ABSTRACT

SYSTEM SIMULATION AND MODELING OF ELECTRONICS DEMANUFACTURING FACILITIES

by
Ketan Giridhar Limaye

Over the last decade, pressure on the electronic industry has been increasing as concerns for product take-back, product stewardship and global warming have continued to grow. Various end-of-life management options are being expanded including recycling to recapture values from basic materials through reengineering and recovery of subassemblies and individual components for remanufacturing. While progress has been reported on life cycle assessment (LCA), disassembly planning, design for disassembly, and design for environment (DFE), very little research has been focused on demanufacturing from a systems perspective.

The objective of this thesis is to build an interface between the user who knows the demanufacturing operation and a software engine, which performs the simulation, collects detailed operational data, and displays results. This thesis bridges the gap between the requirement of hard core simulation knowledge and demanufacturing terminology to present a computerized software tool.

Arena, a commercially available discrete event simulation software, acts as an engine for performing these simulations. The developed software tool for demanufacturing contains objects necessary for facility layout, systematic workflow and simulation of the facility. Each object refers to a specific demanufacturing activity and uses detailed simulation logic behind its design to perform that activity. The user selects and locates these objects

to layout the facility for a graphical representation of the demanufacturing operation. Objects provide a user screen to input necessary data for the complete description of the activity and its operational characteristics.

By simulating the facility for various scenarios, the demanufacturer can compare different options for improving operations, resource utilization, equipment and layout changes. To examine improvement options from an economic perspective a first-order model of demanufacturing costs has been developed and integrated with the simulation software. An activity based unit cost model is used to identify fixed and variable costs associated with each product demanufactured. A small electronics demanufacturing facility was observed and evaluated to validate the simulation modeling and operational logic.

The application illustrates the usefulness of demanufacturing system simulation tool to manage and improve the overall efficiency of facilities for economical operation. In summary, a computer-base tool for simulating demanufacturing facility from a systems perspective has been developed and validated. An activity based cost model has been integrated with the simulation to give demanufacturers the ability to examine the full operational and economic trade-offs associated with the business.

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Ketan Giridhar Limaye

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APPROVAL PAGE

SYSTEM SIMULATION AND MODELING
OF
ELECTRONICS DEMANUFACTURING FACILITIES

Ketan Giridhar Limaye

Dr. Reggie J. Caudill, Thesis Advisor — Date
Professor of Industrial and Manufacturing Engineering, NJIT.

Dr. Raj Sodhi, Committee Member — Date
Associate Professor of Mechanical Engineering, NJIT.

Dr. Sanchoy Das, Committee Member — Date
Associate Professor of Industrial and Manufacturing Engineering, NJIT.

BIOGRAPHICAL SKETCH

Author: Ketan Giridhar Limaye

Degree: Master of Science

Date: January, 1999

Undergraduate and Graduate Education

- Master of Science in Mechanical Engineering,
  New Jersey Institute of Technology, Newark, NJ, 1999.

- Bachelor of Engineering in Mechanical Engineering,
  College of Engineering and Technology, University of Pune, Pune, India, 1996.

Major: Mechanical Engineering

This thesis is dedicated to my

beloved parents and other family members

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2.2.2 Necessity of Newer Version of Simulation Softwares

The primary reasons for enhancing simulation software are to achieve the following basic functions:

- Flexible and easy programming language for generating complex algorithms..
- The timing control mechanism, which maintains the list of events about to occur and initiates/terminates activities.
- A database or file structure. The structure provides ease of accessibility to the stored items.
- Easy implementation of initial conditions, random number generators, sample distributions and the standard formats for analysis and printing of simulation results.
- Sophisticated graphical interaction for presentation of results in form of graphs and charts and better error-handling algorithms.
- An animated scene of the modeled system for better understanding of real time status of the parameters of the system and information on their states.

2.3 Simulations in Manufacturing System

2.3.1 Introduction

The increasing competition in many industrial sectors has emphasized automation to improve productivity, quality and also to reduce costs. Since the automated systems are more complex, they can typically be analyzed only by simulation [11]. Reduction in computing costs by microcomputers and engineering workstations have spurred more use of sophisticated simulation softwares. The availability of animation features has provided enhanced visions for better understanding and ease of use by engineers. The overall benefit of using simulation in a manufacturing is a system-wide view of the "local" changes to the manufacturing operations [14, 20].

Every manufacturing system exhibits much the same characteristics, although differing in details. Because of this similarity, simulation models of these systems have more common features. The differences between them will reflect the different ways in which facilities use them to form a particular system [10].

2.3.2 Potential Benefits

In addition to costs savings by simulating and evaluating various process alternatives and operational strategies, a number of specific potential benefits from simulation are listed below [14,20, 21]:

- Increased throughput (parts produced/demanufactured per unit of time)
- Reduced in-process inventories of parts/products
- Increased utilization of machines or workers
- Increased delivery commitments
- Reduced capital requirements or operating expenses
- A higher level of confidence in proposed designs or operational strategies
- Better understanding of the system behavior under different "what if" scenarios

A number of manufacturing issues has been addressed by simulation. The need for and quantity of equipments and operators, layout configuration, performance of the operating variables in terms of percent time utilization and evaluation of operational procedures in terms of scheduling, control strategies and quality control policies are few categories of manufacturing issues [10, 20 and 21].

The simulation results often presents properties and variables as time persistent. According to Averill Law [14], some of the performance measures are listed below

- Throughput
- Time in system for parts/products
- Queue statistics
- Times parts/products spend in transport
- Percent utilization of resources
- Sizes of in-process inventories

2.3.3 Summary to Manufacturing Problems Analyzed by Simulation Techniques

With knowledge of potential benefits, researchers and analysts have approached real world problems ranging from evaluating process flows, operational strategies, equipment changes and facility layouts in various types of systems from manufacturing automobiles to operating fast food restaurants. The objective of manufacturing system simulations is to minimize cost, while improving operational efficiencies.

Flexible Manufacturing Systems (FMS) require a detailed study to optimize design and performance. A shop floor control system (SFCS) is responsible for implementing processing routes and material handling operations and scheduling of processing parts through the system. Simulation tools, have not only analyze and evaluate SFCS in flexible manufacturing system, but also developed a task generator for the specification of control tasks. Smith, Sturrock, Ramaswamy et al. (1994) present a RAPIDCIM approach of combining two traditional steps (simulation of system design for finalization and development of control system for implementation in FMS) of process improvement reducing the development cost [23]. Falkner and Garlid (1986) used a GPSS simulation model to evaluate performance of a FMS at three different lifecycle stages and economic analysis for justification of simulation technique [21]. Mills supports the simulation approach that provides dynamic insight into FMS [10]. The comparison and evaluation of different alternatives builds confidence at all levels. Mills pointed out future possibilities of incorporating dynamic graphical capabilities, user friendly Graphical User Interface (GUI) and a change in methodology of structuring the model for incorporating the scheduling and control logic as a separate algorithm. Warnecke, Steinhilper and Zeh, also utilize a simulation approach for planning and designing control strategies [20]. A controller regulates the interaction between different transportation and manufacturing stations and inspection machines. Chan and Pak point out the need for separate controller simulation software for simulating a FMS and analyzing the interactions in a simulated system [20].

Simulations have also used to develop models for describing manual loads that can be effectively used in manual disassembly systems. Ehrhardt, Herper and Gebhardt undertook a project, which evaluates the strain on a worker as a result of assigned workload and environmental conditions around the work place [24]. 95 % of the simulation studies have addressed the problems on capacity analysis, operator requirement analysis, material handling design and analysis, process improvement and automation feasibility, machine and equipment selection, secondary resource requirement analysis and inventory analysis [25].

Kiran et al. has observed the benefits of simulation during simulation of a medical manufacturing factory for operational changes. They observed that the simulation provides a global view of the entire situation, dynamic graphics provide better visualization and scoreboard of measurement of performance criteria. Simulations have also been used to compare different factory designs for different manufacturing units by quantitatively measuring each criterion affecting the designs [26] and used to help in designing and modifying control procedures in manufacturing systems. Simulations have analyzed the scheduling methods for minimizing the work in progress and operational cost, distribute the workload and provide on time delivery in manufacturing systems [21]. Siegal has simulated two different product types to evaluate the scheduling rules for effective scheduling [21].

2.4 Current Research in Demanufacturing and Disassembly

The literature presented in this section is divided into three categories: Design for disassembly, disassembly process planning and implementation of demanufacturing and disassembly systems.

1. *Design for Disassembly*: After conceptual product design is ready, it is tested using available disassembly tools to evaluate the performance of design from disassembly perspective. It assumes the level of disassembly for a product to maximize value recovered, which depends up on cost and effort of disassembly activity. The process is continued until qualitative improvement is achieved. While dealing with designing for disassembly, aim is to provide disassembly information through the product

design. The designers target their attention towards the following aspects for achieving effective disassembly performance:

- Logical grouping of components into subassemblies: The task is to separate valued and non-valued components. While Simon et al. has addressed economics of disassembly, algorithms developed by Subramani and Dewhurst (1991) facilitate generation for disassembly sequence [27].
- Planning of disassembly for easy accessibility to high valued components and subassemblies. Considerations have also been given for reducing waste awkward movements during disassembly and logical structure to speed up the disassembly. Kroll et al. have suggested a rating scheme that allows creation of quantitative scores to design properties to identify weakness in design and comparing alternatives [48]. Lambert has presented a method for evaluating disassembly sequence by improving economic performance of the disassembly process given technical and environmental constraints [28].
- Using compatible materials such that they can be recovered together and limiting material variability with provision of some code to easily identify different materials in a product. Various guidelines have been suggested to simplify the disassembly process and reduce disassembly time. Tracy Dowie and Mathew Siman have suggested guidelines that can influence the materials and components recovery [29].
- More standardization of fasteners and using only those fasteners, which are easy to disassembly or destroy.

In addition to design for assembly, consideration for disassembly provides the following advantages to demanufacturing systems

- Standardization in disassembly operations improving operational efficiency.
- Reduction in disassembly times reducing the disassembly cost.
- More uniformity of product configuration providing increased throughput of the demanufacturing facility.
- Minimization of manual/automated material handling systems reducing effective transfer times. Longer transfer times incur higher costs and lower operational efficiency.

2. *Disassembly Processes Planning*: The research deals with the revenue generated by recovery of specific materials or groups of materials, components, subassemblies or the entire product. Ishii and Lee have suggested a reverse fishbone diagram for presenting the disassembly sequence for a discarded product [49]. Figure 2.3 shows information for disassembly. The disassembly sequence depends on two specific information areas: product and use. Jovan et al. missed out market value, which is also important aspect required for disassembly [4]. The demanufacturing receives information about the structure of the product, potential recovery value and available techniques. Structural criteria deals with aging, wear, damage, toxicity and value that can be recovered from the product structure.

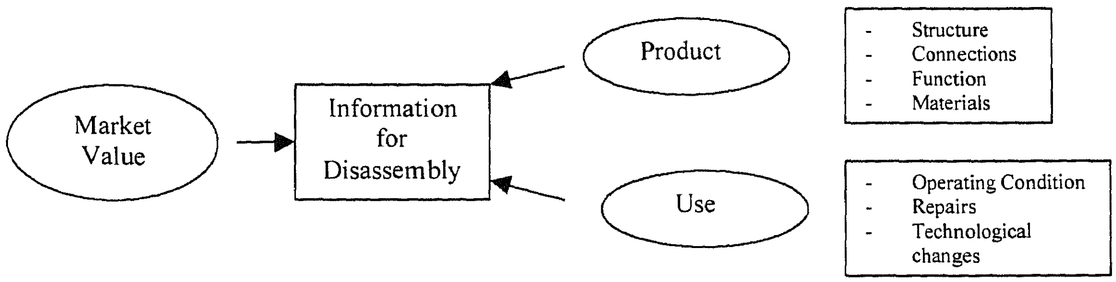


Figure 2.2 Information for Disassembly
[Source 4]

In Sweden at Assembly Technology, Linköpings University a project was undertaken by Dr. Mats Bjökman to identify and study parameters controlling the disassembly system designs [30]. Material composition provides information on recyclablity content and component function information checks for possible reuse or remanufacturing options. In the entire life cycle of a product, the inspection at demanufacturing facility provides information on operational condition when disposed and amount of repairs done. Technological changes provide information on the obsolescence period from manufacturing date. This data would also help for possible upgrade options by remanufacturing components or subassemblies. This demanufacturing process development knowledge serves as a database for next-generation products and their applications. The database will hold information about the product and its use stage. With the database at the back, demanufacturing strategies for increasing value recoveries and benefits in balance with the costs of operations can be developed for more complex product structures [27].

3. *Implementation of Disassembly and Demanufacturing Systems*: Disassembly system, a part of demanufacturing system, should be feasible with respect to criteria on cost, energy use and environmental burden [4]. Economic feasibility requires that within

given rules and regulations, agreements and licenses, the total value of recovery should be as high as possible. The energy use implies that the energy conservation potential of the recovery process obtained by reducing use of virgin materials with the second generation and reduction in waste should be larger than energy requirements of recovery process [28]. The total amount of harmful waste should decrease with increase in selective disassembly strategies and thereby reducing environmental burden.

After an extensive research on disassembly environment, Jovane et. al suggest future research should concentrate on demanufacturing system design and developing detail methodologies for [4]

- Configuration of manual and automated disassembly facilities
- Economic justification of designed disassembly systems and operational strategies
- Organization of a logistic network for various recovery options

The thesis in deed focuses on these research areas and advances the work through development of a simulation tool for evaluating facility layout changes, operational strategies and configuration of resources.

The reported specific development in demanufacturing systems area for overall An automated cell for disassembly is comprised of industrial robots with a cell control unit for robot subroutines and identification of product features. The robot magazine incorporates flexible disassembly tools and disassembly fixtures; sensors for process control and reaction to uncertainty to product configuration. An efficient material handling system for moving disassembled parts towards collection or dispatching sites. IWF, Berlin is planning to set up such a disassembly cell. In London, Intelligent Systems and Robotics Center (ISRC) and Explosive subsystems & Materials Development at Sandia National Laboratories have developed a robotic work cell for automated disassembly of a gas generator [5]. In Japan, Tokyu Corporation has developed a flexible robot cell for disassembling valves of air brake equipment [4]. In Japan, there are automated facilities for disassembling and recovering basic materials from discarded TV's refrigerators, washing machines and air conditioners. Sony corporation in Japan have established automated disassembly line for CRTs [50], while Siemens is working on design of flexible fixtures for manual and automated disassembly [4].

Cost models have been developed for analyzing the disassembly cost for evaluating disassembly strategy [31], which includes reclamation value, disassembly cost and disposal cost [27].

