represent a very complete picture of the sequence, and we need to add additional graphs to complete the disassembly sequence.

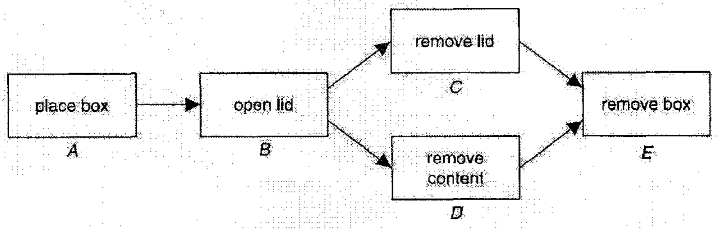


Figure 1 Disassembly precedence graph

2.2 Disassembly tree

The disassembly tree is a very popular representation of the disassembly process. There are three related concepts: disassembly tree, ordered tree, and Fishbone tree notation (De Fazio and Whitney, 1987). The ordered disassembly tree is based on the concept of the disassembly tree but provides an order for the disassembly process. The fishbone tree configuration, like the ordered tree, shows the last part from which the other parts are removed. Examples of the three kinds of disassembly trees are shown in figure 3. Figure 3 is for the product presented in figure 2. From figure 3a we can observe that the product has 2 different feasible ways to be disassembled: (BAC) or (BCA).

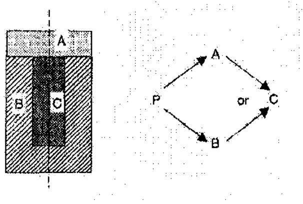


Figure 2 Simple product

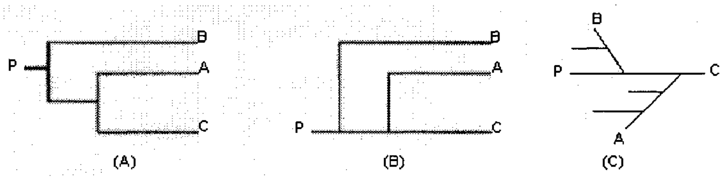


Figure 3 Disassembly tree

Using the disassembly tree theory, Veerakamolmal and Gupta published the graph depending on a module-based disassembly tree and applied a minimum cost-benefit function algorithm to each subtree. [5] The best disassembly plan is then generated for the subtree. The algorithm is also applied to the remaining subtree to determine an optimal or near optimal plan as shown in figure 4.

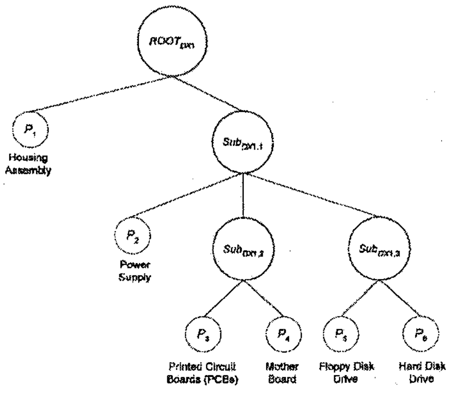


Figure 4 Subtree

2.3 Connection-oriented method

The first study to include all feasible disassembly sequences in a set of trees known as Bourjault's trees was proposed by Bourjault in 1984. [25] In his original concept, the product is described by the connection of its components. To disassemble it is to break their connections. This concept is illustrated in figure 5, which uses the product presented in figure 2. Figure 5a is the connection diagram, in which connection relationships are represented by the numbers 1 through 3. In figure 5b, the initial status is 123, meaning all three connections are existing. Once connection 1 is removed, the remaining connections are 2 & 3. Finally, once both connections 2 & 3 are broken, all components are free as indicated by the symbol ∅. The connection-oriented state diagram, essentially figure 5b, is a directed graph with connection states as nodes and transitions between two states as arcs. We can see that the product starts with all the established connections and finally goes to a state where no connection exists. The main drawback of the connection-oriented approach is that some connections can only be broken in combination with other connections. For example: connection 1 cannot be broken without breaking connection 2 and connection 3 at the same time. This will cause a complex set of constraints.

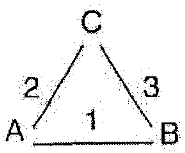


Figure 5a Connection diagram

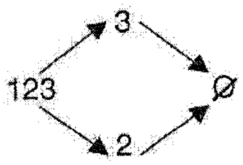


Figure 5b Connection-oriented state diagram

Since the number of feasible disassembly paths increases exponentially with the number of components, N, the number of these trees also increases significantly with N. We can use reduction of Bourjault's tree method to minimize the redundant result. We know from the drawing of the disassembly tree in figure 6 that if a connection state appears more than two times, the author only shows the subtree the first time and circles the same subtree and ignores the corresponding subtree. This results in a reduced tree that still contains the complete information of the original version of Bourjault's tree; the benefit is the disassembly tree is clearer to read. If we want to obtain the complete result, we can just copy the encircled subtree and put it in the corresponding subtree.

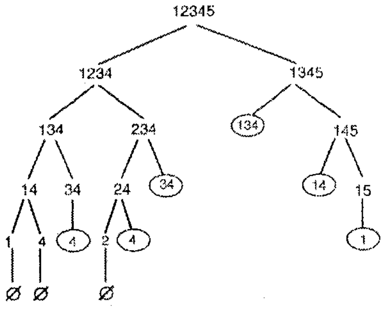


Figure 6 Bourjault's reduced tree

2.4 Component-oriented method

Homem De Mello and Sanderson first advanced this method in 1990. [4] In this approach, the nodes represent the assembly status and the arcs represent the transition steps. The initial product is indicated as a combination of three components A, B, and C, and symbolically shown as ABC in figure 7. Note that the initial product is the same product as shown in figure 2. The original product is defined as 1 partition, but after one step of the disassembly process, 2 partitions will emerge, i.e. {A, B, C}→{A, {B, C}}.

Similarly, using this concept, the next step (final step), will be {{A}, {B}, {C}}. The partition has to be geometrically feasible and is obtained from the product through a feasible disassembly process.

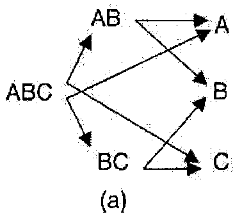


Figure 7a The AND/OR graph

full notation

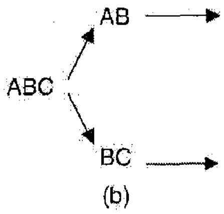


Figure 7b The AND/OR graph

concise notation

2.5 AND/OR graph

Rather than using states as nodes, another possible way to present the sequences is using subassemblies. When faced with a large number of N (component numbers), the number of subassemblies is far less than the number of states, as the benefit of using subassemblies as nodes is to reduce the size of the connection graph. However, the operation of product disassembly that we are dealing with is usually represented by an arc that indicates the points from the parent subassembly to the child subassembly. Because the disassembly operation can lead to many different sequences, the graph may have many arcs. The AND/OR graph as shown in figure 7a is equivalent to the state diagram of figure 5. The AND/OR graph even for simple parts can appear very busy, which has led to its nickname, "spaghetti diagram". In the graph presented in figure 7a, if S= AB, then S_1= A and S_2= B. In the same way, if S= BC, then S_1= B and S_2= C. In this way, we can obtain the information by one of the two branches that are included in the graph, while other information can similarly be obtained from the other branch, (as the other one follows obviously). Figure 7b is a concise AND/OR graph, equivalent to the one in figure 4.

2.6 Carpenter's Approach

Lee and Kumara proposed this approach in 1992. [6] Their carpenter's approach was used to generate disassembly sequences and directions for the case of: full disassembly and assembly, part replacement by individual disassembly, and part replacement by group disassembly. For all three, a "freedom and interference spaces" process was applied. These spaces can be developed from data from a CAD model, or through human observations.

Freedom and interference spaces used to remove a particular part from an assembly based on this part are degree of freedom (FD) and degree of interference (ITF) from the other parts. For instance, a product that consists of two parts, x and y, is shown in figure 8. For these parts, disassembly is achieved by 1 single translation in four possible directions along the X and Z axes: L, left; U, up; R, right; D, down. Part y in the example can be disassembled only along the X+ and Z- directions (i.e., 'RD'). These are the directions of FD of y when the ITF of x exists. The ITF of x on y is acting along the X- and Z+ directions (i.e., 'LU').

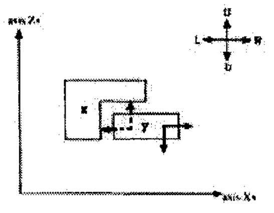


Figure 8 Degree of freedom graph

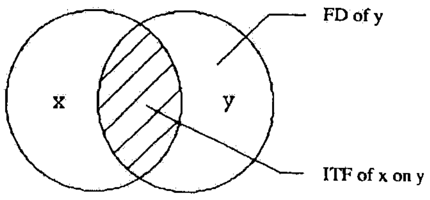


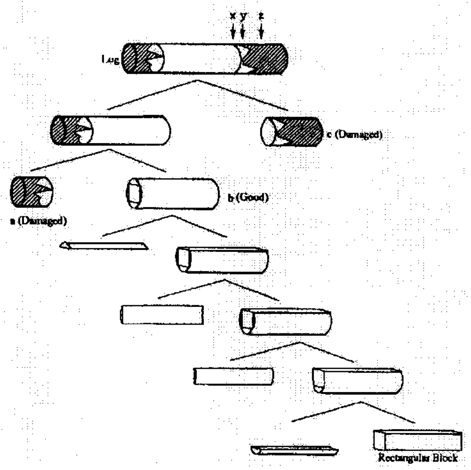
Figure 9 FD and ITF space of two-part assembly graph

Generally, this condition can be translated by the FD and ITF space as shown in figure 9. In this figure, the authors do not specify the FD of x because they are focusing on the FD of y. If their focus was changed to x, then the emphasis would be the FD of x and ITF of x on y will be changed to ITF of y on x.

In the carpenter's approach, attempts are made to minimize the number of disassembly steps and the number of parts disassembled in a part replacement. The idea is to assume that a carpenter wants to cut a rectangular block out of a log as shown in figure 10. However, both ends of the log are damaged (shaded parts) and cannot be used. Under this condition, the carpenter will cut out the damaged part as much as possible with the least number of cuts. Because of this, the carpenter will take a cut at x instead of at y or at z to minimize the damaged part c. Applying the same concept to the disassembly problem, the assembled part can be separated into two parts:

1. The maximum group, which does not include the objective part;
2. The minimum group, which includes the objective part.

The minimum group then can be further divided into two groups. This procedure is continued until there is no other part that can be further disassembled. The grouping structure is shown in figure 11.



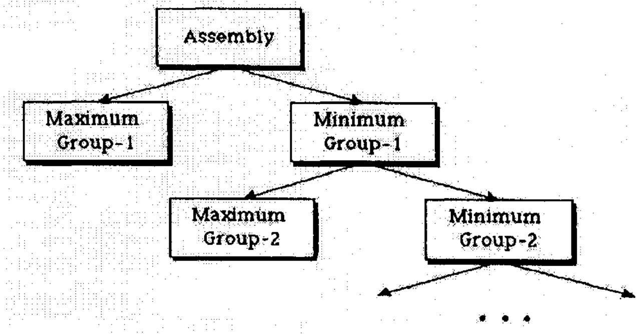


Figure 10 The concept of carpenter's approach

Figure 11 The grouping structure

2.7 Branch-and-Bound Approach

The papers published in 1991 by Subramani and Dewhust [7] discussed the disassembly problem and used a branch-and-bound approach to minimize total disassembly cost.

First, in the disassembly problem, the authors referred to the process of moving a part with respect to its local constraints. Local constraints are the constraints that exist between parts that are in direct contact with other parts or between parts that will obstruct each other's removal. This information is represented in terms of the disassembly directions of parts with respect to their contacts or obstructions. The term "disassembly direction" means the feasible direction of motion for a part with respect to any of its contacts. The observation of many kinds of contacts reveals that there are only a few feasible motions between the contacting parts. For instance, if we want to disassemble a cylindrical pin from a hole, there are two different ways to do so: positive or negative direction along the axis of the pin, or rotation about its axis. So, each disassembly direction of relative motion can be represented as a four tuple element, (A, F1, F2, T). A is the axis's name (X, Y, Z); F1 is the translational degree of freedom, which can take the values of +1 or −1; F2 is the rotational degree of freedom, which can take the values of +1, -1, 0, or F, (the value 0 indicates that rotation is unrestricted, and F means the part has to be removed without rotation); T is a number such that coaxial directions will take the same number; and parallel directions that are not coaxial will have different numbers.

Second, in the disassembly diagram, the authors use this model for the assembly to generate an easy, straight, optimal disassembly pathway for all the parts in the assembly through the application of a systematic procedure. This model includes information about the disassembly precedence of all kinds of parts that have different disassembly directions. Obviously, the direction means six positive and negative vectors along the three coordinate axes X, Y and Z. The diagram in figure 12 is shown to illustrate the Branch-and-Bound concept.

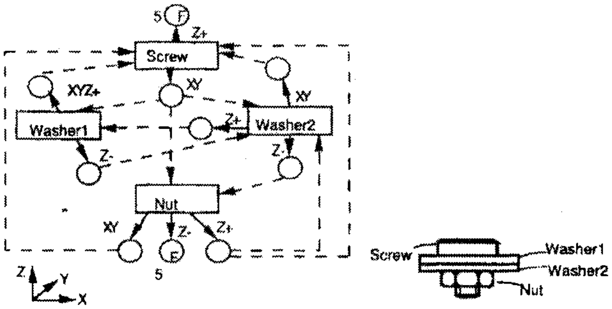


Figure 12 Disassembly diagram for screw/washer/nut

The overall idea is to select the component for which total disassembly cost is the lowest in each disassembly stage. When the costs are stable, we can obtain the optimal disassembly precedence plan.

2.8 Petri Nets (PNs)

Moore, Gungor and Gupta have made use of Petri Nets (PNs) to solve disassembly problems. [8] Petri Nets, the flexible modeling tool for simulating various pathways, have been used since the 1980s for modeling both assembly and disassembly processes. The application of Petri Nets to end-of-life products is used to obtain the feasible disassembly precedences. Their approach was to developing a method based on PNs to generate an optimal or near optimal disassembly precedence plan. First, they analyze the product and then create a matrix that quantifies the geometric precedence relationships between each neighboring part. In their algorithm, each time a part is removed, directional movements "d" in x, -x, y, and –y direction are set. Due to the geometric constraints, they use AND, OR, and complex AND/OR methods to define the type of precedence relationships, resulting in the Disassembly Precedence Matrix (DPM).

In another publication, these authors added one more condition: The XOR relationship. [9] Take figure 13 for example, the XOR relationship for this product exists between parts 3, 4, and 5. Either part 3 or part 4, but not both, must be removed prior to part 5 because we cannot suspend part 5 in the air. In this new approach, the disassembly precedence matrix has also added one more definition factor. In the DPM, $B = [b_{ij}]$, whenever b_{ij} equals –1, this means that part i XOR precedes part j.

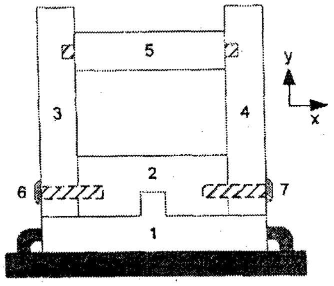


Figure 13 Moore's sample product

The AND/OR relationship can be recognized from the CAD representation. After generating the DPM, the authors used Petri nets to obtain the pathways, then added a cost function to each pathway. In their study, the cost is affected by the type of tool used, disassembly movement change and removal of hazardous or valuable materials. In real life applications, it is very important to remove the hazardous parts as soon as possible in order to protect the employee from a potentially dangerous situation. Likewise, if we can obtain the valuable part as soon as possible, then we can benefit from its reuse right away. Other factors that affect the disassembly time may depend on the product or particular needs. In the paper they used three factors to determine the total cost: α for tool change, β for disassembly direction change, and δ for delaying removal of a part with hazardous content. Let C_q be the cost associated with q^{th} marking and defining the cost function as $C_{q+1}=C_q + \Delta t_j + a\alpha + b\beta + (|H-H^r|)\delta$, and using $H = 5$, $\alpha = \beta = 2$ and $\delta = 3$, and finally disassembly times are assumed to be deterministic and the same for all parts. The cost of disassembly can therefore be calculated. From the cost results, they obtained near optimal or optimal transition firing sequences and, consequently, the optimal DPP with respect to cost [8 10-12].

In a subsequent paper, these authors have simplified their methodology without affecting the execution of the original DPN. [13]

Tiwari, Sinha et al. presented a cost-based indexing methodology. [14] It has been presented to construct the product disassembly process to guarantee the operation of disassembly sequences in a competent and cheap way. Besides, the study proposes a structure for disassembly systems to describe a Petri Net (PNs) that is based on decision controller to decide the type of disassembly operations to be performed by integrating the firing rules and index switches. The decision controller consists of many parts; the history of the component, data generation, indices enumeration, Petri net model generator, Petri-net-based decision module and Overall Disassembly Sequence Petri Net Graph (ODSPG) are named. The indices include five events: Serviceability index, Disassembly index, Dismantling index, Recycling index and Dumping index. The indexing methodology is summarized in figure 14.

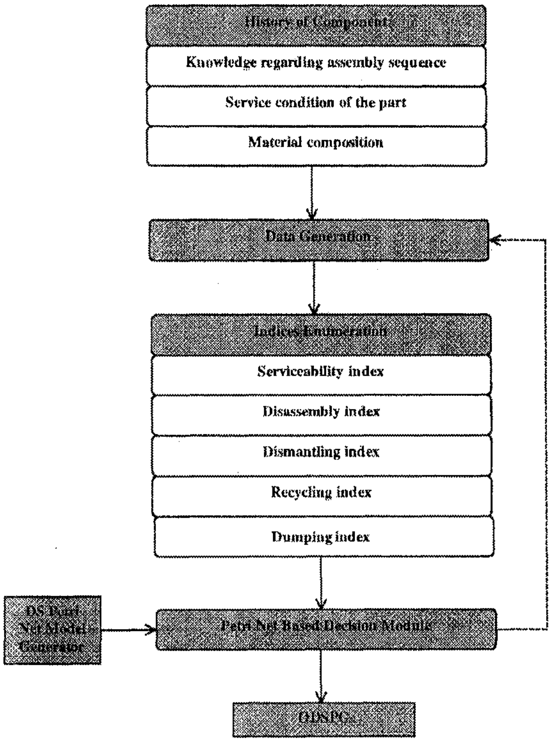


Figure 14 Disassembly system decision controller

In the controller, a Petri net generator for the disassembly process is conceptualized that generates a Petri net model according to the disassembly condition of the products. Input from the PN model generator and indices enumeration module is fed to the PN-based decision module. This module can give decision support and output in the form of a disassembly Petri net graph. After firing each transition, it also updates the data generation module.

The most significant module of this controller is the Petri-net-based decision module because different indices are converted into a switch index that is critical to the decision-making strategy. The indices give information above where the subcomponents should be sent, and this information is transformed into proper index switches.

After firing of each transition, the data generation module is updated by the reaction from the decision module, and indices are modified according to the present condition of the component. These indices are again converted into the switch index for the next transition, and the whole process is stopped after firing the last transition.

Zussman, Zhou, and Caudill extended the original assembly Petri Net into Disassembly Petri net. [15] That net clearly describes a product's topology, contacting relations, and precedence relations. Here, a joint or disassembly process means 'transition'. And a product of its parts or subassembly means 'place'. These are associated with utility information like cost or benefit. In the paper, pre-firing and post-firing values are also associated with each transition. The pre-firing value is a decision value whose magnitude shows the priority level for a transition to fire, that means its associated disassembly operation to perform. The post-firing value is a probability that indicates the success rate of its disassembly operation. Referring to the pre-firing value, it is determined by an internal planning algorithm. This value is decided before the corresponding disassembly operation, or firing of the transition. This value is also used to decide the firing priority of the transitions. Referring to the post-firing value, it is a probability value associated with a transition. It is updated according to the sensing result of the corresponding disassembly operation performed by external resources. The value represents the success rate of a disassembly operation. The pre-firing value represents the End-Of-Life (EOL) value for a product, subassembly, or component to be reused, material-recycled, refurbished and utilized. The post-firing value corresponds to the cost to perform a particular disassembly operation. Figure 15 illustrates the disassembly Petri net with remanufacturing values.

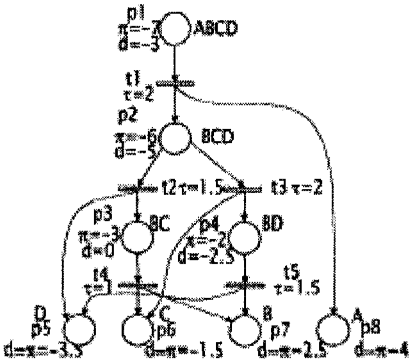


Figure 15 Disassembly Petri net with remanufacturing value

Tang, Zhou and Gao focused on the fuzzy Petri Net based on disassembly planning with human factors. [16] Disassembly is labor intensive. The large amount of human intervention creates a lot of uncertainties in disassembly operations. There are two types of human operations in disassembly. First, the heavy duty tasks are usually handled by machines, and people use hardware or software to control those machines. Their performance is based on their understanding of instructions. Second, the simple dismantling tasks involve people. These people are making decisions regarding which sequence or tool they need to follow. As in the previous statement, human intervention impact is usually through using qualitative linguistic terms to evaluate. A linguistic variable differs from a numerical variable in that values are not numbers but words or artificial language. For instance, the labor cost of an operator is a linguistic variable, and its values cannot be numerical; rather, they are high, low and fair. Fuzzy set theory provides a good tool to represent such unclear input data by formulating the values using membership functions. By taking advantage of both fuzzy logic and Petri net, the paper proposes an Fuzzy Attributed Petri Net(FAPN) model to analyze human-in-the-loop disassembly planning, through the reuse of a discarded product or subassembly; operation time for each disassembly task and the profit are assumed deterministic. See figure 16.

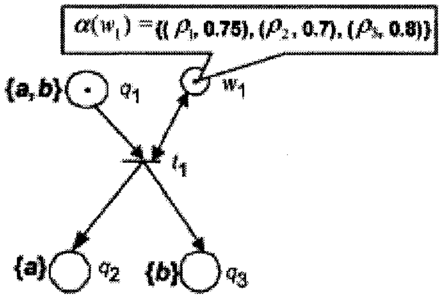


Figure 16 Simple example of FAPN

In another paper, these authors [17] focused on the stages of process decision making in a disassembly system. They assumed the stages preceding the decision are ready for the data input of the decision and the stages following are ready to receive the decision result and keep the disassembly going. A methodology was proposed to execute the decision making in a disassembly process efficiently. They do not generate the disassembly sequence before disassembling a whole product. In each disassembly step, the proposed methodology makes decisions based on dynamically updated status of parts in the product. To implement reasoning in a parallel way, a fuzzy reasoning Petri Net model has been proposed. The method unites fuzzy logic and Petri net theory. Using the knowledge and previous experience the multi-criterion fuzzy demanufacturing rule was found. It can be presented in a uniform model to make the decision as shown in figure 17.

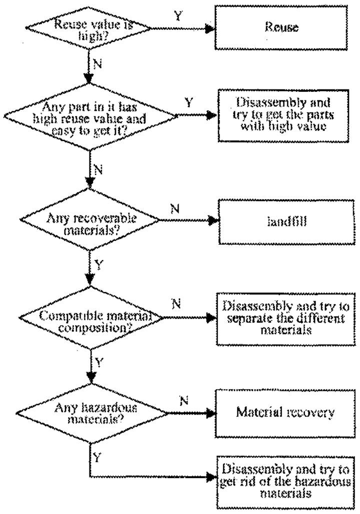


Figure 17 Decision making in a disassembly process graph

Tang and Zhou dealt with the analysis and management of the uncertainty essential in Disassembly Process Planning (DPP). [18] As shown in figure 18, the DPN is integrated with a Learning Bayesian Network (BN). The BN is constructed by the following three factors: the defectiveness of each disassembly unit, the disassembly time of individual transition, and the skill level of an operator. The DPN permits one to model the immediate execution of the disassembly operations and system resources. The learning BN lets people encode the probabilistic relation of uncertainty and its impact. The integration of DPN with a learning BN is called a Learning embedded DPN.

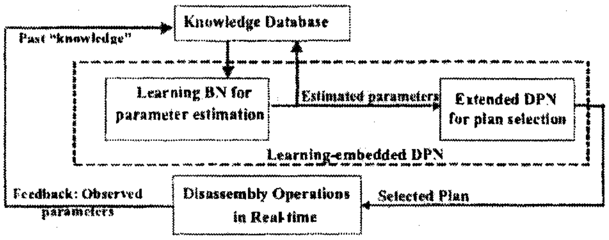


Figure 18 The structure of the adaptive DPP

Jehng, Peng and Zhou presented a methodology to model and analyze the demanufacturing process for the product using the Petri net technique. [19] A PN is represented by retired product explosion topology and its precedence relations during the disassembly process. They develop an adaptive scheme to investigate the disassembly process by adding four parameters to DPN that are denoted by value function (utility function), cost function with each transition, decision value and success rate function to control the dynamic disassembly procedure for the near optimal benefit.

Fernandez and Zerhouni [20] considered the disassembly system in the following terms: every operation in the disassembly system with no precedence relation is carried out in parallel. The modeling approach consists of separating the disassembly system into stations. Each one has the same structure and represents the same continuous Petri Net. The author's idea is fundamental to benchmarking the process. In addition to the duration of startup, this temporal aspect allows the determination of the stationary behavior of the disassembly process. The work presents an analysis method of a disassembly tree modeled by CPN (continuous Petri Net) and the mathematical modeling tolls chosen in the paper are the VCPN (variable speed continuous Petri net). This extension of Petri net constitutes a good approximation of discrete PN. The principle of this approximation is to replace the discrete markings of the classical PN by a continuous one. It is necessary to reconsider the transition firings. The solution adopted in VCPN is to replace the firing of a transition with a firing rate. However, this approach has allowed the determination of the asymptotic stocks and machine's speed in the restricted case when there is only one station where maximal speed is the slowest of the system.

Seeluangsqwat and Bohez proposed a new generic black token timed Petri Net (PN) model for design and performance analysis of a dual kanban for flexible assembly system (FAS) and disassembly system (DAS). [21] Integrating FAS and DAS, they develop a new generic PN and add pull system to the model. The new PN model is based on invariant analysis and linear programming to evaluate the performance and analysis. Kanban cards go through a series of events that can be easily included in the PN model. The kanban card in the just in time (JIT) manufacturing is similar to the tokens in PN.

Rai R., Rai V. et al. presented a disassembly sequence generation methodology by using the Petri net technique. The sequence associates the cost, indices, Profit and Loss Matrix (PLM). [22] They combine heuristics to generate and search a partial reachability graph and firing sequence of transitions of the Petri net model to achieve an optimal or near optimal disassembly sequence. The methodology avoids the conversion of the PLM matrix into a two-commodity network problem and uses Petri nets model to capture the precedence relations of the disassembly process in order to pass over the conversion step. Unfortunately, the model limits the search space to two levels only. The first level of limited search space restricts the flexibility to incorporate PLM reduction. The second level is the heuristic function that must be used to explore the markings of the Petri net. Based on the two limit level, the space and new near optimal or optimal solution are difficult to obtain. The flexibility and the heuristic function are two big factors for applying this theory.

Suzuki, Kanehara, Inaba, and Okuma substitute the Petri net for the AND/OR net to clarify graph structural properties of the assembly network. [24] They also make a number of assumptions on the assembly tasks: exactly two subassembly are joined at each assembly task; after parts have been put together, they remain together until the end of the assembly process; whenever two parts are joined all contacts between them are established; assembly operation and disassembly operation are invertible operations, and assembly and disassembly operation does not exist simultaneously in one sequence.

The assembly marked Petri net, APN shown in figure 19 is mapped from the AND/OR net of figure 20 by drawing each node and arc in the AND/OR net to each place and transition in APN. APN is a 4- tuple, APN = (P, T, D, M), where (i) P = p_1, p_2,...p_r is a set of subassembly; (ii) T = t_1, t_2,...t_r is a set of task; (iii) D is a state shift matrix (r × s); (iv) M is a marking that expresses the state of assembly (r × s) . In the definition r is the number of subassemblies and s is the number of tasks. The authors assume that p_1 represents the product. Besides, each element of D has the value of 1 (t_j is an input transition for p_i) or –1 (t_j is an output transition for p_i) or 0 (otherwise), and each element of M has the non-negative integer value. The properties of APN are described as follows: APN is a connected graph of which the root place and each leaf place correspond respectively to the product and each part of the product; each transition has a single input arc and two output arcs; and the two outputs of each transition do not reach the same place.

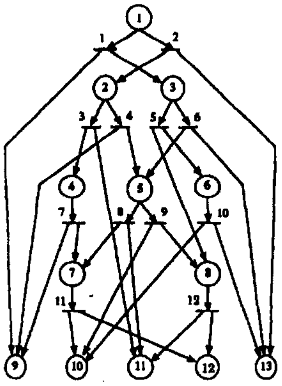


Figure 19 Petri net graph for disassembly

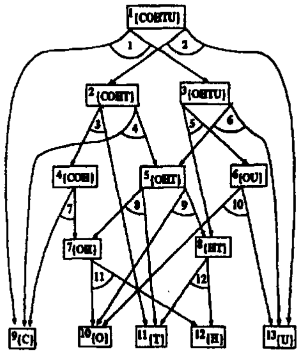


Figure 20 AND/OR net for the ballpoint pen

The literature review presented above indicates that much research has been undertaken to model the disassembly process given its importance in the end-of-life handling of consumer products. The Petri net has been demonstrated to be an effective modeling approach and, consequently, has proven successful in understanding the disassembly process and applying it to gain economic and environmental benefits. However, there are two aspects of Petri net that require improvement; first, the rules by which the net is developed are way too complicated, and second, the cost parameters are too arbitrary. The intention of this thesis is to address these two issues.

CHAPTER 3

RESEARCH METHODOLOGY

This thesis relies on the following technical bases: Solid modeling; Systematic assembly time; Disassembly Precedence Diagram; Petri Net; Disassembly Process Planning; and Optimal Disassembly Sequence. Each of these technical bases is presented below, followed by a discussion of the proposed plan to link all these technical bases together in order to reach the optimal disassembly plan.

3.1 3-D Solid modeling

SolidWorks^{TM}, a solid model software from SolidWorks, Inc., at the outset is used to build the 3-D CAD model of the part in question. The part is shown in figure 21 as a fully assembled part and in figure 22 in exploded view to depict the disassembled parts as the first step in the study of the disassembly process.