CHAPTER 3

DEMANUFACTURING SYSTEM SIMULATION TOOL DEVELOPMENT

3.1 Introduction to Demanufacturing System

Corporate strategy describes the long-term goals of the company. A growing concern about the environment and potentials of product take back has spurred corporations to extended stewardship to include asset recovery from discarded products.

The traditional LCA framework considers all life cycle stages of a product from raw material extraction and synthesis to its final disposal. The Multi-lifecycle approach enhances recovery and use of disposed products and waste streams through multiple cycles [3]. Figure 3.1 shows the integration of the various stages a product follows through its life cycle. These stages are as follows:

1. Raw material Extraction
2. Material Synthesis: includes both virgin and reengineered materials
3. Production
4. Distribution
5. Use
6. Demanufacturing: Initial stage of value recovery
7. Remanufacturing, reengineering and reuse: Initial stages of next generation life cycle.

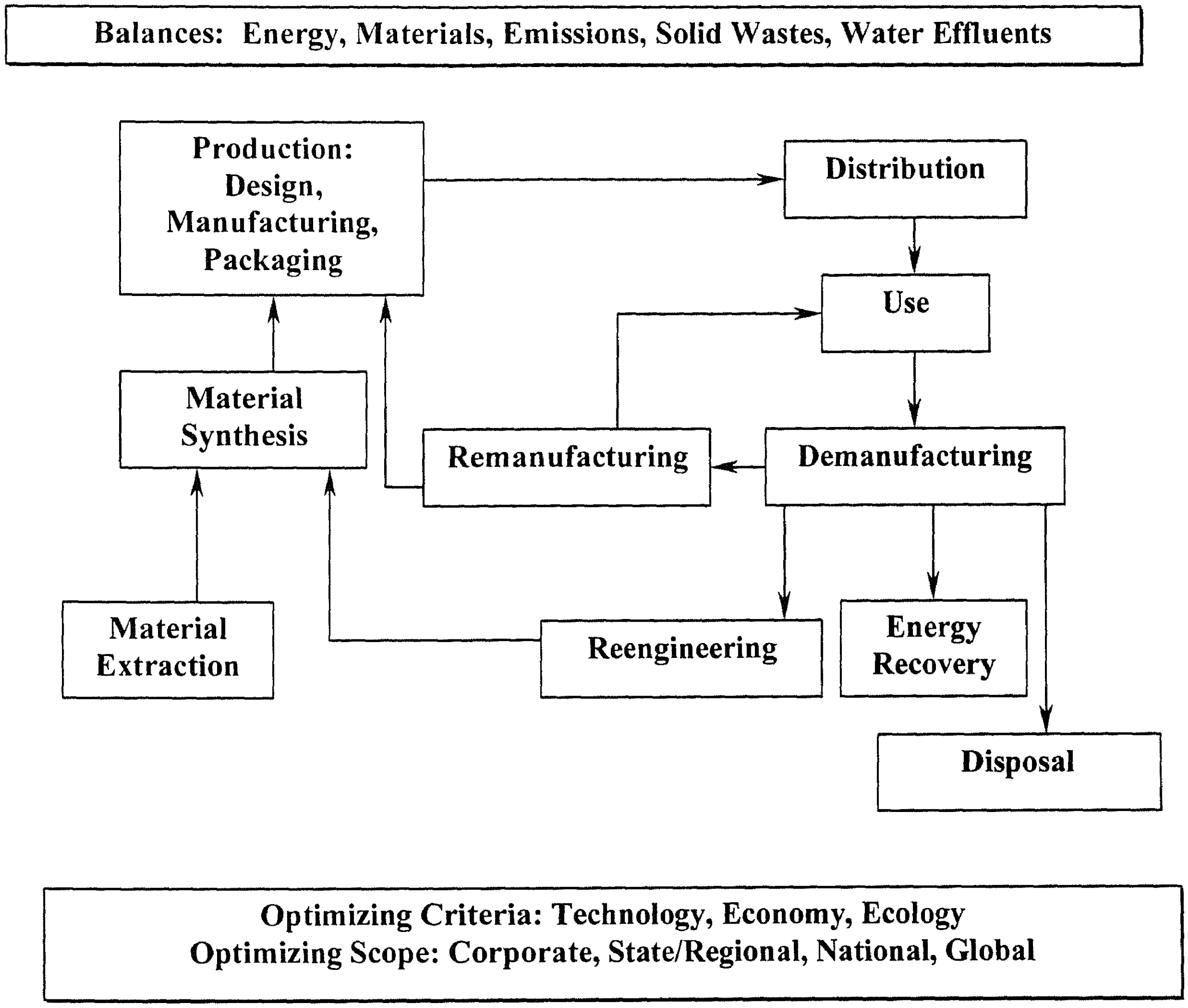


Figure 3.1 Total Lifecycle Considerations for Analysis and Modeling [Source 3]

The demanufacturing stage includes all the methods for recovery options as a common activity. This structure includes all the major processes, through which discarded product go to recover the valuable components, subassemblies and basic materials. The flow of typical discarded products includes three major areas: collection system bringing batches of discarded products to the demanufacturing facility, demanufacturing activity recovers values as outputs of the demanufacturing activity. The external transportation system used for collection of discarded product and subsequent distribution of recovered

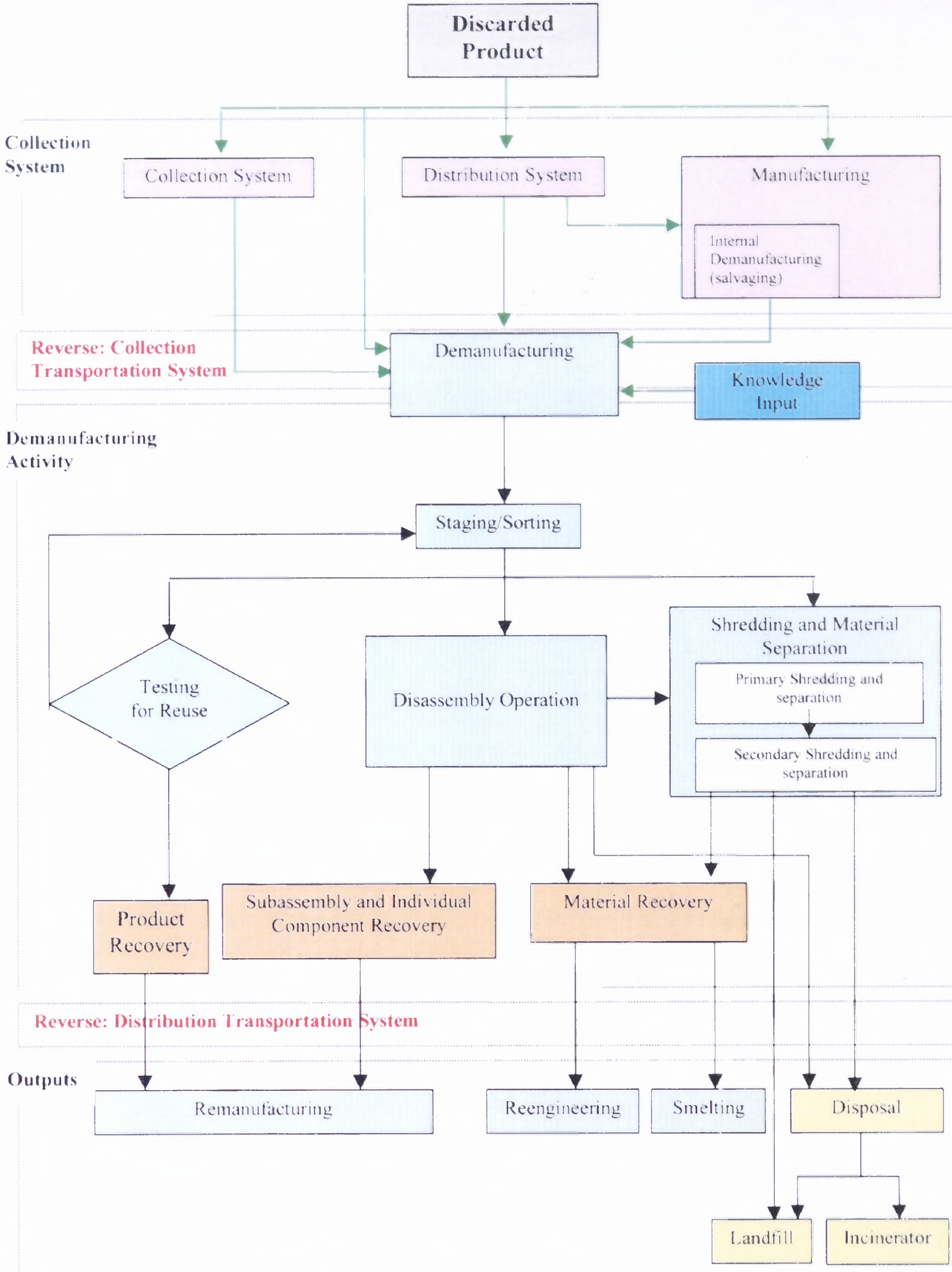


Figure 3.2 Generic Model for Demanufacturing

materials/components is considered as a sub-system of demanufacturing model. Above figure 3.2 is a flow diagram illustrating the basic operation of the overall demanufacturing process.

Collection System:

Discarded products and materials are transported to the demanufacturer from a variety of sources, including distributors, manufacturers and municipal collection systems. Sometimes, the manufacturers remove the proprietary components and liabilities information associated with the product before sending the remaining product to a demanufacturer for further disintegration and value recovery. This activity is identified as internal demanufacturing or salvaging.

Because of the toxic releases from the exhaust and consumption of non-renewable resources like gasoline, oil and diesel, the impacts associated with transportation associated with either collection or distribution system, are attributable to product from a LCA perspective. Therefore, the transportation, central to reverse logistic and collecting is considered as a separate activity in the demanufacturing system. The impacts from transportation are dependent on the amount of distance traveled, the mode of transport used and specific consumption of fuel used. Since collection is performed primarily by truck, a truck transportation model is developed and presented in section 3.2 and Appendix A, B, C and D

Demanufacturing Activity:

Upon receipt, the products are sent to storage area, where demanufacturer performs a preliminary screening to determine if the product is to be tested for reuse, disassembled or directly sent to the shredder. Depending on the product, its condition, and current market demand of parts and basic materials, the demanufacturer establishes a disassembly plan to maximize value to be recovered. This value may be to resale or remanufacture the product; recover parts, components and subassemblies; recover basic materials for recycling and reengineering; or, send commingled materials to a smelter to recover high-valued constituents. The knowledge serves as an input to reduce disassembly effort and maximize the value recovered. The individual activities and components of the demanufacturing process are discussed in the next few paragraphs.

Knowledge Input:

Knowledge provides a logical input required for the demanufacturing activity. The input serves as a database for products coming into facility containing the following information about the products

- Product type, make and disassembly procedure
- Current market demands and prices of basic materials, individual components and subassemblies
- Recyclablity of materials that compose a product
- A listing of recyclable, reengineerable or remanufacturable components and materials
- Record of disassembly timings and list of disassembly criteria for various products
- Library on disassembly techniques from past disassembly experiences

- Knowledge information for cost of demanufacturing operation: Total cost includes procurement cost (if any), carry costs and cost associated with the value added at each step in the reclamation process. These cost may vary with type of demanufacturing process used and the amount of knowledge input on specific product and processes. Lead-time deals with total time needed to process or acquire an item. It includes inspection time, wait and queue time, move times or procurement times.

Staging and Sorting:

The staging and sorting operation is considered as a front-end shop control activity. Uncontrolled variability is introduced into the front-end of process because the actual quantity of products and product types entering the demanufacturing system (disassembly activity) can not be determined until after the products have been accepted and thoroughly inspected. Also, there are three critical attributes adhere to parts/products. Those are total cost of the recovery process, lead-time and variability [32]. Variability is associated to short term fluctuation that occurs in the scrap rate associated with an item. Scrappage of item can occur at any time prior to its inclusion into demanufacturer's inventory. Variability is introduced, however, when items come from different sources.

Sorting is an operation that determines fate of inspected parts performs following basic function:

- Sorting of products depending upon product type and condition
- Formulation of batches depending upon the disassembly process plan
- Staging of batches according to their fate category

Each facility has predetermined guidelines on the quality and quality selection for reuse remanufacture or recycling of products. At first the products in poor condition are separated and batches are formed for potential shredding and separation processing for recovery of basic materials. The separation and staging of products is a key decision for disassembly operation affecting the overall disassembly time, throughput and eventually the profit gained by the firm. For example batches of products of same disassembly families provide faster disassembly and lower set up and material-handling time by keeping tooling and workstation setup and sizes of bins fixed.

Inspection and Testing:

Selected products before going to disassembly are tested for their potential reusability, since the maximum recovery value is reuse. The products/parts found to be in working order are sent for resale or to remanufacturers to be repaired (upgrade) and then resold. Some products may be sent directly to the shredder because of poor condition observed during first hand inspection and testing. Because the probability of a particular item being defective is not deterministic, one can only approximate the likelihood of serviceable products, which can be resold. This estimate can be more accurate when all of the products in question come from the same source. Products coming into the facility from different sources introduce variability in terms of product condition, product types, and quantity of different product types.

The inspection helps to detect wear or assess the condition of parts subject to wear [33]. Inspection identifies fitness of components for further use or calculates degree of wear. The process should detect as easily and clearly as possible. This may involves visual check as well as instrumental or functional tests.

Disassembly Operation:

Disassembly is the recovery of materials and subassemblies by separating components in a somewhat reverse assembly order [33]. Time and easiness or efforts for disassembling are key variables to earn or loose money. For efficient disassembly key issues include use of minimum number of tools, a product design for easy accessibility to high valued components, avoid complex fasteners and glued parts, limit direction of disassembly, a clear disassembly plan to recover maximum value and proper scheduling. The level of disassembly is decided by the recoverable value embedded in the product and varies with the product and its condition. The operation can be performed to recover an individual component, a subassembly or specific material. For example if the component is a circuit board then it is sent to shredder for recovery of metals like copper and gold. The shredded impure metals containing non-metal impurities are sent to smelter for recovery of pure metal. The plastic components may be sorted by polymer type or left commingled are sent for recycling/reengineering or for energy recovery.

Figure 3.3 shows the relationship between disassembly depth and recovery options in terms of value if the product follows the disassembly sequence up to basic material recovery. Disposal is not included in the figure because it is an independent activity that can occur at any time during disassembly process. As the recovery process can be considered as an entry point for the recovered materials in life cycle stages.