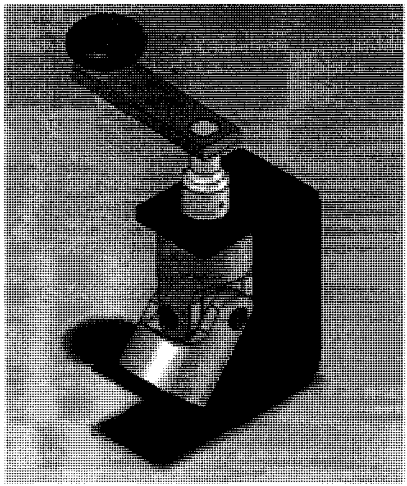


Figure 21 Fully assembled product

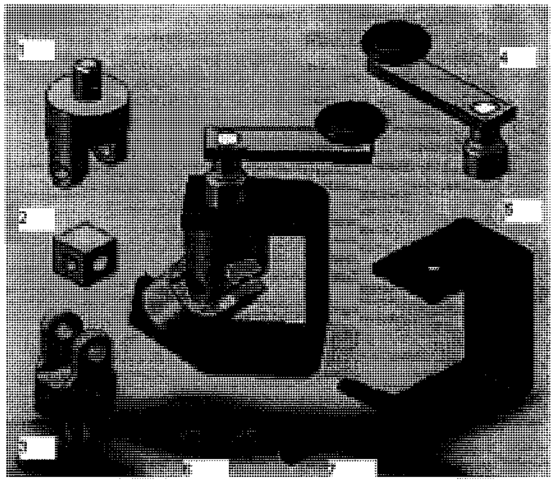


Figure 22 Exploded view of product shown in figure 21

From these figures, the geometric and spatial relationships between the components of the part can be studied. They also provide significant clues to the eventual sequence of disassembly steps.

3.2 Systematic Assembly Time

In this thesis, the Boothroyd's approach to determining manual assembly time is adopted. This approach consists of decomposing the assembly time into two main components: handling and insertion. [23] Each of these 2 main components is discussed as follows.

3.2.1 Manual Handling Time

Disassembly research is primarily driven by the desire to recycle and/or to remanufacture used parts. There have been many publications related to disassembly research. One of the earliest and best known textbooks was published in 1994 by Geoffrey Boothroyd, P. Dewhurst and W. Knight. [23] They introduced the time concept into the assembly process and defined the parts features that greatly affect the handling time. These features are: size, thickness, weight, nesting, tangling, fragility, flexibility, slipperiness, stickiness, the necessity of using two hands, the necessity of using grasping tools, the necessity of optical magnification, and the necessity of mechanical assistance. A table for the handling times associated with the part features indicated above was developed by these authors and shown in figure 24. In this table, a 2- digit classification code was used with meanings as explained below.

Each digit can be a number between 0 and 9. The first digit can belong to two groups:

Group 1 (digit 0 to 3): Part size is normal, it has a normal weight, and it can be manipulated and grasped by one hand.

Group 2 (digit 4 to 7): Part size is such that a grasping tool is needed to handle the part.

Groups I and II are further divided into many categories to show various types of orientation required based on the symmetry of the part. According to Boothroyd there are two types of special symmetry called α symmetry and β symmetry.

Alpha (α) symmetry: defined by the angle through which a part must be rotated about an axis perpendicular to the axis of insertion.

Beta (β) symmetry: defined by the angle through which a part must be rotated about the axis of insertion.

For example, figure 23, shown below, considers a rectangular part that is to be inserted into a rectangular hole. First, we rotate it about an axis perpendicular to the insertion axis. The rectangular part will repeat its orientation every 180 degrees, so we have an α angle of 180 degrees. Next, we consider the rotation of the rectangular part about the axis of insertion. The orientation of the rectangular part about this axis will repeat every 90 degrees, implying a β symmetry of 90 degrees.

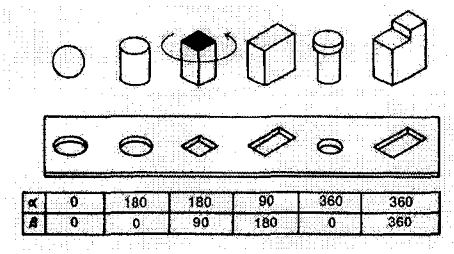


Figure 23 α & β Symmetries

The second digit of the handling code is based on the flexibility, slipperiness, stickiness, fragility and nesting characteristics of the part. The second digit also depends on the group divisions of the first digit in the following way:

I. For a first digit of 0 to 3: The second digit classifies the part's size and thickness.

II. For a first digit of 4 to 7:
  1. The second digit classifies the part's thickness.
  2. The usage of a tool
  3. The optical magnification tool requirement.

3.2.2 Manual Insertion Time

The classification system for manual insertion and fastening processes is based on the interaction between parts that touch each other. For manual insertion and fastening, the types of assembly tasks by screw, weld, rivet, force fit and so on must be investigated. These joints are found in almost any product. The design features that notably affect manual insertion and fastening times include reachability of assembly location; ease of operation of assembly tool; observability of assembly location; and the assembly alignment and arrangement. Similar to the handling times, the part's insertion times are related to the design features mentioned above through a 2- digit classification code.

The first digit can be in one of two groups:

Group 1 (digit 0 to 2): After insertion, the part is not fastened immediately.

Group 2 (digit 3 to 5): After insertion, the part is secured immediately.

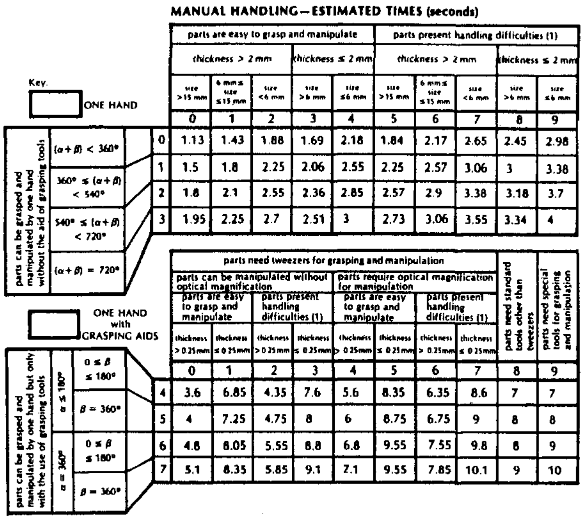
Groups I and II are further divided into many categories of obstructions and/or vision restrictions.

The second digit also depends on the first digit in the following way:

I. First digit of 0 to 2: Holding parts to maintain the orientation or location.

II. First digit of 3 to 5: Applying screwing, fastening and the plastic deformation process.

The tables' manual handling and manual insertion are shown in figures 24 and 25 respectively, in which the classification codes mentioned above were defined by Boothroyd with the corresponding times obtained from numerous experiments. This data was used for the assembly process. Once the handling codes and insertion codes are specified, it is very easy to estimate the total time for the entire process. This information is helpful to the manufacturer or designer in the redesign of the part.



MANUAL HANDLING—ESTIMATED TIMES (seconds)

Key:

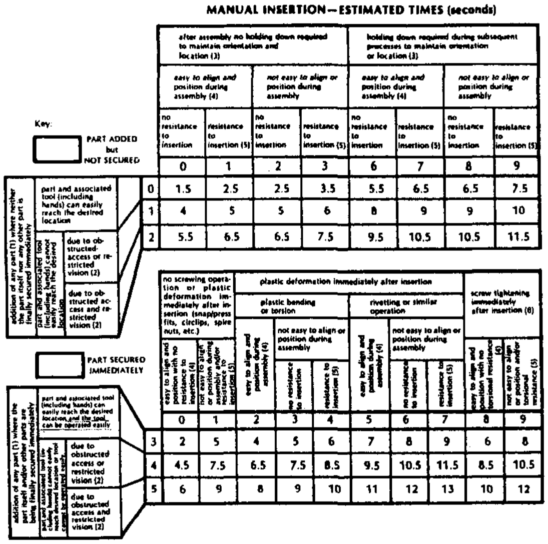
ONE HAND

			parts are easy to grasp and manipulate					parts present handling difficulties (1)				
			thickness > 2 mm			thickness ≤ 2 mm		thickness > 2 mm			thickness ≤ 2 mm	
			size > 15 mm	6 mm ≤ size ≤ 15 mm	size < 6 mm	size > 6 mm	size ≤ 6 mm	size > 15 mm	6 mm ≤ size ≤ 15 mm	size < 6 mm	size > 6 mm	size ≤ 6 mm
			0	1	2	3	4	5	6	7	8	9
parts can be grasped and manipulated by one hand without the aid of grasping tools	(α+β) < 360°	0	1.13	1.43	1.88	1.69	2.18	1.84	2.17	2.65	2.45	2.98
	360° ≤ (α+β) < 540°	1	1.5	1.8	2.25	2.06	2.55	2.25	2.57	3.06	3	3.38
	540° ≤ (α+β) < 720°	2	1.8	2.1	2.55	2.36	2.85	2.57	2.9	3.38	3.18	3.7
	(α+β) = 720°	3	1.95	2.25	2.7	2.51	3	2.73	3.06	3.55	3.34	4

ONE HAND with GRASPING AIDS

				parts need tweezers for grasping and manipulation								parts need standard tools other than tweezers	parts need special tools for grasping and manipulation
				parts can be manipulated without optical magnification				parts require optical magnification for manipulation					
				parts are easy to grasp and manipulate		parts present handling difficulties (1)		parts are easy to grasp and manipulate		parts present handling difficulties (1)			
				thickness > 0.25 mm	thickness ≤ 0.25 mm	thickness > 0.25 mm	thickness ≤ 0.25 mm	thickness > 0.25 mm	thickness ≤ 0.25 mm	thickness > 0.25 mm	thickness ≤ 0.25 mm		
				0	1	2	3	4	5	6	7	8	9
parts can be grasped and manipulated by one hand but only with the use of grasping tools	α ≤ 180°	0 ≤ β ≤ 180°	4	3.6	6.85	4.35	7.6	5.6	8.35	6.35	8.6	7	7
		β = 360°	5	4	7.25	4.75	8	6	8.75	6.75	9	8	8
	α = 360°	0 ≤ β ≤ 180°	6	4.8	8.05	5.55	8.8	6.8	9.55	7.55	9.8	8	9
		β = 360°	7	5.1	8.35	5.85	9.1	7.1	9.55	7.85	10.1	9	10

Figure 24 Manual handling times [23]



MANUAL INSERTION—ESTIMATED TIMES (seconds)

Key:

PART ADDED but NOT SECURED

				after assembly no holding down required to maintain orientation and location (3)				holding down required during subsequent processes to maintain orientation or location (3)			
				easy to align and position during assembly (4)		not easy to align or position during assembly		easy to align and position during assembly (4)		not easy to align or position during assembly	
				no resistance to insertion	resistance to insertion (5)	no resistance to insertion	resistance to insertion (5)	no resistance to insertion	resistance to insertion (5)	no resistance to insertion	resistance to insertion (5)
				0	1	2	3	6	7	8	9
addition of any part (1) where neither the part itself nor any other part is finally secured immediately	part and associated tool (including hands) can easily reach the desired location		0	1.5	2.5	2.5	3.5	5.5	6.5	6.5	7.5
	part and associated tool (including hands) cannot easily reach the desired location	due to obstructed access or restricted vision (2)	1	4	5	5	6	8	9	9	10
		due to obstructed access and restricted vision (2)	2	5.5	6.5	6.5	7.5	9.5	10.5	10.5	11.5

PART SECURED IMMEDIATELY

				no screwing operation or plastic deformation immediately after insertion (snap/press fits, circlips, spire nuts, etc.)		plastic deformation immediately after insertion						screw tightening immediately after insertion (6)	
						plastic bending or torsion			rivetting or similar operation				
							not easy to align or position during assembly			not easy to align or position during assembly			
				easy to align and position with no resistance to insertion (4)	not easy to align or position during assembly and/or resistance to insertion (5)	easy to align and position during assembly (4)	no resistance to insertion	resistance to insertion (5)	easy to align and position during assembly (4)	no resistance to insertion	resistance to insertion (5)	easy to align and position with no torsional resistance (4)	not easy to align or position and/or torsional resistance (5)
				0	1	2	3	4	5	6	7	8	9
addition of any part (1) where the part itself and/or other parts are being finally secured immediately	part and associated tool (including hands) can easily reach the desired location and the tool can be operated easily		3	2	5	4	5	6	7	8	9	6	8
	part and associated tool (including hands) cannot easily reach desired location or tool cannot be operated easily	due to obstructed access or restricted vision (2)	4	4.5	7.5	6.5	7.5	8.5	9.5	10.5	11.5	8.5	10.5
		due to obstructed access and restricted vision (2)	5	6	9	8	9	10	11	12	13	10	12

Figure 25 Manual insertion times [23]

3.3 Disassembly Precedence Matrix (DPM)

In the disassembly precedence matrix, all component movements can be in direction d, where d can be {x, -x, y, -y, z, -z}. The DPM is derived from the geometrical precedence relationships between the parts of the product. There are three kinds of precedence relations: 'AND' relation; 'OR' relation; complex 'AND/OR' relation. Looking at figures 6, 7 and 8, both C_1 and C_2 must be removed prior to C_3 being free. In figure 26, this relation means C_1 AND C_2 precedence, while in figure 27 C_1 or C_2 forms an C_1 OR C_2 precedence. In figure 28, C5 and (C2 or C3) must be removed prior to C1 being free. Thus, we have a complex AND/OR precedence.

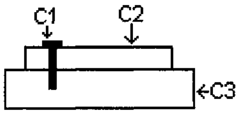


Figure 26. AND precedence graph

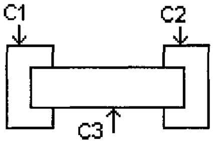


Figure 27.OR precedence

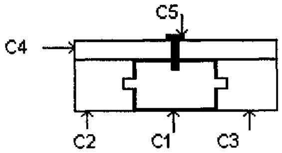


Figure 28. AND/OR precedence

We use the definition DPM, DP = [dp_{gh}], g, h = 1, …, n (n is the number of the parts) as:

$$dp_{gh} = \begin{Bmatrix} 1, & \textit{part g AND precedes part h} \\ d, & \textit{part g OR precedes part h} \\ 0, & \textit{otherwise} \end{Bmatrix} \qquad (1)$$

For the product, the universal joint shown in figure1, the DPM, has been derived as shown in figure 29.

	1	2	3	4	5	6	7
1	0	0	0	0	-Z, -X	0	0
2	0	0	0	0	-Z	0	0
3	0	0	0	0	X, -X	0	0
4	Z	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	1	1	0	0	0	0	0
7	0	1	1	0	0	0	0

Figure 29. DPM for product in figure 21.

To simplify the construction of the DPM, the following rules can be applied: Using the notation DP_h for column h of the DPM and DP_g for row g of the DPM.

Rule 1: $DP_h = 0$ if part h has no precedence (first one to disassemble)

Rule 2: $DP_g = 0$ if part g has no antecedent (last one to disassemble)

Rule 3: $dp_{gh} = 1$ if g is AND precedent to h

Rule 4: $dp_{gh} = d$ if g is OR precedent to h

Rule 5: $dp_{fh} = dp_{gh} = d\ (f \neq g) \rightarrow$ f and g together are OR precedent to h

Rule 6: $DP_h = \{dp_{gh} \mid dp_{gh} = \{1,d\}\}$

Let AG_j = set of AND precedents to j

$OG_{j,d}$ = OR precedent group to j in direction of d

Nz_i = number of non-zero entries in DP_i (the number of antecedents to i)

3.4 Petri Nets

Petri Nets (PNs) have recently emerged as a promising approach for modeling flexible and automated manufacturing systems. PNs are a graphical and mathematical modeling technique that is useful for modeling concurrent, asynchronous, distributed, parallel, non deterministic, and stochastic systems.

A PN is defined as a 5-tuple (P, T, A, W, M_0), where P = $\{p_i\}$ is a set of places or conditions, i = 1,…., m; T = $\{t_j\}$ is a set of transitions from one place to another, j = 1,….,n; $A \subseteq (P \times T) \cup (T \times P)$ is a set of direction arcs; W: A → {1, 2, ….} is a set of weight functions on arcs; M_0: P → {0, 1, ….} is the initial marking.

A marking, M_q, denotes the current state of a PN, after the q^{th} transition firing. When a transition fires, the marking will change. We define the input place of t_j, IP(t_j), and output place of t_j, OP(t_j), as:

$$IP\ (t_j) = \{p_i \in P \mid IN\ (p_i, t_j) \neq 0\} \quad (2)$$

$$OP\ (t_j) = \{ p_i \in P \mid OUT\ (p_i, t_j) \neq 0\} \quad (3)$$

Where IN (p_i, t_j) is a directed arc from place p_i to transition t_j, and

OUT (p_i, t_j) is a directed arc from transition t_j to place p_i.

A transition t_j is enabled in a marking M_q iff

$$M\ (p_i) \geq IN\ (p_i, t_j)$$

When a transition fires, a new state M' is reached such that

$$M'\ (p_i) = M\ (p_i) + OUT\ (p_i, t_j) - IN\ (p_i, t_j)$$

We say that M' is reachable from M.

3.4.1 Algorithm for generating disassembly PN:

The algorithm consists of the following three steps:

Step 1: Initialize variables

$T = \{t_b, t_i, t_f\}$ $j = 1$ to k

(t_b is the beginning transition; t_f is the final transition)

$P = \{P_i, P_f\}$

(P_i is the place at beginning; P_f is the place at end)

$A = \{\varnothing\}$

(A is a set of arcs)

$AG_j = OG_{j,d} = \{0\}$

$nz_i = 0$ ($i = o$ to k)

$A = \{a_{ij}\}$

$$a_{ij} = \begin{cases} -\,w(i,j), \text{ arc goes from pi to tj;} \\ w(i,j), \text{ arc goes from tj to pi;} \\ 0, \text{ otherwise.} \end{cases} \tag{4}$$

Step 2: Complete T and P

Step 2.1: Observe DP_j for places associated with AND and OR precedence groups.

If $dp_{ij} = 1$, add i to AG_j; add p_j to P.

If $dp_{ij} = d$, add i to $OG_{j,d}$; add $ta_{j,d}$ to T to represent the ANDs within $OG_{j,d}$; add $pa_{j,d}$ to represent the ANDs within $OG_{j,d}$, add pc_j to control the Ors in $OG_{j,d}$, and po_i to represent completion of the Ors in $OG_{j,d}$.

Step 2.2: Add places for parts with no antecedents.

j has no antecedents if $|AG_j| = 0$ and j has no OR groups. In this case, add p_j to P

Step 3: Define Arcs and Arc Weights.

The construction of the Petri net will be illustrated later in the chapter dealing with case studies.

3.5 Disassembly Process Plan (DPP)

In the disassembly process plan, we use the disassembly Petri Net and a disassembly tree as explained below to develop all feasible disassembly sequences.

In the Disassembly Petri Net, we assume the depth of search to be two-transition deep. This means that at each iteration we check on the Petri Net AND/OR precedence relationships to determine whether the transitions are reasonable to fire or not. While we check the reasonable firing transitions we also record the actions taken to develop the complete disassembly tree. In the disassembly tree we use the method called Reduction of Bourjault's Tree, to obtain a clear tree-like drawing. In drawing the disassembly tree, if a disassembly stage appears more than two times, we only show the subtree the first time and circle the same subtree. The rest of the corresponding subtree can be ignored. This results in a reduced tree at the end that still contains the complete information of the original disassembly sequence. The benefit of the Reduction of Bourjault's Tree is a less cluttered net.

3.6 Optimal Disassembly Sequence (ODS) with Boothroyd times

The common disassembly process costs include tool change, movement direction change and part symmetries (α and β). Under these conditions, it requires additional time to assess the situation. Another cost factor is related to the part's characteristics. Take the eye glasses example with the two principal components being the glasses and the metal frame. The first item is fragile and cannot be reused while the second item is more valuable because it can be recycled. In the disassembly process, it is very important to remove the hazardous parts as soon as possible in order to minimize harmful exposure to the employee. Also, if we can take the valuable part out in the shortest possible time, we can reap the benefit right away. For this thesis, we check the Petri Net with the assumed depth of search and use a cost function plus the time data from Boothroyd to determine the near optimal or optimal disassembly sequence.

3.6.1 Cost functions

The cost function consists of, first, a tool change penalty (α_c), second, disassembly direction change penalty (β_c), third, delayed removal of part with hazardous content penalty (δ), and fourth, the reward for removal of valuable part (γ)

Let C_q be the cost associated with the q^{th} marking, M_q. The following cost function can be expressed as:

$$C_{q+1} = C_q + t + a\alpha_c + b\beta_c + (\,|\,H - H^r\,|\,)\delta - c\gamma \qquad (5)$$

Where

a = number of tools used

b = number of movement direction changes

c = number of valuable parts that are obtained during the disassembling process

δ cost for delaying removal of part with hazardous content penalty

γ reward for valuable part. This reward will be reduced in proportion to the time, or transition, the part remains in the disassembly. The reduction is assumed to be 25% per transition.

H set of parts containing hazardous materials

H^r set of hazardous parts that have been removed.

After completing the definition of the cost function, we conduct a number of case studies with the following data: depth of search = 2, $\alpha_c = 2$, $\beta_c = 2$, $\delta = 3$ and $\gamma = 4$ (if valuable and hazardous parts are available). Tool types and disassembly movement directions of parts are given in each different case study. Using these parameters and the Petri Nets to check until no parts are connected to each other, we can obtain the disassembly sequence that has the minimum tool change, disassembly direction changes and the earlier removal of valuable and hazardous parts from the disassembly procedure at the same time. Before we obtain this near optimal disassembly sequence with the cost, we check each component appearing in the disassembly sequence and add the disassembly time that corresponds to the code shown in the Boothroyd time table; after that, we add all parameters a, b, ($| H - H^r |$) and c times their own specific penalty value to the total time to determine the total needed disassembly time.

According to [23], the assembly time is the sum of handling time and insertion time. The times shown in figure 23 and figure 24 are manual assembly times. For our purposes, we need disassembly time, and using the data in figure 23 and figure 24 may at first appear to be inappropriate. However, our own experimental data shown in table 1 indicates that, on a conservative note, actual disassembly time is not far off from its corresponding assembly time. Therefore, in this thesis time data taken from table 1 is used for disassembly time after taking into account a reduction by a factor of .921 as shown in table 1.

Furthermore, adding the correct labor rate, the cost evaluation indeed yields a realistic cost value.

3.7 Summary

In summary, the research methodology used in this thesis is presented in figure 30.

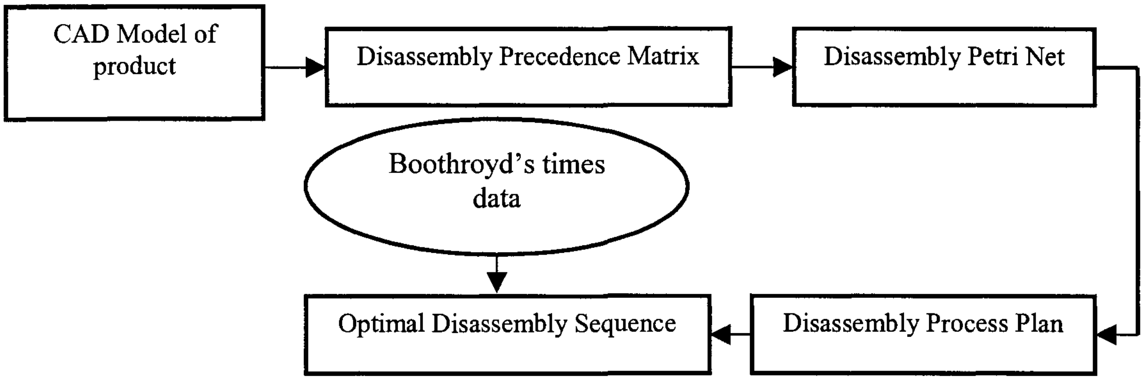


Figure 30. Disassembly process

First, a 3-D CAD tool such as SolidWorks^{TM} is used to create the product. The product can be viewed in an exploded view to clearly identify the individual parts. Next, A DPM is generated. The DPM represents the geometrically-based precedence relationships between the parts of the product. The following step involves the creation of a Petri Net. Once completed, the Petri Net allows us to proceed to a disassembly process plan that consists of feasible pathways in the Petri Net. Finally, using a cost function that includes terms for tool change, disassembly direction change, hazardous part remove, and cost per transition based on realtime time data per [18], an optimal disassembly sequence can be obtained. In the next chapter, a number of case studies will be conducted based on the methodology explained in this chapter.

Table 1. Experimental data for manual assembly and disassembly time

Experiment		Assembly time	Disassembly time	Different rate
1	Screwing a bolt and nut **by hand** Bolt:3.5cm Dia.:0.5cm Nut: 1.2 Dia.:0.6cm	5 sec.	4 sec.	0.8
2	Screwing a bolt and nut **by hand** Bolt:2.0cm Dia.:0.5cm Nut:1.0cm Dia.:0.6cm	7 sec.	7 sec.	1
3	Screwing a socket head cap screw **by Allen key**(7/32)	15 sec.	15 sec.	1
4	Screwing a nut by **socket ratchet wrench** (CR-V 10mm)	20 sec.	16 sec.	0.8
5	Screwing a nut by **Socket ratchet wrench** (CR-V 5/8 in)	14 sec.	12 sec.	0.875
6	Screwing a nut by **Open-end wrench** (9/16 in)	30 sec.	28 sec.	0.933
7	Screwing a standard screw with nut **by screw driver** Screw:2.4cm Dia.:0.5cm Nut:1.0cm Dia.:0.6cm	10 sec.	9 sec.	0.9
8	Screwing a standard screw with standard hole **by hand** Screw:3.5cm Dia.:0.5cm	15 sec.	10 sec.	0.666
9	Screwing a cone point screw with standard hole **by hand** Screw:2.0cm Dia.:0.5cm	13 sec.	9 sec.	0.692
10	Screwing a cone point screw with standard hole **by hand** Screw:3.6cm Dia.:0.5cm	14 sec.	10 sec.	0.714
Average				0.921

CHAPTER 4

CASE STUDIES

In this chapter, four case studies are provided to illustrate the research methodology discussed in the previous chapter.

4.1 Moore's fixture

The fixture shown in figure 31 below was used in Moore's paper. [8] It is used here again to demonstrate how the solution would be created using this thesis's simplified Petri Net methodology and cost function.

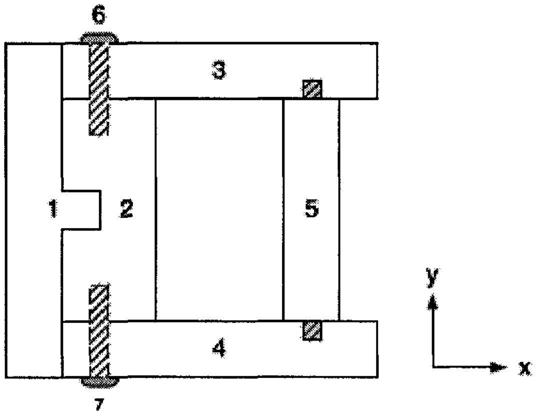


Figure 31 Moore's sample fixture product [8]

As shown in figure 31, the fixture has, all together, 7 parts. Part 1 has no precedent. Parts 2 and 3 are linked by part 6 at one end and by part 7 at the other end. Part 5 is the hazardous part. The DPM for this fixture is shown in figure 32.

	1	2	3	4	5	6	7
1	0	-x	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	y	0	0
4	0	0	0	0	-y	0	0
5	0	x	0	0	0	0	0
6	0	1	1	0	0	0	0
7	0	1	0	1	0	0	0

Figure 32 DPM for fixture shown in figure 31

Referring to the DPM, the following part movements can be observed:

Row1 : WRT 2, 1 can move in the -x direction.

Row2 : All entries are zero because part 2 is the last part left after disassembly.

Row3 : WRT 5, 3 can move in the y direction.

Row4 : WRT 5, 4 can move in the -y direction.

Row5 : WRT 2, 5 can move in the x direction.

Row6 : 6 binds 3 to 2, so 1 in (6,2),(6,3).

Row7 : 7 binds 4 to 2, so 1 in (7,2),(7,4).

(Note: WRT stands for ‘ with respect to’)

The types of tool used as well as basic disassembly time derived from Boothroyd’s tables are shown in table 2.

Table 2 Fixture disassembly data

t_j	Δt_j	Tool type	Disassembly Direction
tb	0	None	None
t1	4.18	2	-x
t2	10.88	3	-x or x
t3	8.19	4	y
t4	8.19	4	-y
t5	6.35	3	-y or y
t6	6.0	1	y
t7	6.0	1	-y
tf	0	None	None

Petri Net Construction

The algorithm for constructing the Petri Net as discussed in section 3.4.1 in the last chapter was applied to the fixture, resulting in table 3.