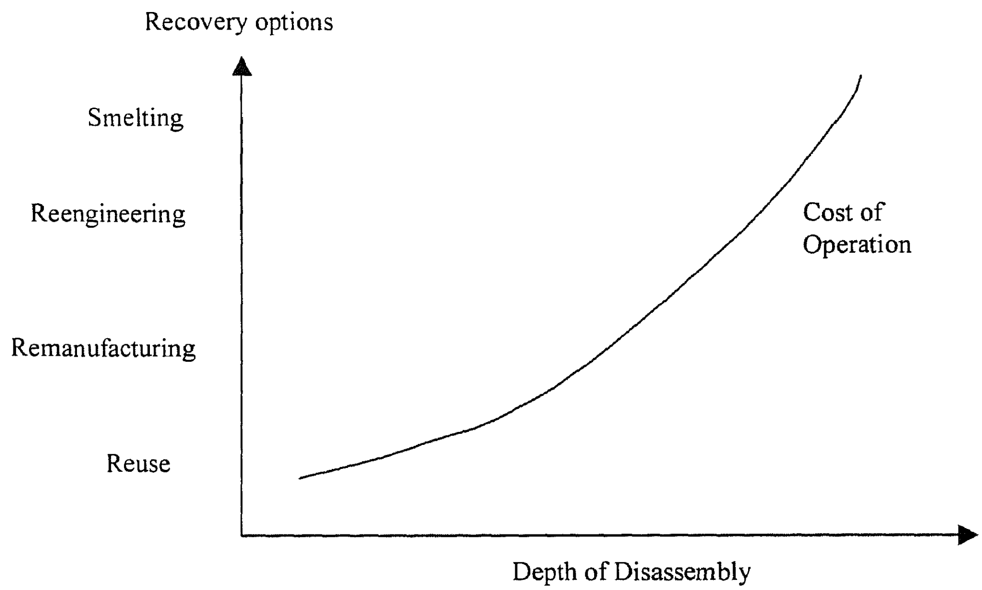


Figure 3.3 Recoverable Value for levels of Disassembly

The remanufacturing option introduces the recovered parts and subassemblies at the production stage, where as the reengineering and smelting option tracks the reverse loop up to material synthesis phase. Smelting operation can be considered as disassembly of product up to molecular level. As observed from the figure 3.3,the disassembly planning and knowledge input in the demanufacturing activity can be can help reducing unnecessary costs by eliminating unnecessary disassembly operations. The minimum disassembly is attributable to maximum value depending upon the product configuration, condition and good disassembly planning.

Shredding and Separation:

A shredder is a machine primarily used for volume reduction, scrap preprocessing, pre-incineration processing and management of hazardous waste. The volume reduction facilitates handling, increases the density and lowers hauling cost. The incineration pre-processing helps material handling, fuel blending and incinerator feed issues. For shredding of electronics scrap and plastics a medium speed shredder is used [34]. A typical shredder is composed of an infeed conveyor, a feeding device and shredding mechanism operated by electrical motor system. Different separation technologies depending upon the material composites of shredded input stream are electromagnetic separation of ferrous from non-ferrous materials, eddy current separation for aluminum, brass and copper. Electrostatic separation for materials based on differences in surface conductivity, preferential charging and attraction of materials to an electric field of opposite charge and gravity separation specific gravity property to separate non-ferrous metals [35].

In the demanufacturing model the input material for shredding comes from the disassembly station and the testing and inspection area. The shredding operation can be considered as a two-stage process. During the first stage, materials like aluminum, steel and waste are separated and in the second stage copper and plastics are separated out [36]. The remaining residue (fluff) is sent for disposal.

Products from demanufacturing model:

The output of the demanufacturing process is identified according to next generation use recovered materials. The options are reuse, remanufacturing, reengineering and smelting with the residue of the disassembly and recovery options going to disposal. The following describes each of these categories.

Reuse:

Reuse is the highest form of waste reduction and value recovery option. The option is justified for the serviceable products with high manufacturing cost, long innovation cycles and long life times [33]. For electronics goods with short life cycles and lacking upgradability, reuse may be difficult. The lack of information on residual lifetime of the recovered components/products, variable market demands and technological advancement reduces possibility of the reuse option. However, when possible reuse is the best option.

Remanufacturing/refurbishing:

Remanufacturing is a process, in which reasonably large quantities of similar products are brought into a central facility, disassembled repaired/upgrade sent for resale. Sorted are then kept together by part types and also identified for their fate. Parts to be remanufactured are kept together by their types, which are further cleaned, inspected for possible type of repair and reuse. Remanufactured parts are then reassembled usually on an assembly line basis where they are integrated with new products to build a finished product meeting quality good of required specification [37]. Sometimes, the process also involves use of technical knowledge input, adding or removal of metal or physical modification of material being processed or refurbished. Up on inspection the defected parts are replaced with either new parts or remanufactured parts. A product receives a new warranty after remanufacturing and a limited warranty after refurbishing or rebuilding [38].

Reengineering:

Reengineering is the reformation or recycling of a recovered material [3]. Reengineering is an activity, which not only recovers the material value but also maintains a database of characteristics, process information for knowledge input during design analysis and synthesis. Following are six different reengineering processes for material recovery:

- Reprocessing
- Smelting
- Compatiblization
- Pyrolysis to fuels
- Pyrolysis to monomers
- Shredding

It addresses the issues of material flows, environmental burdens, energy requirements, additional process materials and cost of processes.

Smelting:

Smelting is any process of melting or fusion, especially to extract a metal. The impure metal (recovered from shredding and separation operation) is mixed along with the impure metal at the smelting facility. The mixture is processed by respective smelting process to produce pure metal. Processes vary depending on the ore and metal involved, but they are typified by the use of the blast furnace and the reverberatory furnace [39].

Metals and plastics are the most common materials used in consumer electronics product. Metals are recovered by electromechanical reduction, in which a direct current is applied between electrodes immersed in wastewater [35]. As with plastics a major problem in metal recycling is the purity of metal. Non metal impurities alter characteristic properties of the metal composition.

Disposal:

In most demanufacturing activities, small amounts of residue (or fluff) must be sent to disposal in a landfill or incineration unit.

Incineration:

Incineration is the process of thermally reducing the volume of solid waste, while producing inoffensive gases and sterilized residue, by application of combustion process [40]. To reduce the bulk of solid waste, burning of paper, plastic and other organic components is often resorted to either in open dumps or incinerators. It can effectively handle combustible solids, semi-solids, sludge and concentrated liquid waste. Heat is recovered from incinerators by generating steam. Plastics, wax papers and rubber have high heat heating units between 10000 and 19500 BTU per pound [41] and food waste, grass clipping have low heat content. In incineration process fly ash, noxious gases, and chemical contaminants may be released into the air. However, new techniques for "scrubbing" pollutants from incinerator stacks are being developed. Incineration of typical garbage reduces its weight and volume by as much as 80% [42]. In the Europe incineration is perceived as form of last resort but not in the US.

The heat from the incinerator generates steam in a boiler, producing as much as 100 megawatts of electricity [40]. A high stack, fan, or steam jet supplied from the boiler supplies a draft. Ash drops through the grate, but many particles are carried along with the hot gases. These particles and volatile gases are burned in a combustion chamber fed by several furnaces. In order to control air pollution, the remaining gases are further treated, with acid gas scrubbers to control sulfuric and nitric acid emissions, and bag houses to remove all remaining dust particles, before they are released into the environment. Objectives of total incineration [43]:

- Maximum volume reduction
- Complete combustion or oxidation of all combustible materials producing sterile, slid, compact and dense slag
- Reduction in residue disposal activity adjacent to incinerator
- Complete oxidation of gaseous products of incineration with air pollution control before release into atmosphere

Landfill:

Traditionally solid and semisolid industrial residues are landfilled. These landfills are covered with thick layer of soil to minimize odor and dispersion of debris. The leaching of various undesirable contaminants degrade surface and sub-surface water supplies [44]. Another potential problem is trapping of gases such as methane, hydrogen sulfide during the decomposition of the landfill refuse. Plastics, which are not biodegradable, pose another problem for landfilling resulting accumulation in landfill areas. This may lead to uneven landfill settling and final compacted properties, and reduce the bearing load for subsequent structures to be constructed on the completed site [43].

Following are three different types of landfilling techniques [3]:

- Area fill: A large surface area is filled with alternate layers of 40 to 70 cm in height of compacted garbage and 15 cm of cover materials.
- Trench fill: In this type waste is compacted in a trench below ground level until the desired height is achieved. This type is suitable for small volumes of garbage.
- Modified area fill: In this type a compacted cell of waste and cover material is may be excavated below ground level

3.1.1 Truck Transportation Model

Transport is a vital element and represents a significant fraction of the total processing cost, energy and environmental burden of demanufacturing. There are three main contributions associated with transportation energy for discarded product collection and recovered products distribution [37, 45]:

1. Energy embedded in the fuels consumed directly by the vehicle together with the associated production energy. This is usually directly proportional to distance traveled, although it may be affected by factors such as loading, type of journey, age of vehicle and level of maintenance.
2. The energy needed to construct and maintain the vehicles, including contributions from tires.
3. Third is the energy needed to provide facilities for the vehicle to carry out its journey, which includes construction and maintenance of roads and garage facilities.

Only transportation by truck is considered in this thesis. Trucks are available in various sizes ranging from small gasoline driven pick-ups to large articulated trucks with gross weights in excess of 32 ton. A transportation model is developed and presented in Appendix A

The Direct Energy of Fuel (DEF) in terms of kWh/mile can be expressed keeping the structure of equation (1) same as follows:

$$\text{DEF} = \frac{1}{\text{Fuel Efficiency}} * \left[\frac{2}{3} + \left(\frac{1}{3} * \text{Load Ratio}\right) + \frac{2\ (\text{for Empty}}{3\ \ \text{Return})}\right] * \frac{\text{Truck Tare Weight}}{\text{Actual Load}} * \text{Energy Content of Fuel} \quad (3.2)$$

Therefore,

Total Transportation Energy = 1.43 * DEF

$$= \frac{\mathbf{1.43}}{\text{Actual Load}} \left(\frac{1}{\text{Fuel Efficiency}} * \left[\frac{2}{3} + \left(\frac{1}{3} * \text{Load Ratio}\right) + \frac{2\ (\text{for Empty}}{3\ \ \text{Return})}\right] * \frac{\text{Truck Tare Weight}}{\text{Actual Load}} * \text{Energy Content of Fuel} \right) \quad (3.3)$$

This is the transportation energy in kWh per mile per pound of product transported.

Emissions from transportation

Emissions from the transportation are divided into two groups:

1. Fixed Emissions: Due to the tare weight truck.
2. Variable Emissions: Depend on the actual load carried by the truck.

The total emission from each category is the summation of fixed and variable emissions. Keeping the same assumption for the tare weight of trucks, fixed emissions are calculated. Variable emissions are calculated on the basis of the actual load being transported by the truck and so they are the function of weight of product, which can be calculated as a product of individual weight to total number of products being carried. Table 3.6 presents emissions summary for three different truck types

Table 3.1 Emissions summary
[Source: 46, Page 40]

Emissions	**Light Truck**		**Medium Truck**		**Large Truck**	
$* 10^{-3}$ lb. per mile	**Fixed**	**Variable**	**Fixed**	**Variable**	**Fixed**	**Variable**
Solid						
Solid	1.02	0.2 * LOAD	1.9	0.2 * LOAD	3.0	0.2 * LOAD
Air						
Particulate	3.57	0.7* LOAD	6.65	0.7* LOAD	10.5	0.7* LOAD
Hydrocarbons	8.21	1.61* LOAD	15.29	1.61* LOAD	24.15	1.61* LOAD
CO	34.94	6.85* LOAD	65.08	6.85* LOAD	102.75	6.85* LOAD
NO_2	8.26	1.62* LOAD	15.39	1.62* LOAD	24.3	1.62* LOAD
Lead	0.045	0.009* LOAD	0.09	0.009* LOAD	0.14	0.009* LOAD
Others	3.39	0.76* LOAD	7.25	0.76* LOAD	11.45	0.76* LOAD

Table 3.1 (cont.) Emissions summary

Water						
Suspended solids	3.16	0.62* LOAD	5.89	0.62* LOAD	9.30	0.62* LOAD
Acid	0.33	0.065* LOAD	0.61	0.065* LOAD	0.98	0.065* LOAD
Others	0.01	0.0028* LOAD	0.02	0.0028* LOAD	.04	0.0028* LOAD

Note:

1. **LOAD**: It is the Actual Load being carried by the truck.
2. The summation of constant and variable emissions for each type will give the total emissions of that type

The total emissions arising from transportation by truck are then the function of number miles the truck travels and the amount of load it carries.

3.1.2 Need for a Computer Based System

Analysis of various operational scenarios can be performed to improve the overall efficiency of demanufacturing operation. These scenarios can be conducted and observed for improvement capability either by experimenting with the actual system or experimenting on the model of system. Experiments on the actual system involve physical changes and modifications in the current system. However, it is rarely feasible to experiment on the actual system because of practical difficulties including cost and time of experimentation and impacts on current workload.

The mathematical modeling strives for either an analytical solution or numerical solution (simulation). Mathematical models represent the system in terms of logical and quantitative relationships that are then manipulated and changed to see how system will react if the mathematical model truly represents the system. Mathematical models may be analytically solved for different changes in the controlling variables (different operational strategies) for performance analysis. As the system and therefore its model get more complex, precluding any possibility of analytical solution, the model is numerically solved to examine the performance of output measures.

It can be inferred upon examination of demanufacturing systems, that the mathematical models will be fairly complex and impossible to solve analytically. An activity based computer model is needed to understand the behavior of demanufacturing activity under operational changes. The system changes its state when an activity such as disassembly, transportation or batching occurs. These activities can also be called as events. As described in Chapter two, simulation techniques of such systems are called discrete event simulations, where system advances in time and changes its state only at countable number of points in a given interval of time [14, 21].

In 1983, the first general-purpose simulation language called SIMAN designed for modeling manufacturing systems was developed for microcomputers. In 1985, Cinema was introduced as a graphical animation system. In 1993, Systems Modeling Corporation released ***Arena***, which uses SIMAN as simulation engine and CINEMA for animation [47]. Because of its object oriented approach, user defined customized templates and integration with ***Microsoft Visual Basic*** for formatted data input and customization of (output) performance reports, ***Arena*** is used as the basis for this research.

The software is widely used in various business sectors such as manufacturing transportation, logistics, supply chain, call center, packaging, and service (e.g., restaurants, front office banking) systems [47].

3.2 System Simulation Methodology

3.2.1 Typical Simulation Methodology

A typical problem under study is normally divided into steps as shown in the flowchart in figure 3.4. The general steps followed are as follow [9, 11 and 12]:

1. *Identify the problem*: The problem definition involves identification of the problem in the system, its boundaries and other aspects required for problem clarification; for example, problems related to inventory control for determining the optimal replenishment policy, arising due to the stochastic nature of demand and lead-time. Or in queuing theory, the problem may be balancing the cost of waiting against the cost of idle time arising from the probabilistic nature of inter-arrival times of customers and service time. These problems are similar to scheduling and operational problems in demanufacturing systems arising from variability of products coming in and value that can be recovered from them constrained by operational costs.
2. (a) *Identify the decision variable*

   (b) *Decide the objective and decision rules*

In context of the demanufacturing problem, the supply, number of operators, size of bins, level of disassembly for maximized recoverable value, optimum disassembly plan for lower disassembly time for a predetermined level of disassembly are identified as decision variables. These decision variables measure the performance of the system in terms of throughput and total profit gained. The amount of information necessary depends on the level of exactness desired and the quality of information available. Following are two types of questioning categorized [13, 14]:

- Questions on model development: Answers to these types of questions help demanufacturing system model development in terms of modeling details, animation details, statistical analysis of decision variables. Following is a list of few questions that can be asked by a modeler:
  - What is the objective of demanufacturing study?
  - What types of output results relate to demanufacturing simulation objective?
  - What is to be included in the demanufacturing simulation model?
  - At what level of details should the demanufacturing model be included?
  - How is validation going to be performed?
  - How detailed the animation should be for representing demanufacturing operations?
  - What are primary resources of the system and what task they perform? The resources are the parameters running to deliver the system output. In case of demanufacturing, disassembly workstations and operators are primary resources.
- Questions regarding system to be modeled: The information needed for execution of a simulation model is primarily obtained from answers to these questions. The modeler is also concerned about the quality of information gathered. Following is a list of a few such questions:
  - Are disassembly process plans (level of disassembly) or process flow diagrams available?

- Is the information about the product to be disassembled available?
    - How much value you are recovering from the product?
    - Have you decided the number of sort bins required and their contents?

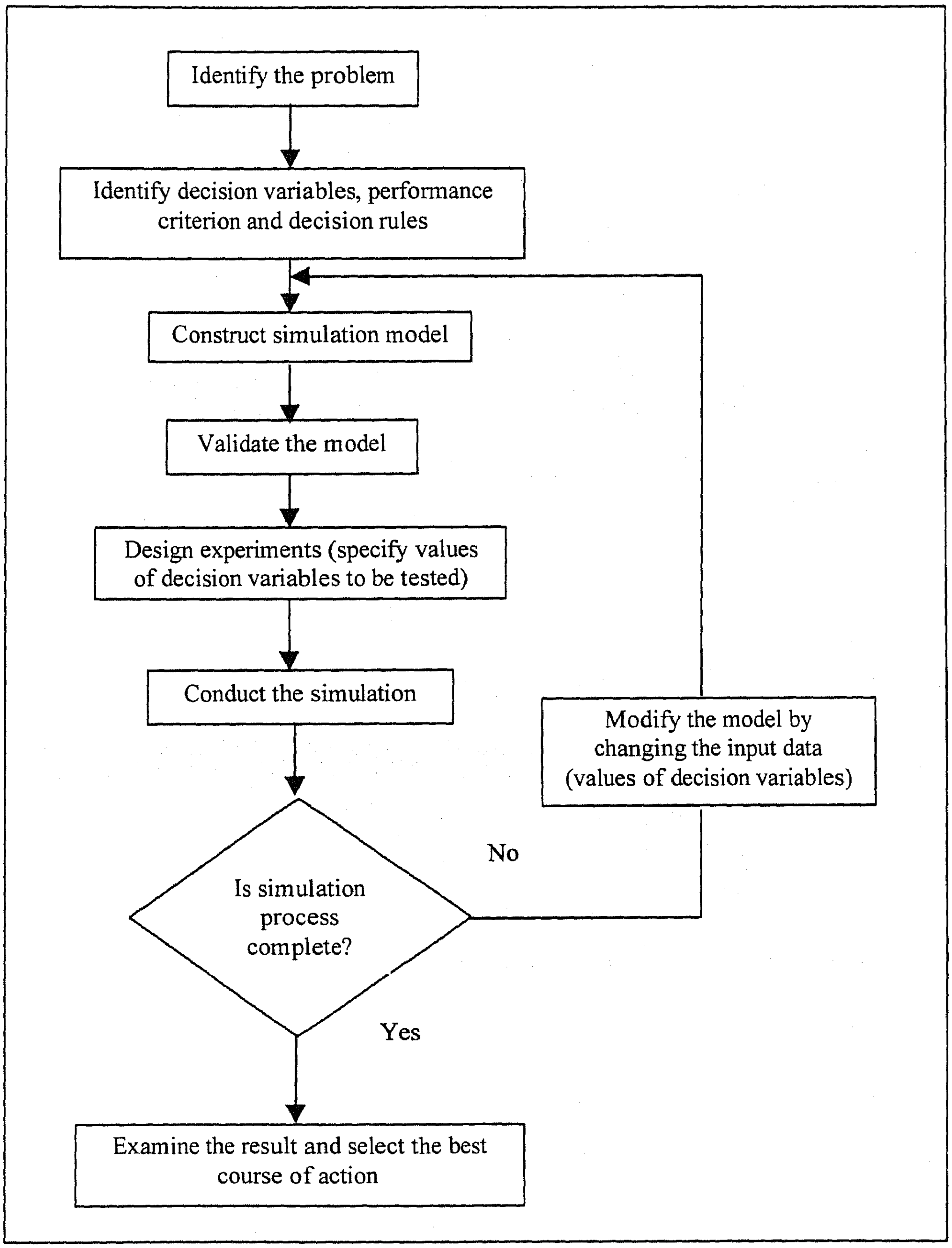


Figure 3.4 Simulation Process Flowchart
[Source 9]

- Are you aware of the variations involved in the arriving products? The variation is not only in the product type but also in the make of the individual product itself.
- Are there any physical, technological, or legal constraints on how the system operates?
- How decisions are made and are there any exceptions?
- What type of data is already available?
    - What is the quality of data?
    - If data is not available, who will provide data estimate?
    - Will they require that a sensitivity analysis be conducted?

3. *Construct a numerical model*: This is the representation of the real system into a particular simulation language, which will be used for analysis on computer. In many cases, a flow chart is used to describe the process.
4. *Validate the model*: Validation is a process of confirmation of the designed numerical model. To ensure whether the model is truly representing the real system being analyzed and results will be reliable.
5. *Design the experiments*: List all the values of variables to be tested (i.e. list courses of action for testing) at each run and vary those in due courses of run for getting desired result. This step deals with two important and contradictory objectives: accuracy and cost.
6. *Run the simulation model*: This is only a procedure to get the results in the form of operating characteristics. The procedure involves issues such as random number generators, stopping rules and derivation of results.

7. *Examine the results in terms of problem solution*: The results are examined for their reliability and correctness. If the simulation process is complete, i.e. if the results are in given confidence interval, then select the best course of action, otherwise make the desired changes in the model decision variables, design and return to step 3

The process can be viewed as an iterative one until you reach the desired objective.

The simulation tool is developed keeping the same methodology described above using combinations of modules existing in the standard Arena software. The tool develops an interface providing demanufacturing terminologies for simulation of demanufacturing facility.

3.2.2 Definitions of Primitive Objects

Arena has a modular structure with lower level programming languages like C/C++, FORTRAN and graphical user interfaces like *Visual Basic*, and higher level User-created templates. Figure 3.5 shows Arena's hierarchical structure and level of abstraction [13].

The demanufacturing system model utilizes the modules from every abstraction level to develop the customized templates. It incorporates arrive, depart, advanced server, simulate modules from the Common Panel for modeling activities, which are constructed by combining modules from support and SIMAN template. As the complexity of demanufacturing system under study increases the model goes down the hierarchy to develop the customized templates. The demanufacturing system uses branch module from blocks template and assign, delay modules from support template. The description of the significance of these modules in demanufacturing simulation tool is described in next few sections.

The model development code can be written in procedural languages like C/C++, FORTRAN and graphical user interface of Visual Basic for future specialized purposes. For example, complex decision algorithms in staging and planning of disassembly processes or accessing disassembly, scheduling data from an external application/source and storing the current operational data.

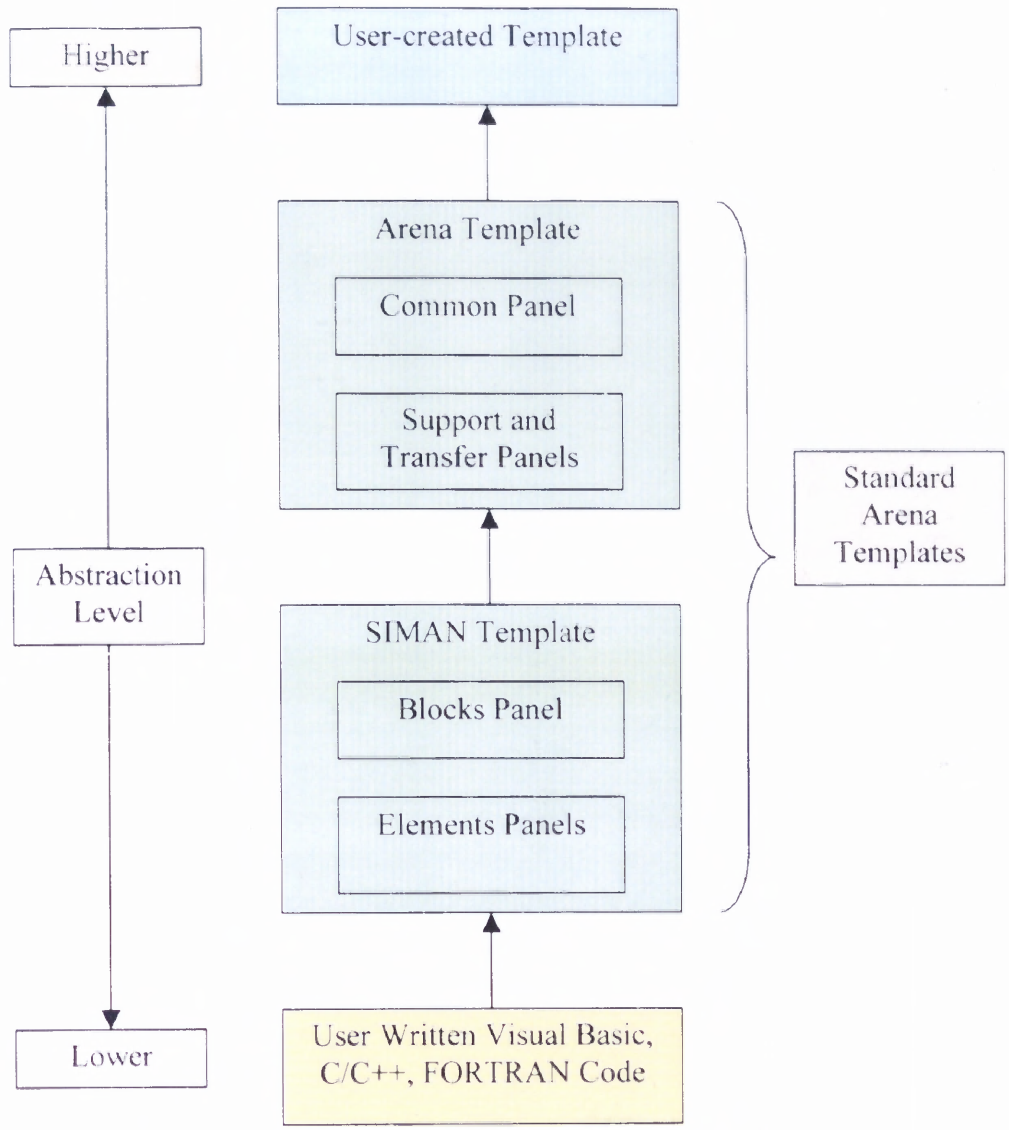


Figure 3.5 Abstraction Levels of Arena
[Source: 13]

The customization provides facilities like design for application oriented logic, use of technical terminologies of that specific application and higher abstraction for benign users.

3.2.1.1 Arrive: Arrive module creates the modeling entities representing the various products in demanufacturing system. The module is divided into three categories shown in figure 3.6. *Enter Data* section is used for description of the current station.

Animation Picture

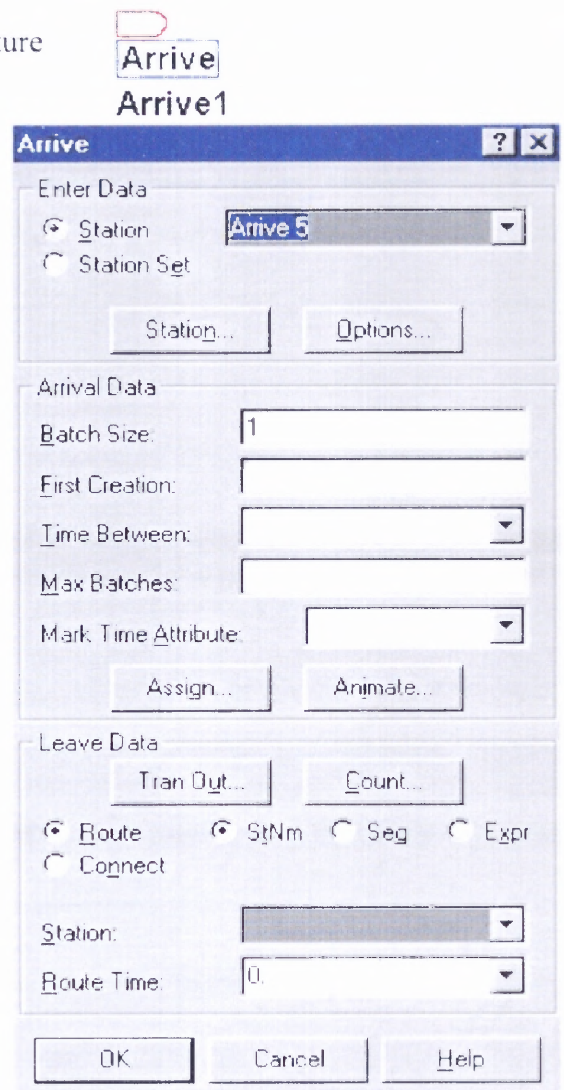


Figure 3.6 Arrival Module
[SM Corporation]

The station name, which may be the unloading dock location for products arriving from collection sources, can be written in the combo box or can be selected from the list in the combo box. The station set is a group of similar stations, where different stations are stored in an array with its index. The second section is *Arrive Data* section, which holds information on entities generation. *Batch Size* and *First Creation* control the number of products to be created and time of their creation. *Time Between* and *Max Batches* entries decide the intervals between successive arrivals and maximum batches of discarded electronics products to generate by this arrival module.