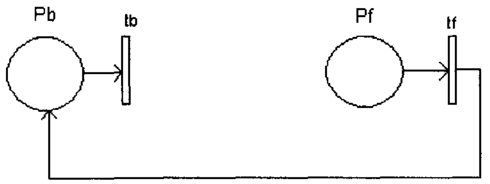
Table3. Fixture construction steps for Petri net

i	j	dp_{ij}	Action
1	1	$dp_{11} = 0$	
1	2	$dp_{12} = -x$	add 1 to $OG_{2,-x}$ add $ta_{2,-x}$ to T to represent the ANDs in $OG_{2,-x}$ add pc_2 to control the ORs in $OG_{2,-x}$ add po_2 to represent completion of the ORs in $OG_{2,-x}$
1	3	$dp_{13} = 0$	
1	4	$dp_{14} = 0$	
1	5	$dp_{15} = 0$	
1	6	$dp_{16} = 0$	
1	7	$dp_{17} = 0$	
2	1	$dp_{21} = 0$	
2	2	$dp_{22} = 0$	
2	3	$dp_{23} = 0$	
2	4	$dp_{24} = 0$	
2	5	$dp_{25} = 0$	
2	6	$dp_{26} = 0$	
2	7	$dp_{27} = 0$	
3	1	$dp_{31} = 0$	
3	2	$dp_{32} = 0$	
3	3	$dp_{33} = 0$	
3	4	$dp_{34} = 0$	
3	5	$dp_{35} = y$	add 3 to $OG_{5,y}$ add $ta_{5,y}$ to T to represent the ANDs in $OG_{5,y}$ add pc_5 to control the ORs in $OG_{5,y}$ add po_5 to represent completion of the ORs in $OG_{5,y}$
3	6	$dp_{36} = 0$	
3	7	$dp_{37} = 0$	
4	1	$dp_{41} = 0$	
4	2	$dp_{42} = 0$	
4	3	$dp_{43} = 0$	
4	4	$dp_{44} = 0$	
4	5	$dp_{45} = -y$	add 4 to $OG_{5,-y}$ add $ta_{5,-y}$ to T to represent the ANDs in $OG_{5,-y}$ add pc_5 to control the ORs in $OG_{5,-y}$ add po_5 to represent completion of the ORs in $OG_{5,-y}$
4	6	$dp_{46} = 0$	
4	7	$dp_{47} = 0$	
5	1	$dp_{51} = 0$	
5	2	$dp_{52} = x$	add 5 to $OG_{2,x}$ add $ta_{2,x}$ to T to represent the ANDs in $OG_{2,x}$ add pc_2 to control the ORs in $OG_{2,x}$ add po_2 to represent completion of the ORs in $OG_{2,x}$
5	3	$dp_{53} = 0$	
5	4	$dp_{54} = 0$	
5	5	$dp_{55} = 0$	
5	6	$dp_{56} = 0$	

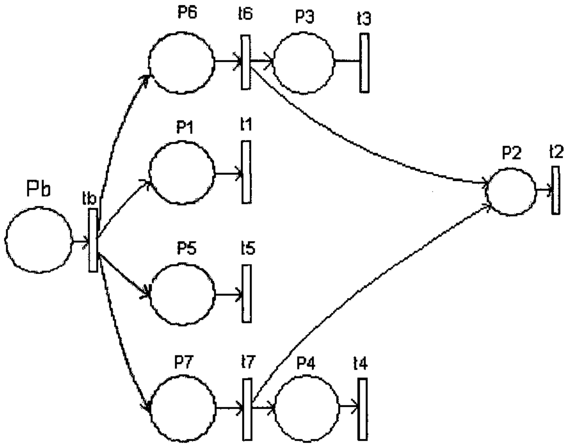
5	7	$dp_{57} = 0$	
6	1	$dp_{61} = 0$	
6	2	$dp_{62} = 1$	add 6 to AG_2 add p_2 to P
6	3	$dp_{63} = 1$	add 6 to AG_3 add p_3 to P
6	4	$dp_{64} = 0$	
6	5	$dp_{65} = 0$	
6	6	$dp_{66} = 0$	
6	7	$dp_{67} = 0$	
7	1	$dp_{71} = 0$	
7	2	$dp_{72} = 1$	add 7 to AG_2 add p_2 to P
7	3	$dp_{73} = 0$	
7	4	$dp_{74} = 1$	add 7 to AG_4 add p_4 to P
7	5	$dp_{75} = 0$	
7	6	$dp_{76} = 0$	
7	7	$dp_{77} = 0$	

The Petri Net is finally constructed through the following steps:

1. Start with P_b, t_b, P_f, t_f



2. Look at the table of AG, link t_b to 3, 4, 5, 6 and add t_3, t_4, t_5, t_6



3. Again work with the table of AG:

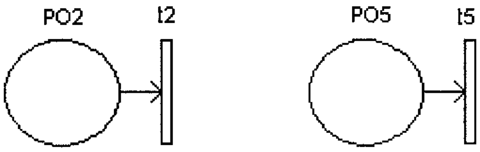
   6 is connected to 2

   7 is connected to 2

   6 is connected to 3

   7 is connected to 4

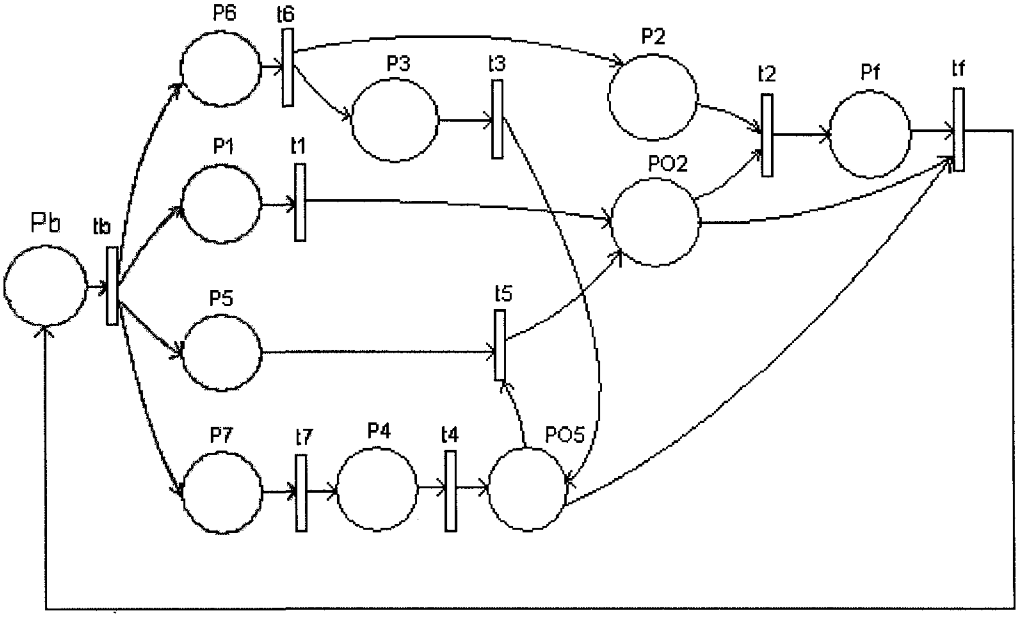
4. Add PO_2, PO_5 and link PO_2 to t_2 ; PO_5 to t_5.



5. Link PO_2 to t_f ;

   Link PO_5 to t_f.

6. Petri-Net



Basic Handling and Insertion time

Table 4 contains the details for the seven transitions (or actions) of the Petri Net

Table 4 Fixture details for the seven transitions of the Petri net

	Dimension Metric	Manual Handling Time		Manual Insertion Time		Code Description
T1	L:10mm W:2mm	Code	04	Code	30	One hand, parts are easy to grasp and manipulate. Part secured immediately and no screwing operation or plastic deformation immediately.
		Time	2.18	Time	2.0	
T2	L:6mm W:4mm	Code	02	Code	18	One hand, parts are easy to grasp and manipulate. Part added but not secured, Holding down required, not easy to align, No resistance to insertion.
		Time	1.88	Time	9.0	
T3	L:8mm W:2mm	Code	03	Code	08	One hand, parts are easy to grasp and manipulate. Part added but not secured, Holding down required, not easy to align, No resistance to insertion.
		Time	1.69	Time	6.5	
T4	L:8mm W:2mm	Code	03	Code	08	One hand, parts are easy to grasp and manipulate. Part added but not secured, Holding down required, not easy to align, No resistance to insertion.
		Time	1.69	Time	6.5	
T5	L:6mm W:2mm	Code	42	Code	30	One hand with grasping aids, parts can be manipulates without optical magnification. Parts present handling difficulties. Part secured immediately.
		Time	4.35	Time	2.0	
T6	L:7mm W:2mm			Code	38	Part and associated tool can easily reach the desired location and the tool can be operated easily Easy to align
				Time	6.0	
T7	L:7mm W:2mm			Code	38	Part and associated tool can easily reach the desired location and the tool can be operated easily Easy to align
				Time	6.0	

Cost function

As indicated in section 3.6.1, the cost function is expressed by the following formula

$$C_{q+1} = C_q + t + a\alpha_c + b\beta_c + (\,|\,H - H^r\,|\,)\delta - c\gamma$$

Where

a = number of tools used

b = number of movement direction changes

c = number of valuable parts obtained during the disassembling process

δ delaying removal of part with hazardous content penalty

γ reward for valuable part. This reward will be reduced in proportion to the time, or transition, remaining in the disassembly. The reduction is assumed to be 25% per transition.

H set of parts containing hazardous materials, and

H^r set of hazardous parts that have been removed.

Applying the 2-deep search strategy mentioned earlier, the cost values at each iteration or pass are determined as follows.

1st pass

1	t_b	T_1
Tool		2
Direction		-x
Time		4.18
Total time=4.18+3=7.18		

2	t_b	T_6
Tool		1
Direction		y
Time		6
Total time=6+3=9		

3	t_b	t_7
Tool		1
Direction		-y
Time		6
Total time=6+3=9		

2nd pass

4	t_b	t_6	t_3	t_5
Tool		1	4	3
Direction		y	y	y or -y
Time		6.0	8.19	6.35
Total time=20.54+4+0+6=30.54				

5	t_b	t_6	t_7	t_4
Tool		1	1	4
Direction		y	-y	-y
Time		6.0	6.0	8.19
Total time=20.19+2+2+9=33.19				

6	t_b	t_7	t_4	t_5
Tool		1	4	3
Direction		-y	-y	y or -y
Time		6.0	8.19	6.35
Total time=20.54+4+0+6=30.54				

3rd pass

7	t_b	t_6	t_3	t_5	t_7	t_4
Tool		1	4	3	1	4
Direction		y	y	y or -y	-y	-y
Time		6.0	8.19	6.35	6.0	8.19
Total time=34.73+8+2+6=50.73						

8	t_b	t_7	t_4	t_5	t_6	t_3
Tool		1	4	3	1	4
Direction		-y	-y	y or -y	y	y
Time		6.0	8.19	6.35	6.0	8.19
Total time=34.73+8+2+6=50.73						

4th pass

9	t_b	t_7	t_4	t_5	t_6	t_3	t_2	t_1
Tool		1	4	3	1	4	3	2
Direction		-y	-y	y or -y	y	y	x or -x	-x
		6.0	8.19	6.35	6.0	8.19	10.88	4.18
Total time=49.79+6*2(tool)+2*2(direction)+2*3(hazardous)= 71.79								

10	t_b	t_7	t_4	t_5	t_6	t_3	t_1	t_2
Tool		1	4	3	1	4	2	3
Direction		-y	-y	y or -y	y	y	-x	x or -x
		6.0	8.19	6.35	6.0	8.19	4.18	10.88
Total time=49.79+6*2(tool)+2*2(direction)+2*3(hazardous)= 71.79								

11	t_b	t_6	t_3	t_5	t_7	t_4	t_1	t_2
Tool		1	4	3	1	4	2	3
Direction		y	y	y or -y	-y	-y	-x	x or -x
		6.0	8.19	6.35	6.0	8.19	4.18	10.88
Total time=49.79+6*2(tool)+2*2(direction)+2*3(hazardous)= 71.79								

12	t_b	t_6	t_3	t_5	t_7	t_4	t_2	t_1
Tool		1	4	3	1	4	3	2
Direction		y	y	y or -y	-y	-y	x or -x	-x
		6.0	8.19	6.35	6.0	8.19	10.88	4.18
Total time=49.79+6*2(tool)+2*2(direction)+2*3(hazardous)= 71.79								

As can be seen from the cost results in the 4th pass, there can be four optimal disassembly sequences with an equal minimal cost of 71.79*0.921 = 66.118:

(a) $t_b - t_7 - t_4 - t_5 - t_6 - t_3 - t_2 - t_1$

(b) $t_b - t_7 - t_4 - t_5 - t_6 - t_3 - t_1 - t_2$

(c) $t_b - t_6 - t_3 - t_5 - t_7 - t_4 - t_1 - t_2$

(d) $t_b - t_6 - t_3 - t_5 - t_7 - t_4 - t_2 - t_1$

The above results match perfectly with those indicated in Moore's paper.

4.2 Ballpoint pen

A ballpoint pen is shown in figure 33. It is used here again to demonstrate how a solution would be created using this thesis's simplified Petri Net methodology and cost function.

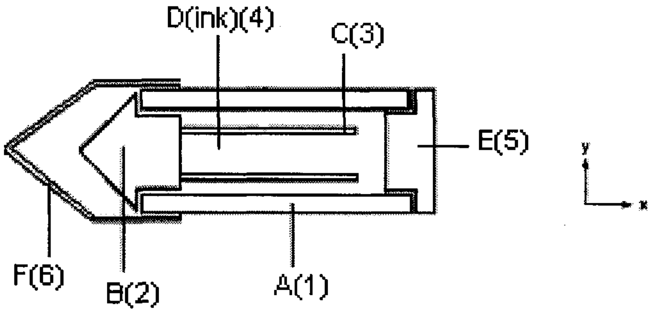


Figure 33 Ballpoint pen

As shown in figure 33, the Ballpoint pen has, all together, 6 parts. Part 5 and part 6 have no precedent. Parts 3 and 4 are binded by part 2. Part 4 is the hazardous part. The DPM for this Ballpoint pen is shown in figure 34.

	A(1)	B(2)	C(3)	D(4)	E(5)	F(6)
A(1)	0	x	0	0	0	0
B(2)	0	0	1	1	0	0
C(3)	0	0	0	x	0	0
D(4)	0	0	0	0	0	0
E(5)	x	0	0	0	0	0
F(6)	-x	0	0	0	0	0

Figure 34 DPM for ballpoint pen shown in figure 33

Referring to the DPM, the following part movements can be observed:

Row1: WRT D, A can move in the -x direction.

Row2: B binds C to D, so 1 in (2,3), (2,4).

Row3: WRT D, C can move in the x direction.

Row4: All entries are zero because part 4 is the last part left after disassembly.

Row5: WRT A, E can move in the x direction.

Row6: WRT A, F can move in the -x direction.

The types of tools used as well as basic disassembly time derived from Boothroyd's tables are shown in table 5.