Time of arrival can be assigned to user defined attribute. User can also assign states to resources and generate products with different identities using the Assign Module explained later in this chapter. The leave data section allows counting the number of generated using *count* option. And user can decide the way of travel for leaving products using *Trans Out* option. This option provides access to either a transporter or a conveyor. The user can also specify the name of next station and the time of travel for the leaving product.

3.2.1.2 Advanced Server: A server is an active processor, which represents a disassembly workstation, a store for discarded products. The server represents the resource, its queue, its type and the processing time required. Like arrival module, the server is also divided into three categories viz. enter data, process data and leave data. Figure 3.7 shows the three sections and default animation picture of server.

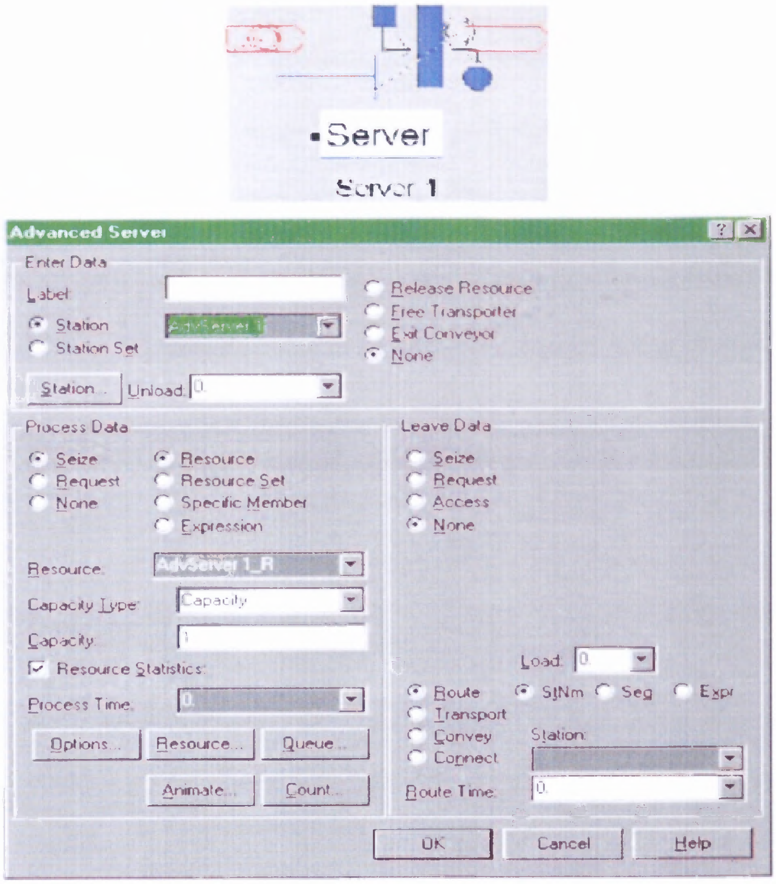


Figure 3.7 Advanced Server Module
[SM Corporation]

Advanced server module provides facility of designing a sub-routine logic to incorporate with in the server logic. This logic can be a delay for tool set up time or a wait till some signal is received for further processing of discarded electronics products.

The enter data section keeps information on resource name i.e. name of disassembly workstation and a *Trans In* option to free a transporter, exit a conveyor or free a resource acquired previously by the active product entity.

The *Server Data* section holds the disassembly workstation's processing information. The incoming product entity can seize, request a resource or a member of resource set. It also processes according to a pre-assigned schedule as per disassembly process plan or user can input a capacity for that particular disassembly station. If the capacity type is capacity, then a numeric value for the capacity of workstation is required along with the process timings. The capacity is the ability to process given number of products simultaneously. The Resource button holds the information about different states of disassembly workstation, type of workstation i.e. stationary or moving, its down times and failure probability distribution. The queue module "queues" the incoming entities and releases them as per the user-selected rule. The general rules are *First In First Out*, *Last In First Out*, *Higher Value First* or *Lower Value First*. The leave data section is similar to the leave data section of arrival module.

3.2.1.3 Depart: A depart station is a physical area from which the active product entities are disposed. The station name is a name of the location of collection and shipment area, which can be written in the combo box or can be pulled from the list. The station name can be a member of a set of similar stations. Figure 3.8 shows the depart module with its sections.

To compute and record the flow times of departing products, individual tally option can be used. The interval statistic option provides the time difference between a selected attribute and the time at the departing station. Similarly the expression option allows to calculate the tine based upon user defined expression. The options command button provides options for releasing overlapping resources such as operators or a specific member of a set.

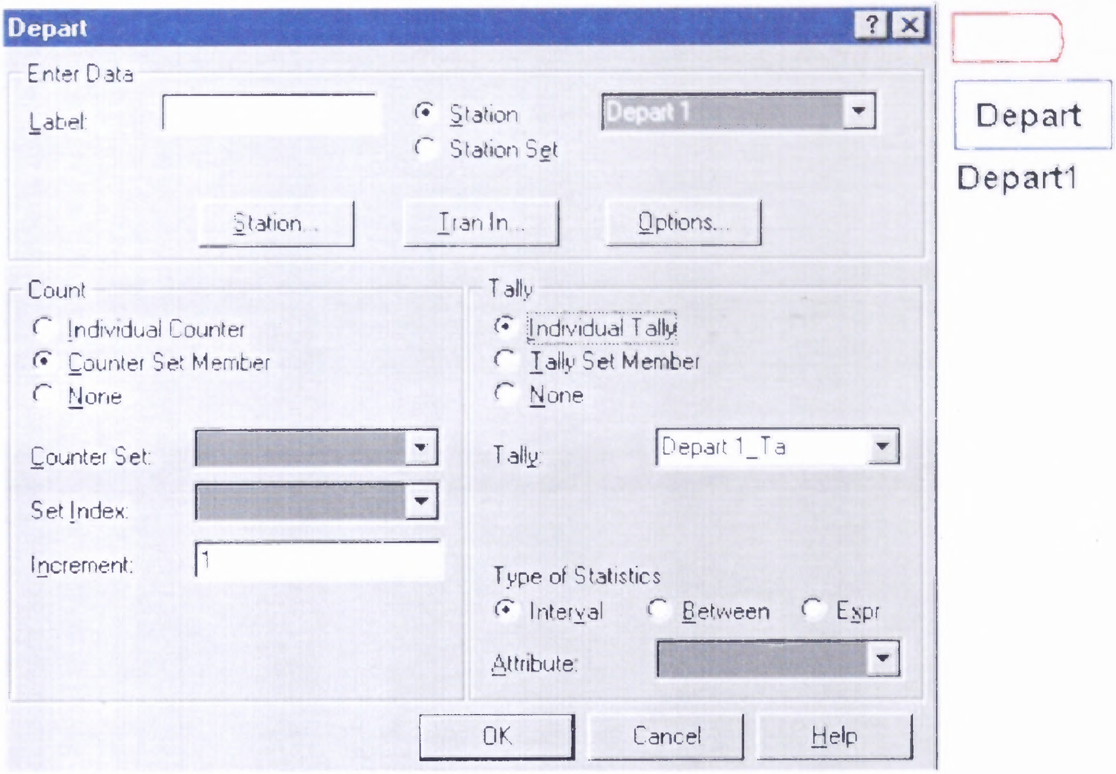


Figure 3.8 Depart Module
[SM Corporation]

The count section counts the number of product entities completing the pre-assigned schedule of path. The counter can be a set with index for counting different types of products disposing by the same depart station. As stated earlier the tally section tallies the number of disposing products according to type of statistics selected.

3.1.2.4 Batch: The batch module is used to group the individual products to form a single batch for disassembly processing and transfer activities. The operations that are scheduled for batch processing use this module.

Figure 3.9 shows the batch module with its logic symbol.

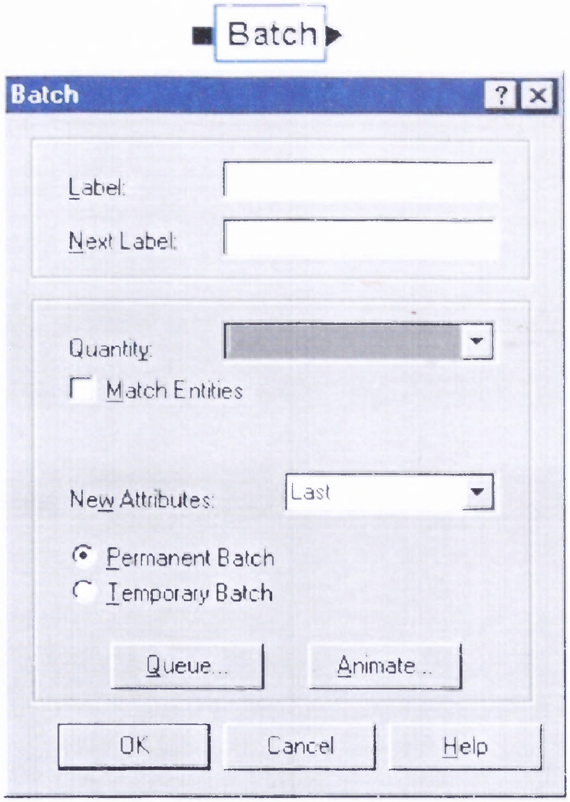


Figure 3.9 Batch Module
[SM Corporation]

A new attribute can be assigned to the newly formed batch. There are two types of batch forming methods: permanent batch and temporary batch. When a batch is permanently formed then the attributes of individual entities are lost and the batch entity receives the attributes of either first or last entity. However, temporary batch can be split at any time in the model using *split* module and the attributes of either first or last entities are assigned to this batch entity. After splitting the temporary batch the individual entities regain all their attribute values. For demanufacturing modeling permanent batches of various product types are formed before processing and then the products are moved as a batch entity through out the logic

If the created products are of different types for example different products arriving at demanufacturing facility, then these can be grouped according to their type by selecting option *Match Entities*.

3.2.1.5 Delay: Delay is a module, which holds the active entity advances the simulation clock by a specified unit of time. Figure 3.10 shoes the user screen for delay module.

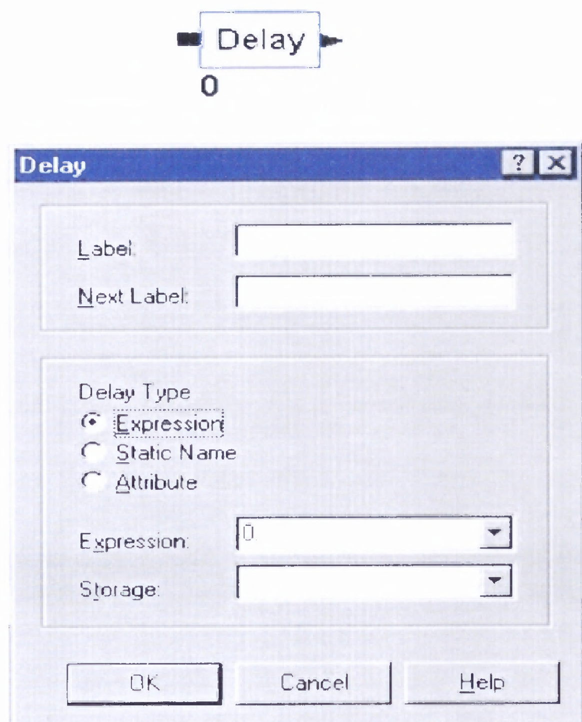


Figure 3.10 Delay module
[SM Corporation]

The delay type is specified by three ways. User can write a mathematical expression, which evaluates the delay period. The delay can be a value of static variable or a value of an attribute. The delayed entities are held in a common storage or a user defied storage until the delay period is over. The delay period in demanufacturing system is a tool set up time or time required for delivering the bin manually to collection/shipment area

3.2.1.6 Inspection: Inspection station provides facility of providing the information on failure probability of product, which is currently under process. Figure 3.11 shows inspection data input screen which is used to model inspection "operator".

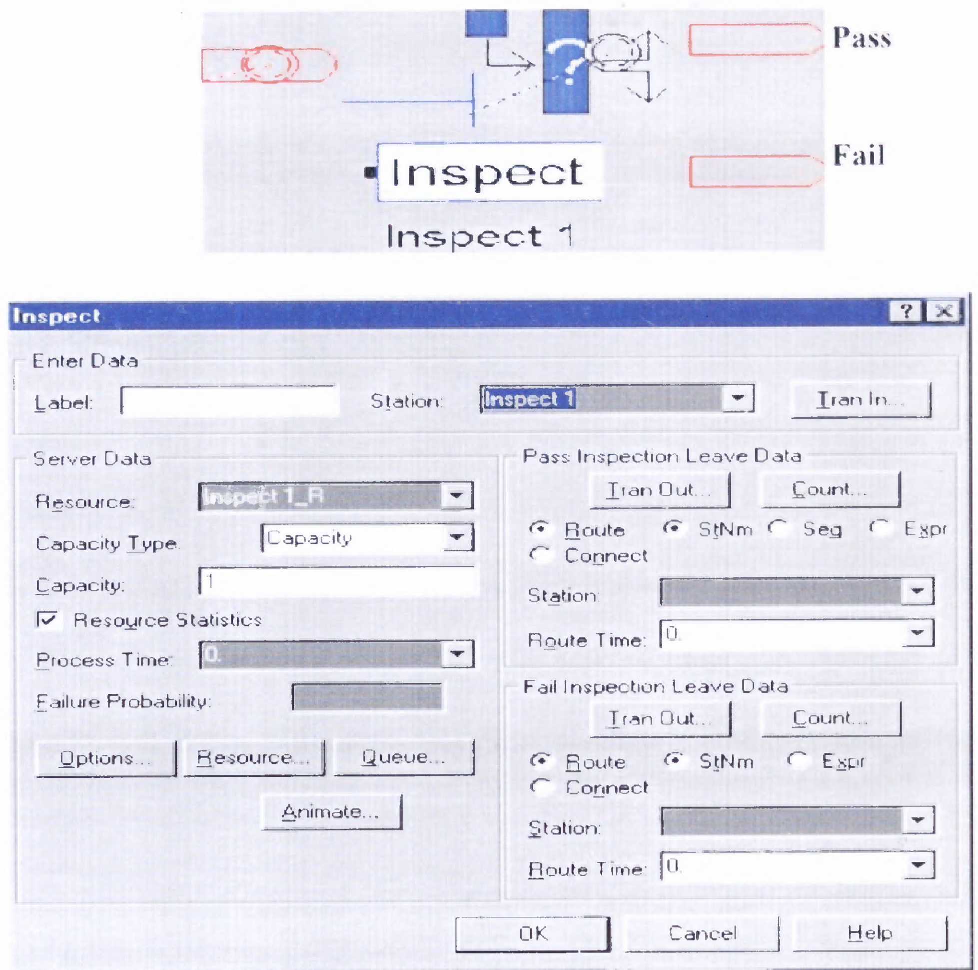


Figure 3.11 Inspection Module
[SM Corporation]

The enter data and server data sections are same as an advanced server module, except that in server data section you require an additional data input information. The process time in this section means time required for the inspection process and the failure probability is the percent failure rate of discarded electronics products. It has minimum zero value and one maximum. For example if the failure probability is 0.2 then out of 100 products/batches 2 batches fail the inspection test.

The failed products/batches go to the fail inspection leave data for disassembly operation to recover value embedded in subassemblies and individual components and the passed products/batches go to pass inspection leave data to resale or remanufacturing location for repair. Both the leave data sections are same as explained in arrival or advanced server module.

3.2.1.7 Branch: The Branch is an object from block module for duplicating the entities as per the user requirement. The demanufacturing model utilizes capability of branch module to generate streams to sorted bins for disassembled products and figure 3.12 shows the branch module.

The Label block uses the default name or the user specified name as the name of that instance of the branch block. The *Max Number of Branches* gets the user input for maximum number of sorted bins. The branch can be operated on a specific condition or probability provided by the user. The Branch types section provides the screen for stating the condition. The screen provides four different conditions and those are *If*, *With*, *else* and *Always*. When the second condition is used, the branch takes given probability or expression in *with* condition and creates the entity. Whenever *always* condition is used that branch will always be counted for the total number of entity replications.

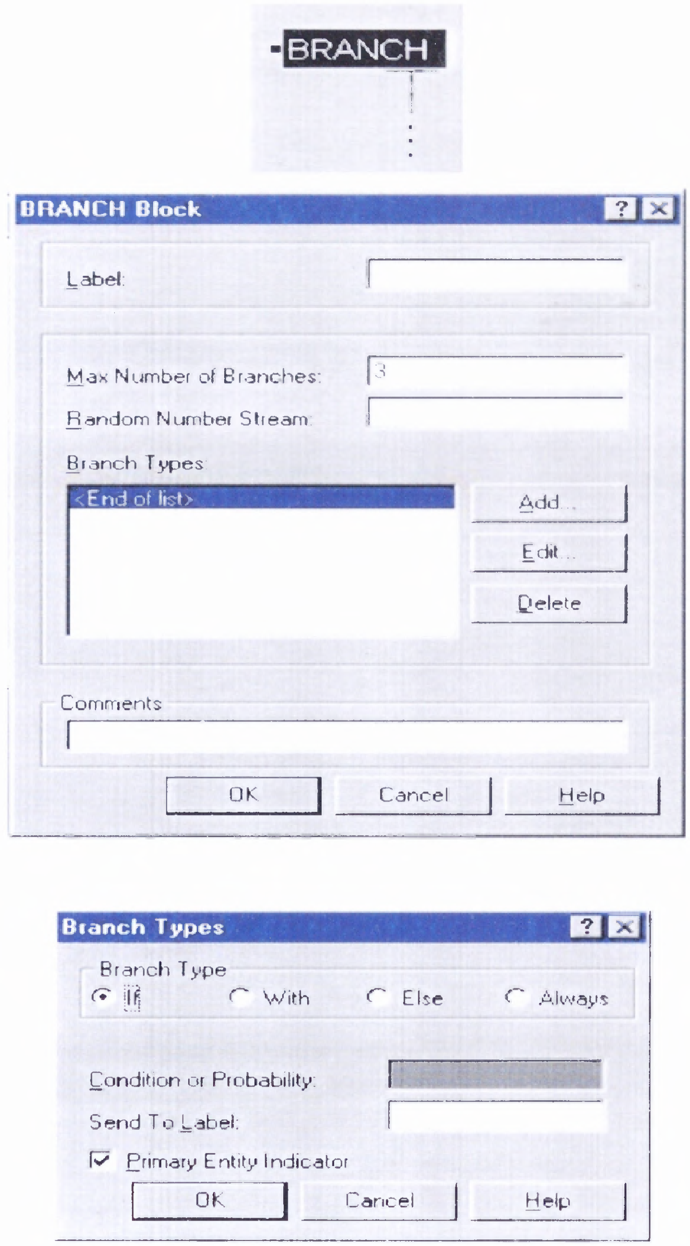


Figure 3.12 Branch Module
[SM Corporation]

The condition is a logical expression, which will give boolean output. The disassembly of a product would generate a branch, if condition the condition written in that branch is true or the probability value requires branching for that active product entity. The branch option is used for creating number of bins after disassembly of the product.

3.2.1.8 Assign: The assign module is in support panel and used for assigning values to properties of products, disassembly workstations and inspection stations. Figure 3.13 shows the assign module with list of all assignable properties

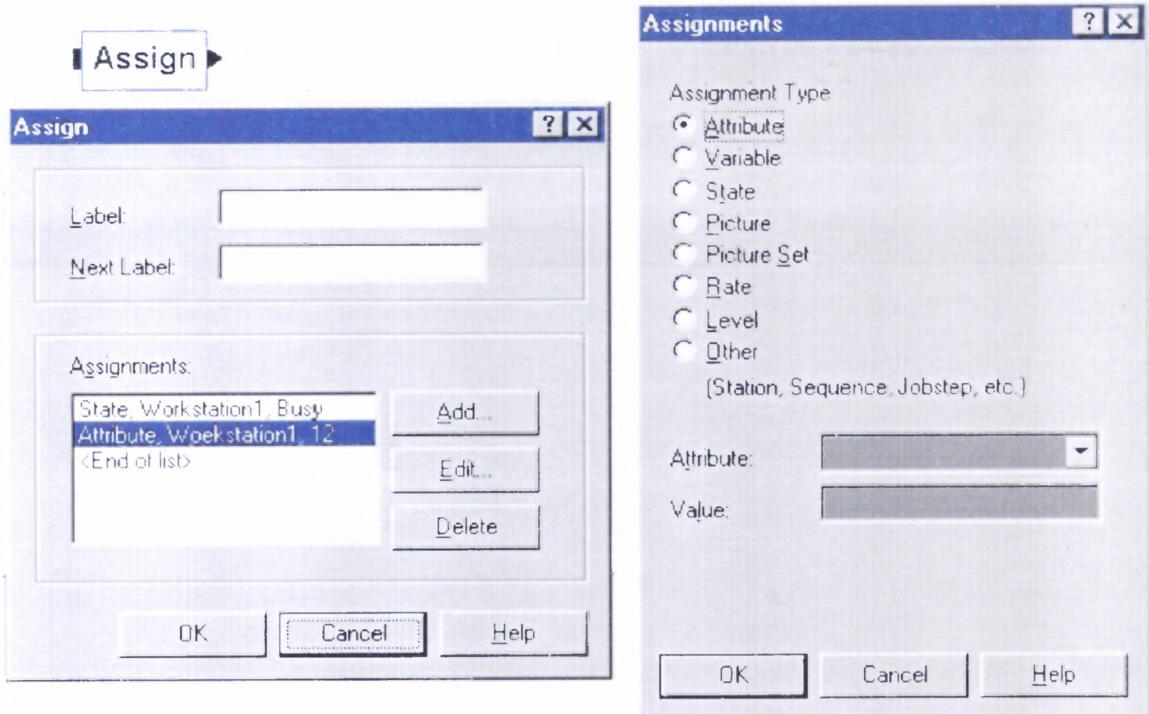


Figure 3.13 Assign Module
[SM Corporation]

The assignable properties are attributes, variables, states of resource i.e. disassembly workstation or operator, Rate, Level, picture (an individual or from a set of picture) and other assignments to stations, sequences. The variable differs from attribute because it user defined. The attributes and variables are assigned by their values. The states are assigned to a disassembly workstation as per their definition in the description of workstation. Predetermined states are allocated to a resource depending upon the function performed by the resource and these states are assigned in the logic of model.

The picture is related to product picture assignments where user can change the product picture when product undergoes different processes of demanufacturing to graphically represent various product states throughout the system.

3.2.1.9 Sets: A set, a module from common panel consists of a group of similar objects required to define demanufacturing system. The objects are stored with an index assigned to them. Figure 3.14 shows the user screen for sets module.

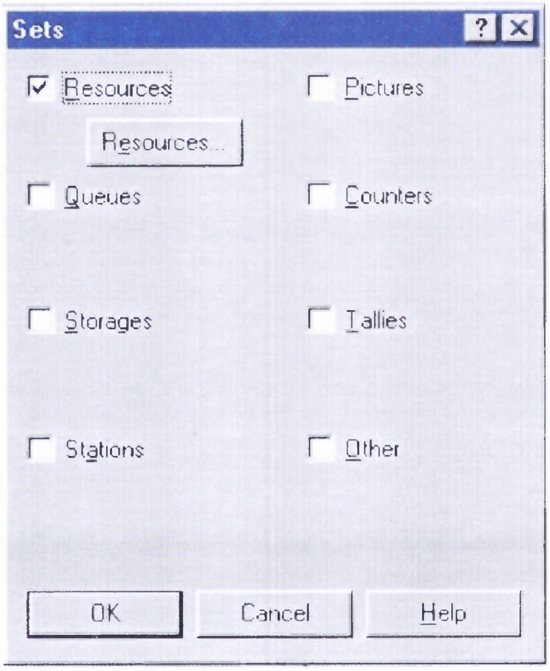


Figure 3.14 Sets Module
[SM Corporation]

The set module groups resources, counters, pictures, queues, storages, tallies, stations and other user identified objects. When the check box is selected, the "command button" appears on the screen, that allows definition of group and listing of all the group members. The group members are accessed by the group name and index variable. The index variable can be a user-defined variable or an attribute. The demanufacturing system defines products, their pictures, various counters and locations as stations using this module for representing a different groups of identities such disassembly workstations, operators, counters for products and collection/shipment locations.

3.2.1.10 Simulate: Simulate is a data screen for submitting information about simulation time, start time, warm up period and stopping condition for the demanufacturing model. Figure 3.15 shows the user screen for simulate.

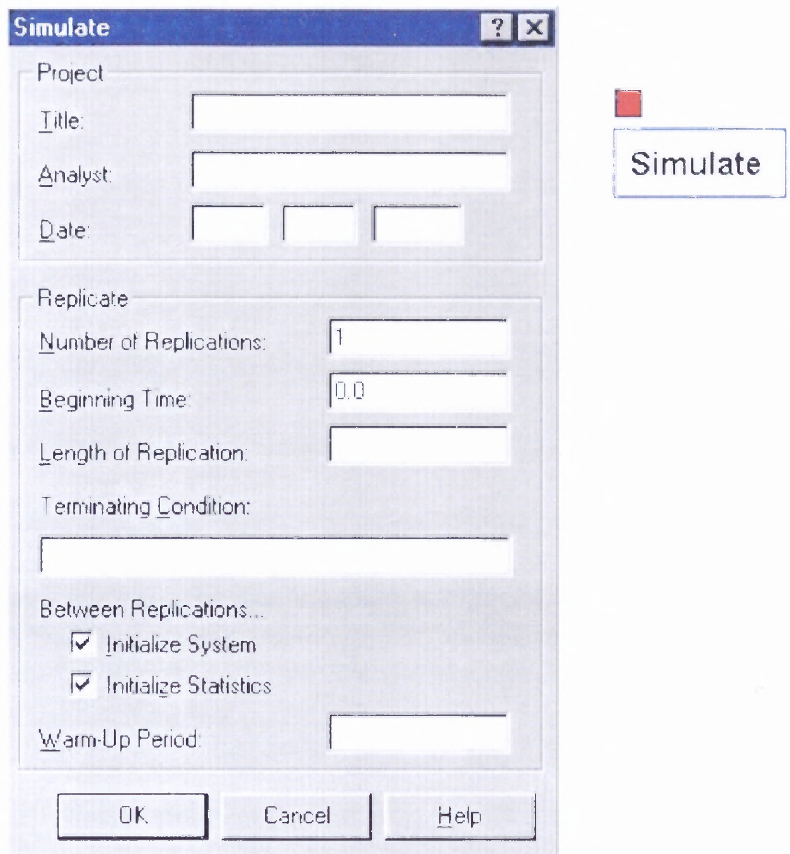


Figure 3.15 Simulate Module
[SM Corporation]

Simulate module is divided into two sections. The first section gets user information as well as date of simulations. The *Replicate* Section get the information on number of replications, start time of replication, duration replication and if the duration is unknown then the condition for stopping simulation run. The system as well as statistics can be initialized at the start of replication. The warm period is used as a starter of simulation and when warm up period is over; the simulation program starts collecting the statistics.

3.3 Customization of Arena for Demanufacturing Simulation

3.3.1 Design of template

A Template is a panel consisting of a group of objects called modules. A module is a single construct that may be selected from a template panel and placed in a model or can be built from the combination of existing modules in other template panels [14]. The panel designed for a demanufacturer contains the objects necessary for facility layout systematic workflow and simulation of the facility.

The information about a module is stored in the template panel library (.tpl) file and is referred to as module definition. In the template panel object (.tpo) file the information contained in the definition file is compressed for use in simulation. A module or object is composed of four different sections such as logic section, operand section, user view section and panel icon section. The logic section acts as a source code for execution of the intended function of a module. The operand section acts as data input source for user defined constraints. The panel icon section stores a graphic image of the module, which will serve as a symbol representing that module on the panel. The user view section contains the default picture of the module and default animation graphic images. These images will be activated during simulation run.

Each object refers to a specific demanufacturing activity and uses detailed simulation logic behind its design to perform that activity. The user selects and locates these objects to layout the facility for a graphical representation of the demanufacturing operation.

Operands provide a user interface for complete description of the activity and its operational characteristics. Operand names are chosen from a demanufacturer's point of view. The construction of user screen provides fewer interactions with technical terms of the *Arena* software and concentrates more on demanufacturing terminologies for ease of operation.

Demanufacturing operation is identified as a group of activities. The panel developed groups these activities and each module represents one of them. Following activities are identified for module development:

- Storage and Staging
- Inspection and testing
- Disassembly Workstation
- Number of Bins
- Bins

The modules are developed in next sections to follow. Each module has its own symbol, animation graphics and uses typical demanufacturing terminologies.