Table 5 Ballpoint disassembly data

t_j	Δt_j	Tool type	Disassembly Direction
tb	0	None	None
t1	2.63	1	x or -x
t2	10.35	2	-x
t3	9.6	3	x
t4	1.5	4	x or -x
t5	10.35	1	x
t6	3.13	2	-x
tf	0	None	None

Petri Net Construction

The algorithm for constructing the Petri Net as discussed in section 3.4.1 was applied to the ballpoint pen, resulting in table 6

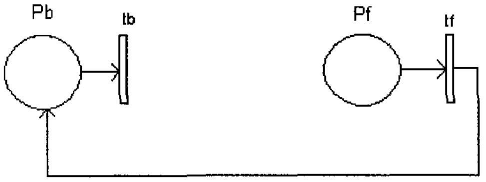
Table 6 Ballpoint construction steps for Petri net

i	j	dp_{ij}	Action
1	1	$dp_{11} = 0$	
1	2	$dp_{12} = x$	add 1 to $OG_{2,x}$ add $ta_{2,x}$ to T to represent the ANDs in $OG_{2,x}$ add pc_2 to control the ORs in $OG_{2,x}$ add po_2 to represent completion of the ORs in $OG_{2,x}$
1	3	$dp_{13} = 0$	
1	4	$dp_{14} = 0$	
1	5	$dp_{15} = 0$	
1	6	$dp_{16} = 0$	
2	1	$dp_{21} = 0$	
2	2	$dp_{22} = 0$	
2	3	$dp_{23} = 1$	add 2 to AG_3 add p_3 to P
2	4	$dp_{24} = 1$	add 2 to AG_4 add p_4 to P
2	5	$dp_{25} = 0$	
2	6	$dp_{26} = 0$	
3	1	$dp_{31} = 0$	
3	2	$dp_{32} = 0$	

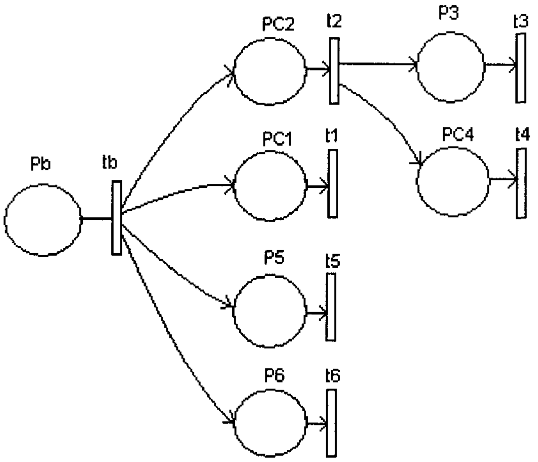
3	3	$dp_{33} = 0$	
3	4	$dp_{34} = x$	add 3 to $OG_{4,x}$ add $ta_{4,x}$ to T to represent the ANDs in $OG_{4,x}$ add pc_4 to control the ORs in $OG_{4,x}$ add po_4 to represent completion of the ORs in $OG_{4,x}$
3	5	$dp_{35} = 0$	
3	6	$dp_{36} = 0$	
4	1	$dp_{41} = 0$	
4	2	$dp_{42} = 0$	
4	3	$dp_{43} = 0$	
4	4	$dp_{44} = 0$	
4	5	$dp_{45} = 0$	
4	6	$dp_{46} = 0$	
5	1	$dp_{51} = x$	add 5 to $OG_{1,x}$ add $ta_{1,x}$ to T to represent the ANDs in $OG_{1,x}$ add pc_1 to control the ORs in $OG_{1,x}$ add po_1 to represent completion of the ORs in $OG_{1,x}$
5	2	$dp_{52} = 0$	
5	3	$dp_{53} = 0$	
5	4	$dp_{54} = 0$	
5	5	$dp_{55} = 0$	
5	6	$dp_{56} = 0$	
6	1	$dp_{61} = -x$	add 6 to $OG_{1,-x}$ add $ta_{1,-x}$ to T to represent the ANDs in $OG_{1,-x}$ add pc_1 to control the ORs in $OG_{1,-x}$ add po_1 to represent completion of the ORs in $OG_{1,-x}$
6	2	$dp_{62} = 0$	
6	3	$dp_{63} = 0$	
6	4	$dp_{64} = 0$	
6	5	$dp_{65} = 0$	
6	6	$dp_{66} = 0$	

The Petri Net is finally constructed through the following steps:

1. Start with P_b, t_b, P_f, t_f.



2. Look at table of AG, link t_b to 1, 2, 5, 6 and add t_1, t_2, t_5, t_6.



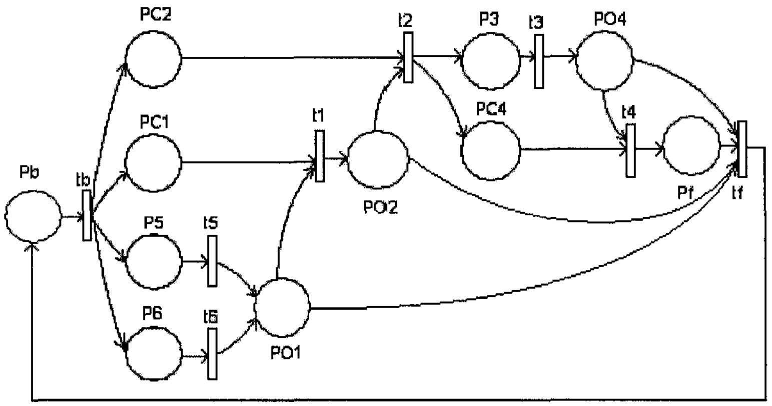
3. Again work with table of AG:

   2 is connected to 3 and 4.

4. Add PO_1, PO_2, and PO_4, and link PO_1 to t_1 ; PO_2 to t_2 ; PO_4 to t_4.
5. Link PO_1 to t_f ;

   Link PO_2 to t_f ;

   Link PO_4 to t_f.
6. Petri-Net



Basic Handling and Insertion time

Table 7 contains the details for the six transitions (or actions) of the Petri Net

Table 7 Ballpoint detail for the six transitions of the Petri net

	Dimension Metric	Manual Handling Time		Manual Insertion Time		Code Description
T1	L:120mm W:10mm	Code	0 0	Code	0 0	Parts can be grasped and manipulated by one hand without the aid of grasping tools.
		Time	1.13	Time	1.5	
T2	L:10mm W:5mm	Code	4 2	Code	3 8	Parts can be grasped and manipulated by one hand but only with the use of grasping tools. Parts present handling difficulties. Part and associated tool can easily reach the desired location. Screw tightening immediately after insertion
		Time	4.35	Time	6.0	
T3	L:100mm W:3mm	Code	4 0	Code	3 4	One hand with grasping aids, parts are easy to grasp and manipulate. Part and associated tool can easily reach the desired location. Plastic deformation immediately after insertion Resistance to insertion
		Time	3.6	Time	6.0	
T4	Liquid			Code	00	Part added but not secured Easy to align and position during assembly
				Time	1.5	
T5	L:5mm W:10mm	Code	4 2	Code	3 8	Parts can be grasped and manipulated by one hand but only with the use of grasping tools. Parts present handling difficulties. Part and associated tool can easily reach the desired location. Screw tightening immediately after insertion
		Time	4.35	Time	6.0	
T6	L:5mm W:10mm	Code	0 0	Code	3 0	Parts can be grasped and manipulated by one hand without the aid of grasping tools. Part and associated tool can easily reach the desired location. Easy to align
		Time	1.13	Time	2.0	

Cost function

As indicated in section 3.6.1, the cost function is expressed by the following formula

$C_{q+1} = C_q + t + a\alpha_c + b\beta_c + (\,|H - H^r|\,)\delta - c\gamma$

Where

a = number of tools used

b = number of movement direction changes

c = number of valuable parts obtained during the disassembling process

δ delaying removal of part with hazardous content penalty

γ reward for valuable part. This reward will be reduced in proportion to the time, or transition, remaining in the disassembly. The reduction is assumed to be 25% per transition.

H set of parts containing hazardous materials, and

H^r set of hazardous parts that have been removed.

Applying the 2-deep search strategy mentioned earlier, the cost values at each iteration or pass are determined as follows.

1st pass

1	t_b	t_5
Tool type		1
Remove direction		x
Time		10.5
Total time=10.5+1*3=13.35		

2	t_b	t_6
Tool type		2
Remove direction		-x
Time		3.13
Total time=3.13+1*3=6.13		

2nd pass

3	t_b	t_5	t_6	t_1
Tool		1	2	1
Direction		x	-x	x or -x
Time		10.35	3.13	2.63
Total time=16.11+2*2+1*2+3*3=31.11				

4	t_b	t_6	t_5	t_1
Tool		2	1	1
Direction		-x	x	x or -x
Time		3.13	10.35	2.63
Total time=16.11+1*2+1*2+3*3=29.11				

3rd pass

5	t_b	t_5	t_6	t_1	t_2	t_3
Tool		1	2	1	2	3
Direction		x	-x	x or -x	-x	x
Time		10.35	3.13	2.63	10.35	9.6
Total time=36.06+4*2+2*2+5*3=63.06						

6	t_b	t_6	t_5	t_1	t_2	t_3
Tool		2	1	1	2	3
Direction		-x	x	x or -x	-x	x
Time		2.63	10.35	10.35	6.63	9.43
Total time=36.06+3*2+3*2+5*3=63.06						

4th pass

7	T_b	t_6	t_5	t_1	t_2	t_3	t_4
Tool		2	1	1	2	3	4
Direction		-x	x	x or -x	-x	x	x or -x
Time		3.13	10.35	2.63	10.35	9.6	1.5
Total time=37.56+4*2(tool)+3*2(direction)+5*3(hazardous)=66.56							

8	T_b	t_5	t_6	t_1	t_2	t_3	t_4
Tool		1	2	1	2	3	4
Direction		x	-x	x or -x	-x	x	x or -x
Time		10.35	3.13	2.63	10.35	9.6	1.5
Total time=37.56+4*2(tool)+3*2(direction)+5*3(hazardous)=66.56							

As can be seen from the cost results in the 4th pass, there can be two optimal disassembly sequences with an equal minimal cost of 66.56*0.921 = 61.30

(a) $t_b - t_6 - t_5 - t_1 - t_2 - t_3 - t_4$

(b) $t_b - t_5 - t_6 - t_1 - t_2 - t_3 - t_4$

4.3 Universal joint

The universal joint is shown in figure 35. It is used here again to demonstrate how the solution would be created using this thesis's simplified Petri Net methodology and cost function.

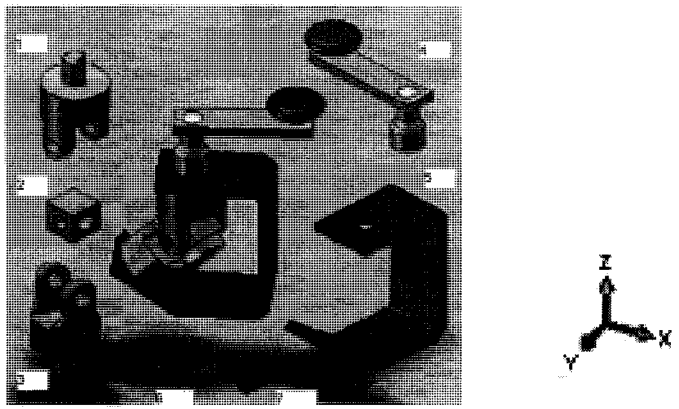


Figure 35 Universal joint

As shown in figure 35, the universal joint has, all together, 7 parts. Part 4, part 6 and part 7 has no precedent. Part 1 and 2 are binded by part 6. Parts 2 and 3 are binded by part 7. The DPM for this universal joint is shown in figure 36.

	1	2	3	4	5	6	7
1	0	0	0	0	-Z, -X	0	0
2	0	0	0	0	-Z	0	0
3	0	0	0	0	X, -X	0	0
4	Z	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	1	1	0	0	0	0	0
7	0	1	1	0	0	0	0

Figure 36 DPM for universal joint shown in figure 35

Referring to the DPM, the following part movements can be observed:

Row1 : WRT 5, 1 can move in the -z direction.

Row2 : WRT 5, 2 can move in the -z direction.

Row3 : WRT 5, 3 can move in the x direction.

Row4 : WRT 1, 4 can move in the z direction.

Row5 : All entries are zero because part 5 is the last part left after disassembly.

Row6 : 6 binds 2 to 1, so 1 in (6,1),(6,2).

Row7 : 7 binds 2 to 3, so 1 in (7,2),(7,3).

The types of tools used as well as basic disassembly time derived from Boothroyd's tables are shown in table 8.

Table 8 Universal joint disassembly data

t_j	Δt_j	Tool type	Disassembly Direction
tb	0	None	None
t1	6.63	1	-Z
t2	9.43	1	X
t3	6.63	1	X
t4	2.63	1	Z
t5	2.63	1	X
t6	10.5	3	-X
t7	10.5	3	-X
tf	0	None	None

Petri Net Construction

The algorithm for constructing the Petri Net as discussed in section 3.4.1 in the last chapter was applied to the fixture, resulting in table 9.

Table 9 Universal joint construction steps for Petri net

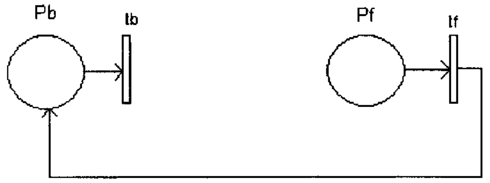
i	j	dp_{ij}	Action
1	1	$dp_{11} = 0$	
1	2	$dp_{12} = 0$	
1	3	$dp_{13} = 0$	
1	4	$dp_{14} = 0$	
1	5	$dp_{15} = -Z, -X$	add 1 to $OG_{5,-z}$, $OG_{5,-x}$ add $ta_{5,-z}$, $ta_{5,-x}$ to T to represent the ANDs in $OG_{5,-z}$, $OG_{5,-x}$ add pc_5 to control the ORs in $OG_{5,-z}$, $OG_{5,-x}$ add po_5 to represent completion of the ORs in $OG_{5,-z}$, $OG_{5,-x}$

1	6	$dp_{16} = 0$	
1	7	$dp_{17} = 0$	
2	1	$dp_{21} = 0$	
2	2	$dp_{22} = 0$	
2	3	$dp_{23} = 0$	
2	4	$dp_{24} = 0$	
2	5	$dp_{25} = -Z$	add 2 to $OG_{5,-z}$ add $ta_{5,-z}$ to T to represent the ANDs in $OG_{5,-z}$ add pc_5 to control the ORs in $OG_{5,-z}$ add po_5 to represent completion of the ORs in $OG_{5,-z}$
2	6	$dp_{26} = 0$	
2	7	$dp_{27} = 0$	
3	1	$dp_{31} = 0$	
3	2	$dp_{32} = 0$	
3	3	$dp_{33} = 0$	
3	4	$dp_{34} = 0$	
3	5	$dp_{35} = X, -X$	add 3 to $OG_{5,x}$, $OG_{5,-x}$ add $ta_{5,x}$, $ta_{5,-x}$ to T to represent the ANDs in $OG_{5,x}$, $OG_{5,-x}$ add pc_5 to control the ORs in $OG_{5,x}$, $OG_{5,-x}$ add po_5 to represent completion of the ORs in $OG_{5,x}$, $OG_{5,-x}$
3	6	$dp_{36} = 0$	
3	7	$dp_{37} = 0$	
4	1	$dp_{41} = Z$	add 4 to $OG_{1,z}$ add $ta_{1,z}$ to T to represent the ANDs in $OG_{1,z}$ add pc_1 to control the ORs in $OG_{1,z}$ add po_1 to represent completion of the ORs in $OG_{1,z}$
4	2	$dp_{42} = 0$	
4	3	$dp_{43} = 0$	
4	4	$dp_{44} = 0$	
4	5	$dp_{45} = 0$	
4	6	$dp_{46} = 0$	
4	7	$dp_{47} = 0$	
5	1	$dp_{51} = 0$	
5	2	$dp_{52} = 0$	
5	3	$dp_{53} = 0$	
5	4	$dp_{54} = 0$	
5	5	$dp_{55} = 0$	
5	6	$dp_{56} = 0$	
5	7	$dp_{57} = 0$	
6	1	$dp_{61} = 1$	add 6 to AG_1 add p_1 to P
6	2	$dp_{62} = 1$	add 6 to AG_2 add p_2 to P
6	3	$dp_{63} = 0$	
6	4	$dp_{64} = 0$	
6	5	$dp_{65} = 0$	
6	6	$dp_{66} = 0$	
6	7	$dp_{67} = 0$	
7	1	$dp_{71} = 0$	