3.3.2 Storage and Staging

This module is designed for modeling the storage area of a facility, which takes name of storage and its capacity as input. The storage releases according to the ranking rules specified using the radio buttons. For parallel as well as sequential operations method, a signal has to be received by storage to release the next, which is modeled using a wait module. The logic incorporates process and wait modules to model the storage and release of products.

Figure 3.16 shows the logic and user screen of the module including the graphics shown on panel icon and model window.

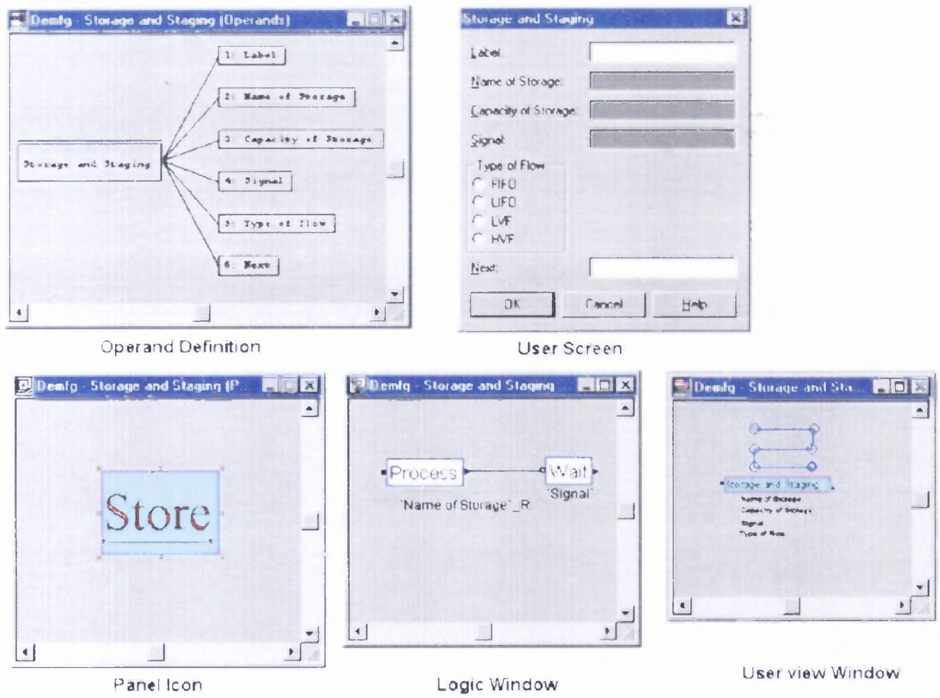


Figure 3.16 Storage and Staging

The graphics shown in user view window will be displayed during simulation. The graphics in panel icon window will servers the purpose of a symbol of this module in the template.

3.3.3 Inspection and Testing

This module is designed representing the inspection stage in demanufacturing system. Figure 3.17 shows all the five components such as logic, user view, icon, user screen and operand definition.

The user provides following inputs:

- Unload time for the batch

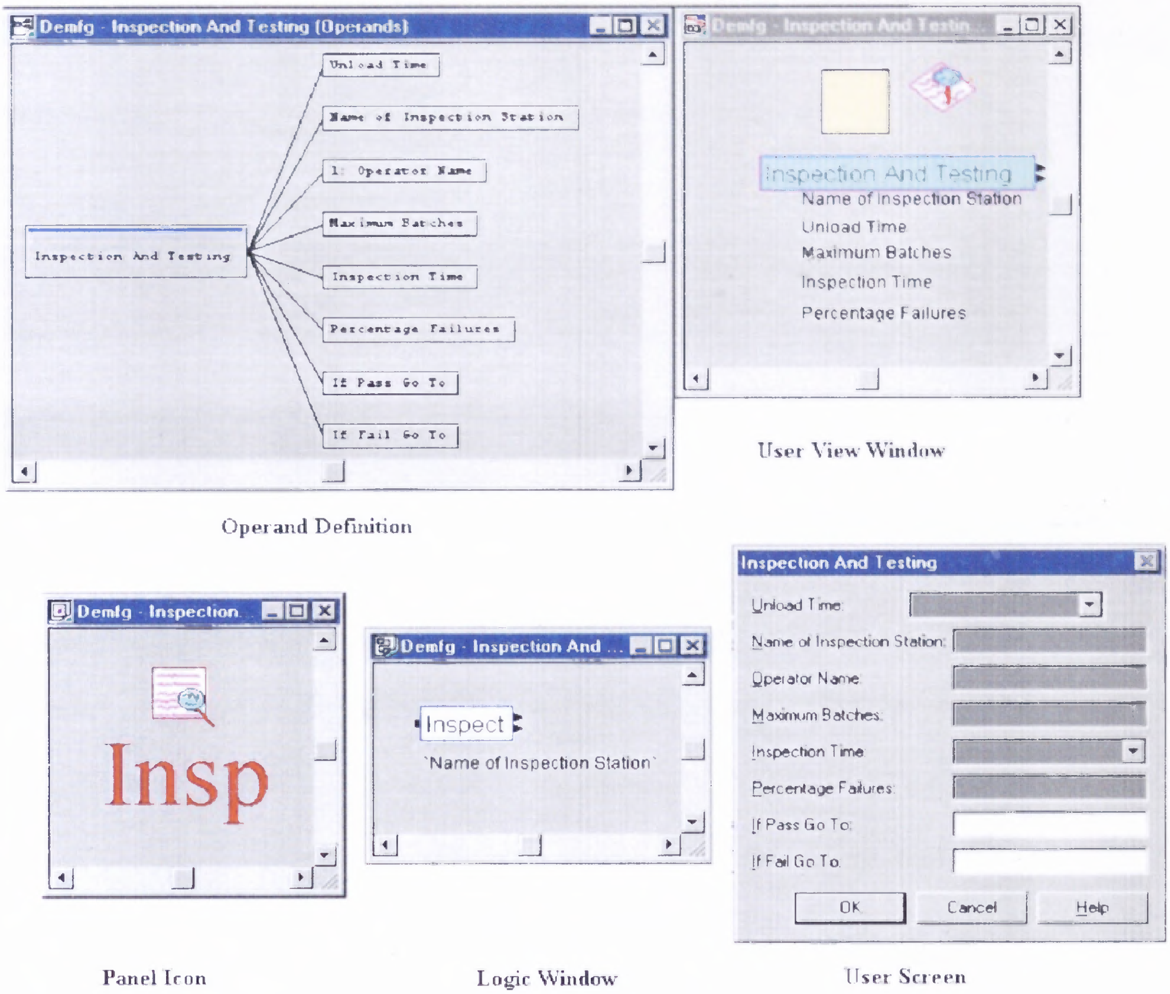


Figure 3.17 Inspection and Testing

- Name of Inspection station and Operator Name
- Maximum batches that can be handled at a time
- Inspection Time
- Percentage of failures from the batch

The logic incorporates only one module, which basically performs the operation. The purpose of developing this module is to provide interface for using demanufacturing terminologies.

3.3.3 Disassembly Workstation

The disassembly workstation is a production resource for demanufacturing systems. Figure 3.18 shows the components used to build the disassembly workstation module.

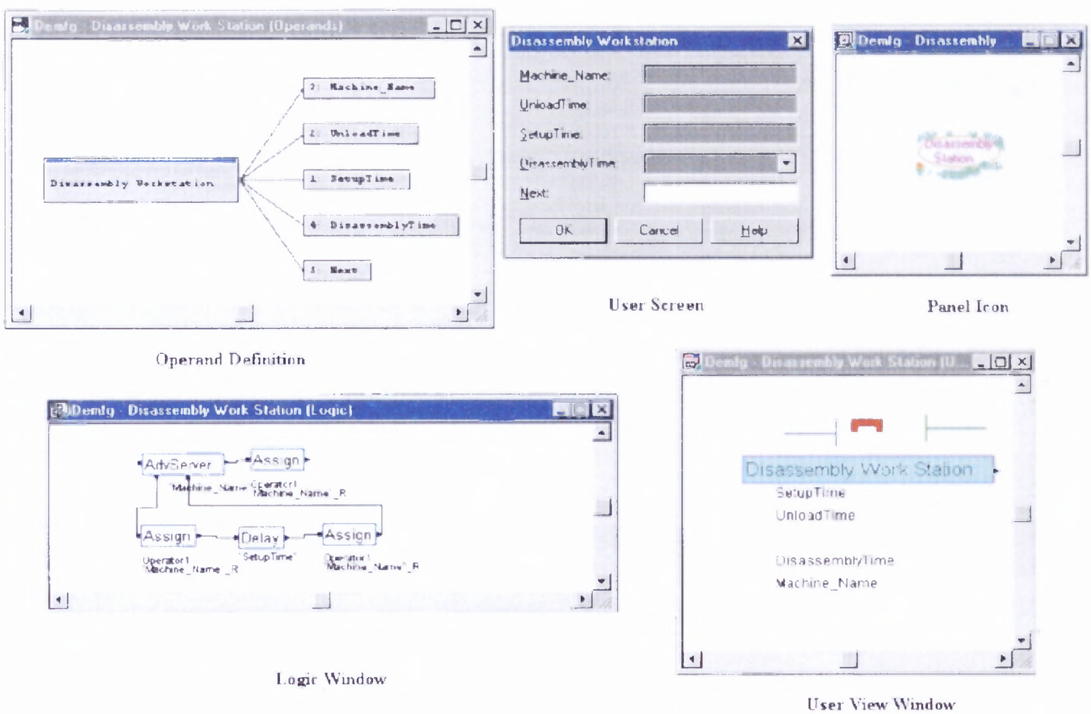


Figure 3.18 Disassembly Workstation

When a batch arrives at the workstation, the operator sets up the tools at the workstation modeled as a time delay for set up time, the batch is again delayed after assigning processing states to the workstation and operator to simulate disassembly time. The logic also follows the same path described earlier.

The workstation is assigned the following states:

- Op_wait: When operator is not available at the workstation for processing, this state is assigned to measure the idle period of the workstation.
- Processing: This is the actual disassembly operation state
- Set up: This is the proportion of time consumed in setting up the workstation.

All the states are predefined into the logic including their animation pictures so that they can be used else where in the model for generating data on percent time utilized by each state.

The user input is required for information on machine name, unload time for the batch, set up and disassembly times. The panel icon and operand definitions provide representation of the module on template and referencing of the user input into the logic respectively.

3.3.4 Number of Bins

The disassembly plan determines the number of bins required for various recovered components or materials after disassembling the product. From programming point of view, the programmer has to generate the given number of entities just after the disassembly is over. This generation can be done using the branch module from the block template. Figure 3.19 shows the designed module.

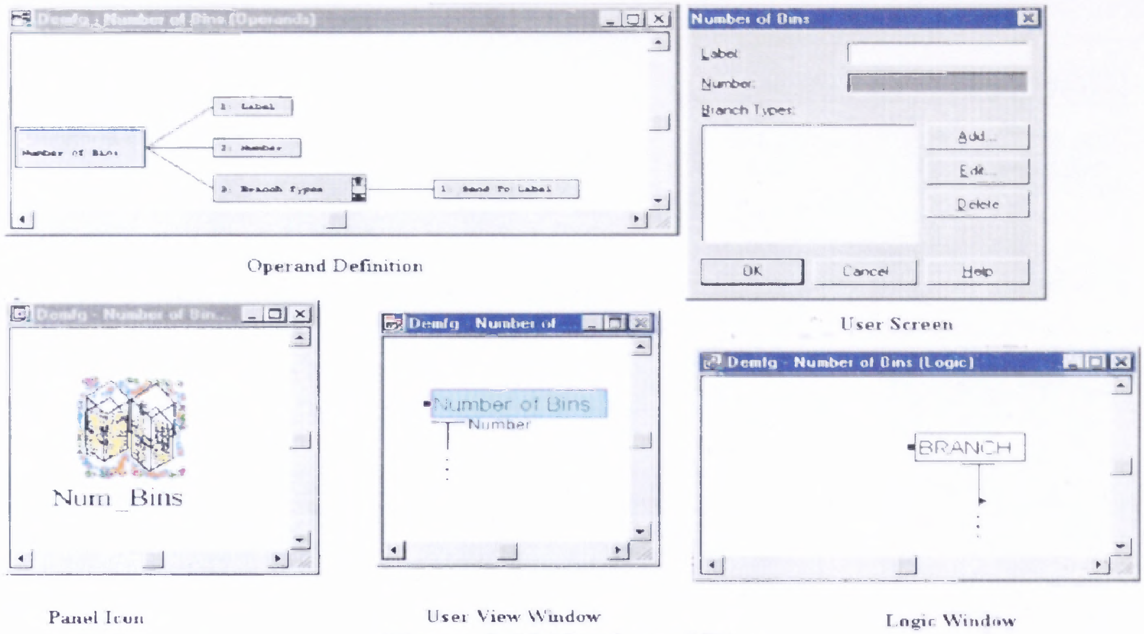


Figure 3.19 Number of Bins

The user view will show the arrows equal to number of branches specified. By default there will be always a single branch because the product has to go to next station if it is not disassemble at that station. The repeat group provided in the User Screen will give access to specify the number of branches using the condition defined for that branch. For example if a branch is modeled to operate only if the product is monitor then for other products that branch will not send disassembled product to its associate bin.

3.3.5 Bins

As described in earlier sections a bin or a container used for collecting the disassembled parts and components. The purpose of sorted bins is to provide bulk handling (convey or transportation) of the disassembled parts to reduce the transfer times. Figure 3.20 shows the design of the bin template.