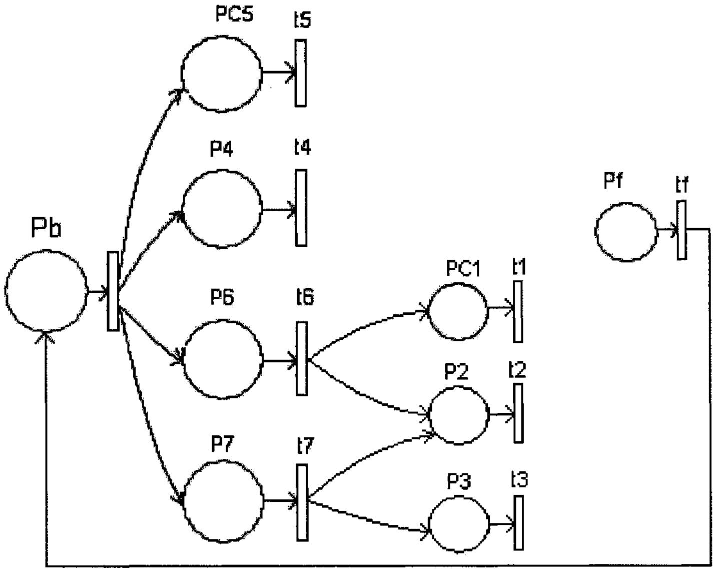
7	2	$dp_{72} = 1$	add 7 to AG_2 add p_2 to P
7	3	$dp_{73} = 1$	add 7 to AG_3 add p_3 to P
7	4	$dp_{74} = 0$	
7	5	$dp_{75} = 0$	
7	6	$dp_{76} = 0$	
7	7	$dp_{77} = 0$	

The Petri Net is finally constructed through the following steps:

1. Start with P_b, t_b, P_f, t_f.



2. Look at table of AG; link t_b to 3, 4, 5, 6 and add t_3, t_4, t_5, t_6.



3. Again work with table of AG:

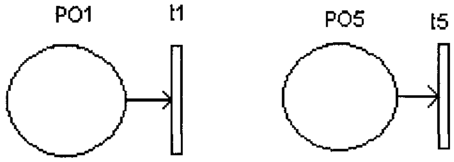
   6 is connected to 2

   7 is connected to 2

   6 is connected to 1

7 is connected to 3

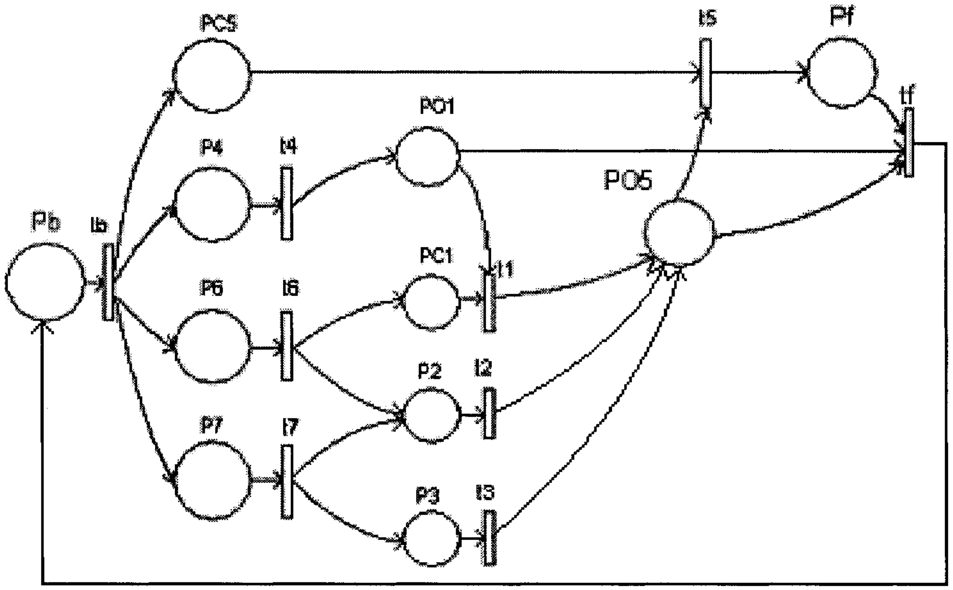
4. Add PO_1, PO_5 and link PO_1 to t_1 ; link PO_5 to t_5.



5. Link PO_1 to t_f ;

   Link PO_5 to t_f.

6. Petri-Net



Basic Handling and Insertion time

Table 10 contains the details for the seven transitions (or actions) of the Petri Net

Table 10 Universal joint detail for the seven transitions of the Petri net

	Dimension Metric	Manual Handling Time		Manual Insertion Time		Code Description
T1	L:30mm W:20mm	Code	00	Code	06	One hand, parts are easy to grasp and manipulate. Part not secured, holding required during operation
		Time	1.13	Time	5.5	
T2	L:15mm W:15mm	Code	01	Code	16	One hand, parts are easy to grasp and manipulate. Part not secured, holding required during operation.
		Time	1.43	Time	8.0	
T3	L:30mm W:20mm	Code	00	Code	06	One hand, parts are easy to grasp and manipulate. Part not secured, holding required during operation
		Time	1.13	Time	5.5	
T4	L:50mm W:10mm	Code	00	Code	00	One hand, parts are easy to grasp and manipulate. Part not secured, no holding required during operation.
		Time	1.13	Time	1.5	
T5	L:60mm W:50mm	Code	00	Code	00	One hand, parts are easy to grasp and manipulate. Part not secured, no holding required during operation.
		Time	1.13	Time	1.5	
T6	L:30mm W:5mm			Code	38	Part and associated tool can easily reach the desired location and the tool can be operated easily Easy to align
				Time	6.0	
T7	L:30mm W:5mm			Code	38	Part and associated tool can easily reach the desired location and the tool can be operated easily Easy to align
				Time	6.0	

Cost function

As indicated in section 3.6.1, the cost function is expressed by the following formula

$$C_{q+1} = C_q + t + a\alpha_c + b\beta_c + (| H - H^r |)\delta - c\gamma$$

Where

a = number of tools used

b = number of movement direction changes

c = number of valuable parts obtained during the disassembling process

δ delaying removal of part with hazardous content penalty

γ reward for valuable part. This reward will be reduced in proportion to the time, or transition, remaining in the disassembly. The reduction is assumed to be 25% per transition.

H set of parts containing hazardous materials, and

H^r set of hazardous parts that have been removed.

Applying the 2-deep search strategy mentioned earlier, the cost values at each iteration or pass are determined as follows.

<u>1st pass</u>

1	t_b	t_4
Tool type		1
Remove direction		z
Time		2.63
Total time=2.63		

2	t_b	t_6
Tool type		3
Remove direction		-x
Time		10.5
Total time=10.5		

3	t_b	t_7
Tool type		3
Remove direction		-x
Time		10.5
Total time=10.5		

<u>2nd pass</u>

4	t_b	t_4	t_6	t_7
Tool		1	3	3
Direction		z	-x	-x
Time		2.63	10.5	10.5
Total time=23.63+4=27.63				

5	t_b	t_4	t_6	t_1
Tool		1	3	1
Direction		z	-x	-z
Time		2.63	10.5	6.63
Total time=19.76+8=27.76				

6	t_b	t_4	t_7	t_6
Tool		1	3	3
Direction		z	-x	-x
Time		2.63	10.5	10.5
Total time=23.63+4=27.63				

7	t_b	t_4	t_7	T_3
Tool		1	3	1
Direction		z	-x	x
Time		2.63	10.5	6.63
Total time=19.76+8=27.76				

8	t_b	t_6	t_4	t_1
Tool		3	1	1
Direction		-x	z	-z
Time		10.5	2.63	6.63
Total time=19.76+6=25.76				

9	t_b	t_6	t_1	t_4
Tool		3	1	1
Direction		-x	-z	Z
Time		10.5	6.63	2.63
Total time=19.76+6=25.76				

10	t_b	t_6	t_7	t_1
Tool		3	3	1
Direction		-x	-x	-z
Time		10.5	10.5	6.63
Total time=27.63+4=31.63				

11	t_b	t_6	t_1	t_7
Tool		3	1	3
Direction		-x	-z	-x
Time		10.5	6.63	10.5
Total time=27.63+8=35.63				

12	t_b	t_6	t_7	t_3
Tool		3	3	1
Direction		-x	-x	x
Time		10.5	10.5	6.63
Total time=27.63+4=31.63				

13	t_b	t_6	t_4	t_7
Tool		3	1	3
Direction		-x	z	-x
Time		10.5	2.63	10.5
Total time=23.63+8=31.63				

14	t_b	t_6	t_7	t_4
Tool		3	3	1
Direction		-x	-x	Z
Time		10.5	10.5	2.63
Total time=23.63+4=27.63				

15	t_b	t_7	t_3	t_6
Tool		3	1	3
Direction		-x	x	-x
Time		10.5	6.63	10.5
Total time=27.63+8=35.63				

16	t_b	t_7	t_3	t_4
Tool		3	1	1
Direction		-x	x	z
Time		10.5	6.63	2.63
Total time=19.76+6=25.76				

17	t_b	t_7	t_6	t_3
Tool		3	3	1
Direction		-x	-x	X
Time		10.5	10.5	6.63
Total time=27.63+4=31.63				

18	t_b	t_7	t_4	t_3
Tool		3	1	1
Direction		-x	Z	x
Time		10.5	2.63	6.63
Total time=19.76+6=25.76				

19	t_b	t_7	t_6	t_4
Tool		3	3	1
Direction		-x	-x	z
Time		10.5	10.5	2.63
Total time=23.63+4=27.63				

20	t_b	t_7	t_4	t_6
Tool		3	1	3
Direction		-x	Z	-x
Time		10.5	2.63	10.5
Total time=23.63+8=31.63				

21	t_b	t_7	t_6	t_1
Tool		3	3	1
Direction		-x	-x	-z
Time		10.5	10.5	6.63
Total time=27.63+4=31.63				

<u>3rd pass</u>

22	t_b	t_4	t_6	t_7	t_1	t_2
Tool		1	3	3	1	1
Direction		z	-x	-x	-z	x
Time		2.63	10.5	10.5	6.63	9.43
Total time=39.69+10=49.69						

23	t_b	t_4	t_6	t_7	t_1	t_3
Tool		1	3	3	1	1
Direction		z	-x	-x	-z	x
Time		2.63	10.5	10.5	6.63	6.63
Total time=36.89+10=46.89						

24	t_b	t_4	t_6	t_7	t_2	t_1
Tool		1	3	3	1	1
Direction		z	-x	-x	x	-z
Time		2.63	10.5	10.5	9.43	6.63
Total time=39.69+10=49.69						

25	t_b	t_4	t_6	t_7	t_2	t_3
Tool		1	3	3	1	1
Direction		z	-x	-x	x	x
Time		2.63	10.5	10.5	9.43	6.63
Total time=39.69+8=47.69						

26	t_b	t_4	t_6	t_7	t_3	t_1
Tool		1	3	3	1	1
Direction		z	-x	-x	x	-z
Time		2.63	10.5	10.5	6.63	6.63
Total time=36.89+10=46.89						

27	t_b	t_4	t_6	t_7	t_3	t_2
Tool		1	3	3	1	1
Direction		z	-x	-x	x	x
Time		2.63	10.5	10.5	6.63	9.43
Total time=39.69+8=47.69						

28	t_b	t_6	t_7	t_4	t_1	t_2
Tool		3	3	1	1	1
Direction		-x	-x	z	-z	x
Time		10.5	10.5	2.63	6.63	9.43
Total time=39.69+2+6=47.69						

29	t_b	t_6	t_7	t_4	t_1	t_3
Tool		3	3	1	1	1
Direction		-x	-x	z	-z	x
Time		10.5	10.5	2.63	6.63	6.63
Total time=36.89+2+6=44.89						

30	t_b	t_6	t_7	t_4	t_2	t_1
Tool		3	3	1	1	1
Direction		-x	-x	z	x	-z
Time		10.5	10.5	2.63	9.43	6.63
Total time=39.69+2+6=47.69						

31	t_b	t_6	t_7	t_4	t_2	t_3
Tool		3	3	1	1	1
Direction		-x	-x	z	x	x
Time		10.5	10.5	2.63	9.43	6.63
Total time=39.69+2+4=45.69						

32	t_b	t_6	t_7	t_4	t_3	t_1
Tool		3	3	1	1	1
Direction		-x	-x	z	x	-z
Time		10.5	10.5	2.63	6.63	6.63
Total time=36.89+2+6=44.89						

33	t_b	t_6	t_7	t_4	t_3	t_2
Tool		3	3	1	1	1
Direction		-x	-x	z	x	x
Time		10.5	10.5	2.63	6.63	9.43
Total time=39.69+2+4=45.69						

34	t_b	t_4	t_6	t_1	t_7	t_2
Tool		1	3	1	3	1
Direction		z	-x	-z	-x	x
Time		2.63	10.5	6.63	10.5	9.43
Total time=39.69+8+8=55.69						

35	t_b	t_4	t_6	t_1	t_7	t_3
Tool		1	3	1	3	1
Direction		z	-x	-z	-x	x
Time		2.63	10.5	6.63	10.5	6.63
Total time=36.89+8+8=52.89						

36	t_b	t_4	t_7	t_3	t_6	t_1
Tool		1	3	1	3	1
Direction		z	-x	x	-x	-z
Time		2.63	10.5	6.63	10.5	6.63
Total time=36.89+8+8=52.89						

37	t_b	t_4	t_7	t_3	t_6	t_2
Tool		1	3	1	3	1
Direction		z	-x	x	-x	x
Time		2.63	10.5	6.63	10.5	9.43
Total time=39.69+8+8=55.69						

38	t_b	t_6	t_1	t_4	t_7	t_2
Tool		3	1	1	3	1
Direction		-x	-z	z	-x	x
Time		10.5	6.63	2.63	10.5	9.43
Total time=39.69+6+8=53.69						

39	t_b	t_6	t_1	t_4	t_7	t_3
Tool		3	1	1	3	1
Direction		-x	-z	z	-x	x
Time		10.5	6.63	2.63	10.5	6.63
Total time=36.89+8+8=50.89						

40	t_b	t_7	t_3	t_4	t_6	t_1
Tool		3	1	1	3	1
Direction		-x	x	z	-x	-z
Time		10.5	6.63	2.63	10.5	6.63
Total time=36.89+6+8=50.89						

41	t_b	t_7	t_3	t_4	t_6	t_2
Tool		3	1	1	3	1
Direction		-x	x	z	-x	x
Time		10.5	6.63	2.63	10.5	9.43
Total time=39.69+6+8=53.69						

4th pass

42	T_b	t_4	t_6	t_7	t_1	t_3	t_2	t_5
Tool		1	3	3	1	1	1	1
Direction		z	-x	-x	-z	x	x	x
Time		2.63	10.5	10.5	6.63	6.63	9.43	2.63
Total time=48.95+2*2(tool)+3*2(direction)=58.95								

43	T_b	t_4	t_6	t_7	t_3	t_1	t_2	t_5
Tool		1	3	3	1	1	1	1
Direction		z	-x	-x	x	-z	x	x
Time		2.63	10.5	10.5	6.63	6.63	9.43	2.63
Total time=48.95+2*2(tool)+4*2(direction)=60.95								

44	T_b	t_6	t_7	t_4	t_1	t_3	t_2	t_5
Tool		3	3	1	1	1	1	1
Direction		-x	-x	z	-z	x	x	x
Time		10.5	10.5	2.63	6.63	6.63	9.43	2.63
Total time=48.95+1*2(tool)+3*2(direction)=56.95								

45	T_b	t_6	t_7	t_4	t_3	t_1	t_2	t_5
Tool		3	3	1	1	1	1	1
Direction		-x	-x	z	x	-z	x	x
Time		10.5	10.5	2.63	6.63	6.63	9.43	2.63
Total time=48.95+1*2(tool)+4*2(direction)=58.95								

46	T_b	t_6	t_7	t_4	t_3	t_2	t_1	t_5
Tool		3	3	1	1	1	1	1
Direction		-x	-x	z	x	x	-z	x
Time		10.5	10.5	2.63	6.63	9.43	9.43	2.63
Total time=48.95+1*2(tool)+4*2(direction)=58.95								

As can be seen from the cost results in the 4th pass, there can be one optimal disassembly sequence with an equal minimal cost of 56.95*0.921 = 52.45

$t_b – t_6 – t_7 – t_4 – t_1 – t_3 – t_2 – t_5$

4.4 Phone handset

A Phone handset is shown in figure 37. It is used here to demonstrate again how a solution would be created using this thesis's simplified Petri Net methodology and cost function.

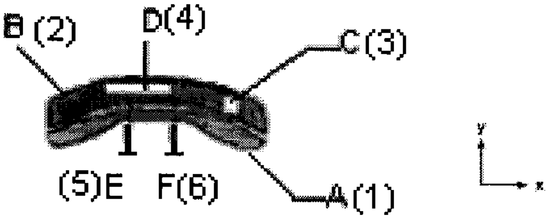


Figure 37 Phone handset

As shown in figure 37, the Phone handset has, all together, 6 parts. Part 5 and part 6 has no precedent. Part 3 is the valuable part. Parts 1 and 2 are binded by parts 5 and 6. The DPM for this phone handset is shown in figure 38.

	A(1)	B(2)	C(3)	D(4)	E(5)	F(6)
A(1)	0	0	-y	0	0	0
B(2)	0	0	y	0	0	0
C(3)	0	0	0	-y	0	0
D(4)	0	0	0	0	0	0
E(5)	1	1	0	0	0	0
F(6)	1	1	0	0	0	0

Figure 38 DPM for phone handset shown in figure 37

Referring to the DPM, the following part movements can be observed:

Row1: WRT B , A can move in the -y direction.

Row2: WRT D , B can move in the y direction.

Row3: WRT D , C can move in the -y direction.

Row4: All entries are zero because part 4 is the last part left after disassembly.

Row5: E binds A to B, so 1 in (5,1),(5,2)

Row6: E binds A to B, so 1 in (5,1),(5,2)

The types of tools used as well as basic disassembly time derived from Boothroyd's tables are shown in table 11.

Table 11 Phone handset disassembly data

t_j	Δt_j	Tool type	Disassembly Direction
tb	0		None
t1	2.8	1	-y
t2	2.8	1	y
t3	9.6	2	-y
t4	5.1	3	-y
t5	6.0	4	-y
t6	6.0	4	-y
tf	0	None	None

Petri Net Construction

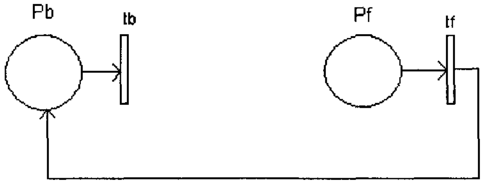
The algorithm for constructing the Petri Net as discussed in section 3.4.1 was applied to the phone handset, resulting in the table 12.

Table 12 Phone handset construction steps for Petri net

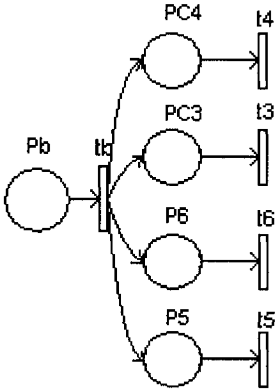
i	j	dp_{ij}	Action
1	1	$dp_{11} = 0$	
1	2	$dp_{12} = 0$	
1	3	$dp_{13} = -y$	add 1 to $OG_{3,-y}$ add $ta_{3,-y}$ to T to represent the ANDs in $OG_{3,-y}$ add pc_3 to control the ORs in $OG_{3,-y}$ add po_3 to represent completion of the ORs in $OG_{3,-y}$
1	4	$dp_{14} = 0$	
1	5	$dp_{15} = 0$	
1	6	$dp_{16} = 0$	
2	1	$dp_{21} = 0$	
2	2	$dp_{22} = 0$	
2	3	$dp_{23} = y$	add 2 to $OG_{3,y}$ add $ta_{3,y}$ to T to represent the ANDs in $OG_{3,y}$ add pc_3 to control the ORs in $OG_{3,y}$ add po_3 to represent completion of the ORs in $OG_{3,y}$
2	4	$dp_{24} = 0$	
2	5	$dp_{25} = 0$	
2	6	$dp_{26} = 0$	
3	1	$dp_{31} = 0$	
3	2	$dp_{32} = 0$	
3	3	$dp_{33} = 0$	
3	4	$dp_{34} = -y$	add 3 to $OG_{4,-y}$ add $ta_{4,-y}$ to T to represent the ANDs in $OG_{4,-y}$ add pc_4 to control the ORs in $OG_{4,-y}$ add po_4 to represent completion of the ORs in $OG_{4,-y}$
3	5	$dp_{35} = 0$	
3	6	$dp_{36} = 0$	
4	1	$dp_{41} = 0$	
4	2	$dp_{42} = 0$	
4	3	$dp_{43} = 0$	
4	4	$dp_{44} = 0$	
4	5	$dp_{45} = 0$	
4	6	$dp_{46} = 0$	
5	1	$dp_{51} = 1$	add 5 to AG_1 add p_1 to P
5	2	$dp_{52} = 1$	add 5 to AG_2 add p_2 to P
5	3	$dp_{53} = 0$	
5	4	$dp_{54} = 0$	
5	5	$dp_{55} = 0$	
5	6	$dp_{56} = 0$	
6	1	$dp_{61} = 1$	add 6 to AG_1 add p_1 to P
6	2	$dp_{62} = 1$	add 6 to AG_2 add p_2 to P
6	3	$dp_{63} = 0$	
6	4	$dp_{64} = 0$	
6	5	$dp_{65} = 0$	
6	6	$dp_{66} = 0$	

The Petri Net is finally constructed through the following steps:

1. Start with P_b, t_b, P_f, t_f.



2. Look at table of AG; link t_b to 5, 6 and add t_5, t_6.



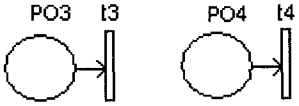
3. Again work with table of AG:

   2 is connected to 3

   3 is connected to 4

   1 is connected to 4.

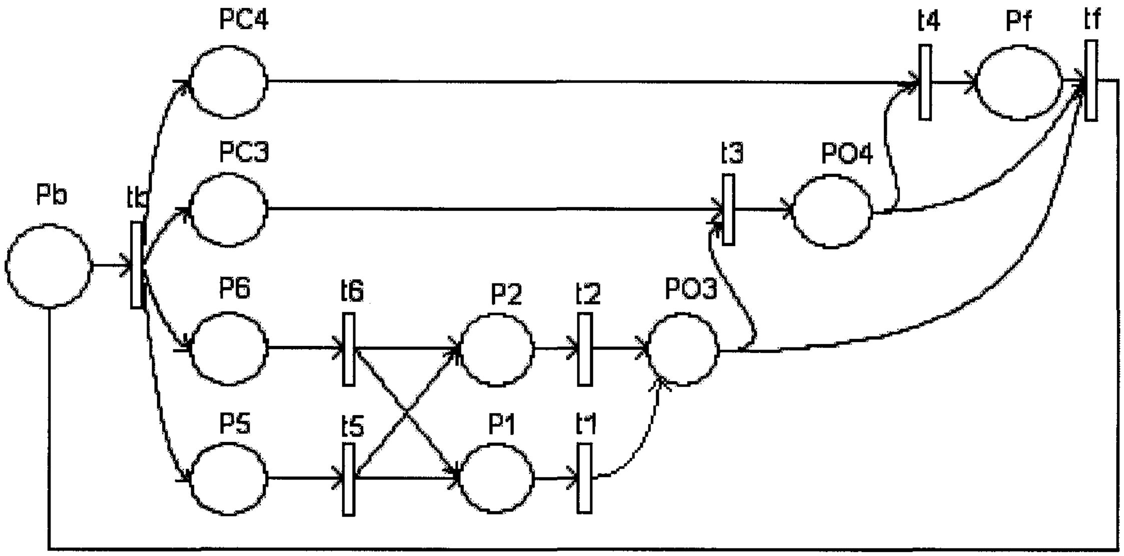
4. Add PO_3, PO_4 and link PO_3 to t_3 ; link PO_4 to t_4.



5. Link PO_3 to t_f,

   Link PO_4 to t_f.

6. Petri-Net



Basic Handling and Insertion time

Table 13 contains the details for the six transitions (or actions) of the Petri Net

Table 13 Phone handset detail for the seven transitions of the Petri net

	Dimension Metric	Manual Handling Time		Manual Insertion Time		Code Description
T1	L:200mm W:50mm	Code	0 0	Code	0 0	Parts can be grasped and manipulated by one hand without the aid of grasping tools. Part added but not secured, sasy to align and position during assembly
		Time	1.3	Time	1.5	

T2	L:200mm W:50mm	Code	0 0	Code	0 0	by one hand without the aid of grasping tools. Part added but not secured, sasy to align and position during assembly
		Time	1.3	Time	1.5	
T3	L:30mm W:30mm	Code	4 0	Code	3 4	One hand with grasping aids, parts are easy to grasp and manipulate. Part and associated tool can easily reach the desired location and the tool can be operated easily Plastic deformation immediately after insertion Resistance to insertion
		Time	3.6	Time	6.0	
T4	L:80mm W:30mm	Code	4 0	Code	0 0	One hand with grasping aids, part are easy to grasp and manipulate. Part and associated tool can easily reach the desired location and the tool can be operated easily Part added but not secured. Easy to align and position during assembly. No resistance to insertion
		Time	3.6	Time	1.5	
T5	L:10mm W:5mm			Code	3 8	Part and associated tool can easily reach the desired location and the tool can be operated easily Easy to align
				Time	6.0	
T6	L:10mm W:5mm			Code	3 8	Part and associated tool can easily reach the desired location and the tool can be operated easily Easy to align
				Time	6.0	

Cost function

As indicated in section 3.6.1, the cost function is expressed by the following formula

$$C_{q+1} = C_q + t + a\alpha_c + b\beta_c + (| H - H^r |)\delta - c\gamma$$

Where

a = number of tools used

b = number of movement direction changes

c = number of valuable parts obtained during the disassembling

	process
δ	delaying removal of part with hazardous content penalty
γ	reward for valuable part. This reward will be reduced in proportion to the time, or transition, remaining in the disassembly. The reduction is assumed to be 25% per transition.
H	set of parts containing hazardous materials, and
H^r	set of hazardous parts that have been removed.

Applying the 2-deep search strategy mentioned earlier, the cost values at each iteration or pass are determined as follows.

<u>1st pass</u>

1	t_b	t_5
Tool type		4
Remove direction		-y
Time		6.0
Total time=6.0		

2	t_b	t_6
Tool type		4
Remove direction		-y
Time		6.0
Total time=6.0		

<u>2nd pass</u>

3	t_b	t_5	t_6	t_1
Tool		4	4	1
Direction		-y	-y	-y
Time		6.0	6.0	2.8
Total time=14.80+1*2(tool)+0*2(direction)=16.80				

4	t_b	t_5	t_6	t_2
Tool		4	4	1
Direction		-y	-y	y
Time		6.0	6.0	2.8
Total time=14.80+1*2(tool)+1*2(direction)=18.80				

3rd pass

5	t_b	t_5	t_6	t_1	t_2	t_3
Tool		4	4	1	1	2
Direction		-y	-y	-y	y	-y
Time		6.0	6.0	2.8	2.8	9.6
Total time=27.20+2*2(tool)+2*2(direction)-0.75*4(recycle reward)=32.2						

6	t_b	t_5	t_6	t_1	t_3	t_2
Tool		4	4	1	2	1
Direction		-y	-y	-y	-y	y
Time		6.0	6.0	2.8	9.6	2.8
Total time=27.20+3*2(tool)+1*2(direction)-1*4(recycle reward)=31.2						

7	t_b	t_5	t_6	t_2	t_1	t_3
Tool		4	4	1	1	2
Direction		-y	-y	y	-y	-y
Time		6.0	6.0	2.8	2.8	9.6
Total time=27.20+2*2(tool)+2*2(direction)-0.75*4(recycle reward)=32.2						

8	t_b	t_5	t_6	t_2	t_3	t_1
Tool		4	4	1	2	1
Direction		-y	-y	y	-y	-y
Time		6.0	6.0	2.8	9.6	2.8
Total time=27.20+3*2(tool)+2*2(direction)-1*4(recycle reward)=33.2						

4th pass

9	T_b	t_5	t_6	t_1	t_2	t_3	t_4
Tool		4	4	1	1	2	3
Direction		-y	-y	-y	y	-y	-y
Time		6.0	6.0	2.8	2.8	9.6	5.1
Total time=32.30+3*2(tool)+2*2(direction)-0.75*4(recycle reward)=39.30							

10	T_b	t_5	t_6	t_1	t_3	t_2	t_4
Tool		4	4	1	2	1	3
Direction		-y	-y	-y	-y	y	-y
Time		6.0	6.0	2.8	9.6	2.8	5.1
Total time=32.30+4*2(tool)+2*2(direction)-1*4(recycle reward)=40.30							

11	T_b	t_5	t_6	t_2	t_1	t_3	t_4
Tool		4	4	1	1	2	3
Direction		-y	-y	y	-y	-y	-y
Time		6.0	6.0	2.8	2.8	9.6	5.1
Total time=32.30+3*2(tool)+2*2(direction)-0.75*4(recycle reward)=39.3							

12	T_b	t_5	t_6	t_2	t_3	t_1	t_4
Tool		4	4	1	2	1	3
Direction		-y	-y	y	-y	-y	-y
Time		6.0	6.0	2.8	9.6	2.8	5.1
Total time=32.30+4*2(tool)+2*2(direction)-1*4(recycle reward)=40.30							

As can be seen from the cost results in the 4th pass, there can be two optimal disassembly sequences with an equal minimal cost of 39.30*0.921 = 36.19

(a) $t_b - t_5 - t_6 - t_1 - t_2 - t_3 - t_4$

(b) $t_b - t_5 - t_6 - t_2 - t_1 - t_3 - t_4$

CHAPTER 5

CONCLUSION

The disassembly method advocated in this thesis requires the analysis of the product part features and design features to determine each part's disassembly time. A Petri net is the ultimate tool used to determine the disassembly sequence. It was shown that, by adopting the strategy of disassembly sequence presented in this thesis, a near optimal or optimal disassembly sequence could be obtained. The two major problems complicating the disassembly plans are a product with a large number of parts, and part classification. Mostly, our disassembly sequence strategy targets simple products.

In this thesis, the depth of search is assumed to be 2- transition deep, and at each iteration, three alternatives are involved. One reason for adopting such a strategy is to limit the extent of the search algorithm. A major concern in generating the disassembly sequence and evaluating the disassembly time is the number of parts in the product, tool changes, disassembly direction changes, hazardous parts, reusable parts, and part symmetry. The results from this thesis clearly demonstrate that, to obtain minimum disassembly time, there should be very few tool changes, very few disassembly direction changes, the earliest possible removal of hazardous parts, and retaining reusable parts.

In future work, a product with a larger number of components should be investigated. Also a different depth of search should be attempted. Furthermore, the cost function could be extended to include other parameters to represent the impacts of reusable materials or parts destined for landfill or incineration. Automated robotic disassembly for complicated products or hazardous products should also be investigated.

We envision that these changes or adjustments can further reduce wasted materials and contribute to a sustainable environment.

CHAPTER 6

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