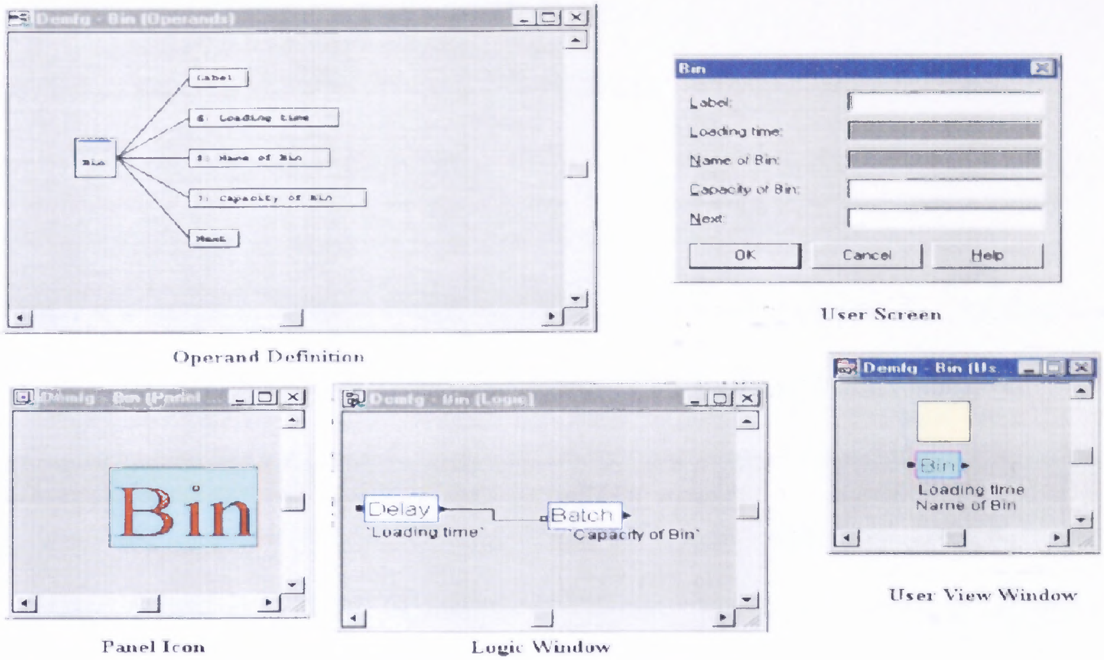


Figure 3.20 Bins

The logic provides a delay for loading the bin into the truck or conveyer. The user inputs are loading time, name of bin and a capacity of bin. The capacity of the bin is also important in terms of utilization of the disassembly workstation or operator because larger bins provide more time for disassembly and reduce transfer times. All the user inputs are referenced into the logic via operand definition window. The user view provides the animation picture for bin, which shows the bin being loaded with the materials are products are disassembled.

A typical demanufacturing facility was observed and modeled in order to validate these developed modules. This validation procedure for the modules and the results of validation are described and presented Chapter Five.

CHAPTER 4

COST MODEL

4.1 Introduction

A cost is the exchange price; a foregoing sacrifice made to secure benefit. The financial standing of an organization is of great concern to management. Competitive businesses need information that will make it possible for managers to identify and eliminate generators of non-value activities, and to be profitable they need additional information to manage activity costs [51]. Operations and facility layout improvements for higher throughput have to be examined for cost and benefit analysis. Activity Based Costing (ABC) assumes that resource consuming activities cause cost; products incur costs by the activities they require for design, engineering, production, packaging and servicing. . According to Brinker [51], " an ABC system identifies and then classifies the major activities of a facility's product process into one of the following four categories: unit level, batch level, product level and facility level activities. Cost in the first three categories of activities are assigned to product using bases (cost drivers) that capture underlying behavior of the costs that are being assigned The cost of facility level activities, however, are treated as period costs or allocated to products in some arbitrary manner" [51]. The activity based perspective in Figure 4.1 is as follows: [52, 53]

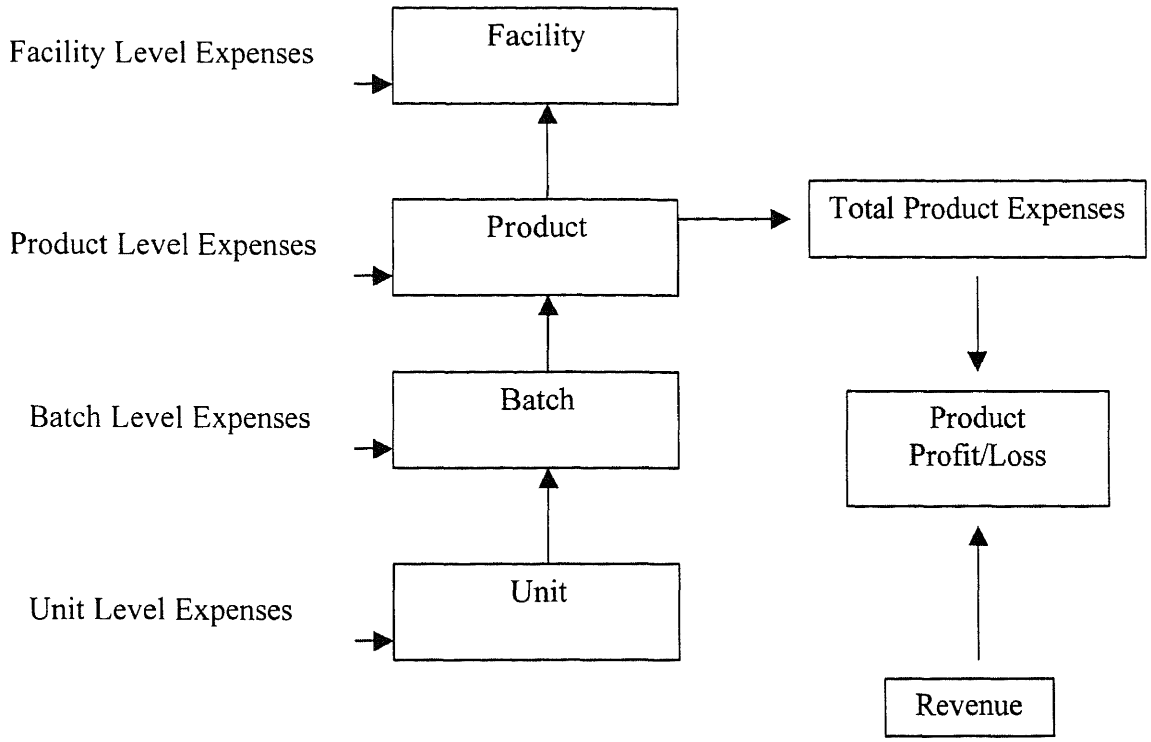


Figure 4.1 Activity Based Perspective for Cost Modeling
[Source 52]

- Unit level Activities: Activities at this level are performed for each unit of product produced. Disassembly activity times of each unit of a product and delivery activity for filled bins are examples of activities performed at unit level.
- Batch level Activities: Activities that consume resources every time a batch of a certain product type is produced. Activities such as staging/testing a batch, receiving batch at disassembly workstation are batch level activities performed at demanufacturing facility.
- Product Level Activities: Certain activities are consumed to develop and support demanufacturing processes. Tool setup activity time, maintaining the product information and developing special testing routines are attributable to specific product.

- Facility Level Activities: These activities are not directly attributable to products but are necessary for functioning of overall demanufacturing activities.

Stages in ABC can be identified as [51, 53]:

- Identify major activities in demanufacturing, for example disassembly, delivering the full bins to collection/shipment area.
- Identify cost driver: A cost driver is a factor, which causes costs to be incurred, in turn these causes are the allocation bases used by activities. For example: Set up hours, Material handling hours.
- Create a cost center (pool) for each activity. A cost center can be defined as a part of business incurring cost, which must be accumulated. It includes major segments such as administration, engineering, finance, demanufacturing services and others.
- Trace costs of activities to products: The step involves identification of activities performed by a product, which includes major activities performed in a facility as well as product specific activities that incur costs.

The result of ABC can be cited by increased revenue or decreased cost. Many systems and products are designed to go through their life cycle with little concern to life cycle cost. The cost associated with different activities such as design, planning, operation and demanufacturing have been isolated from other activities. They are not viewed in an integrated approach for system life cycle cost [54].

From past experience, a large portion of the total cost is the direct cost as a result of execution of different activities. The existence of these costs is the consequence of the decisions made in early stages of the product lifecycle. Further, since these cost are interrelated, the total cost is more addressable as life cycle cost. The life cycle cost, when included serves as a parameter for developing stable economics. Figure 4.2 shows the distribution of life cycle cost over the life of a product

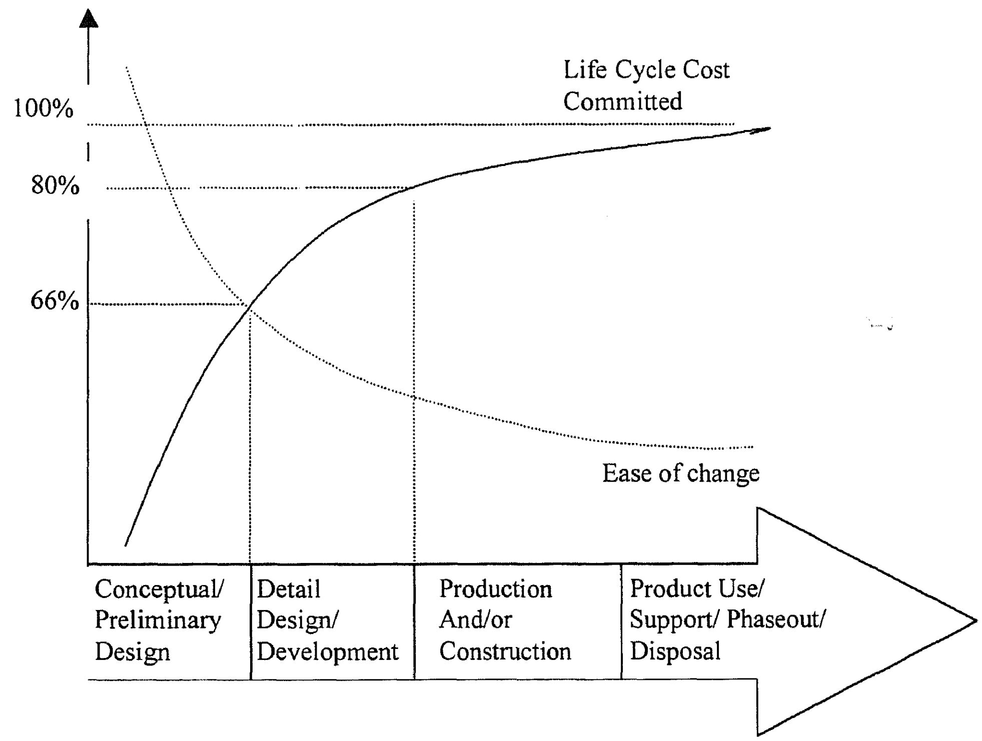


Figure 4.2 Cumulative Life Cycle Cost Committed and Ease of Change for improvement [Source 54]

Though the actual expenditures are at later stage, the total cost for a product is committed in early stages during design and planning. Therefore from a demanufacturing perspective, consideration and implementation of design for disassembly guidelines, incorporation of recoverable materials and standardizing fastening techniques would help to reduce the non-valued activities and increase product level activities performed on product in a demanufacturing facility. To assess multi-lifecycle cost of a product a cost model is developed as part of this thesis research. Figure 4.3 shows the cost savings model for products going through different recovery options.

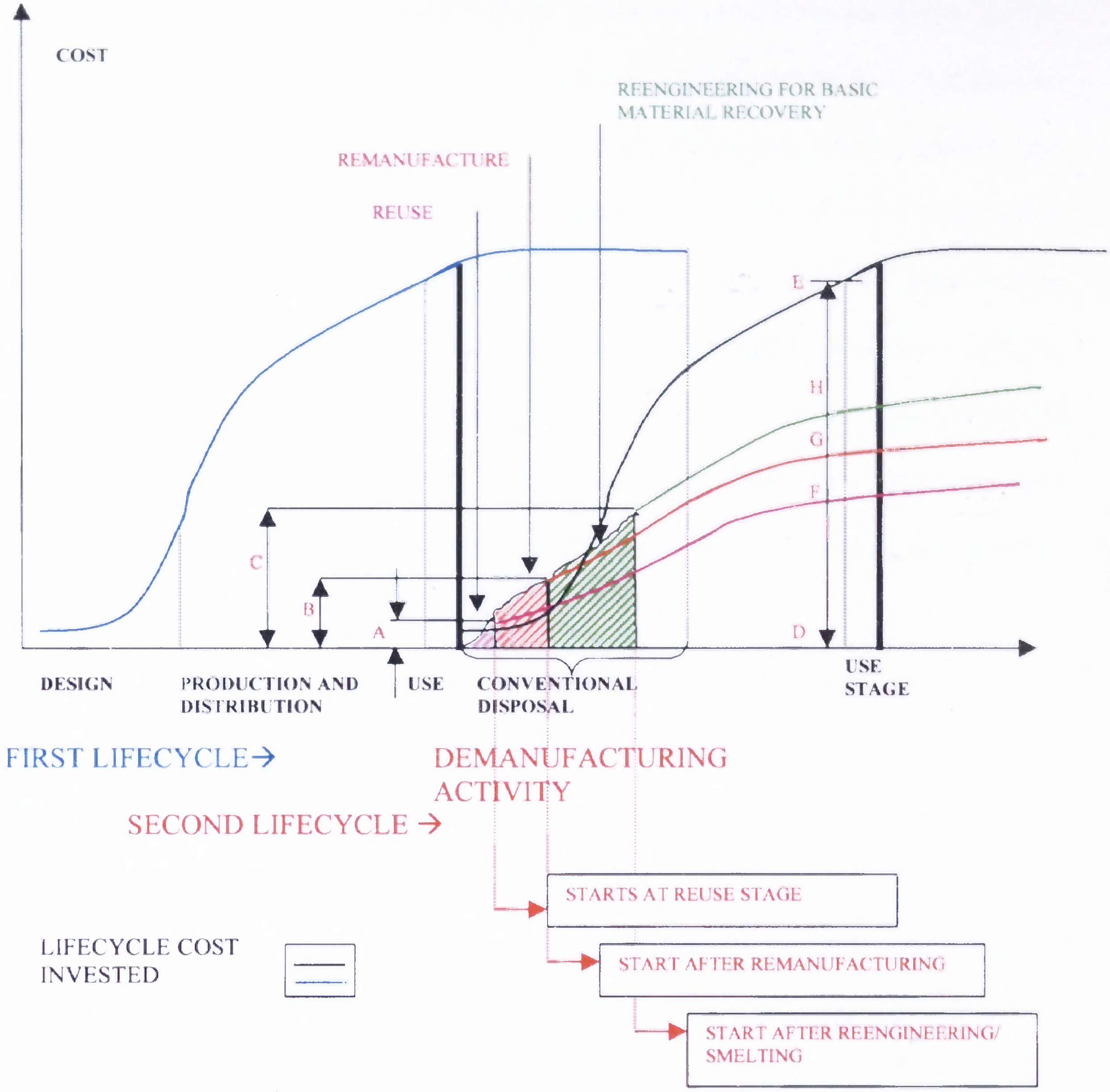


Figure 4.3 Cost Savings in Demanufacturing Systems

Approximately two thirds of the total lifecycle cumulative cost is decided at the conceptualization and design stage, though the actual cost is invested during production and distribution stage [54]. Figure 4.3 suggests the importance of consideration for end-of-life options at earlier stages of product life cycle to reduce second generation investment and resource consumption. The conventional disposal of preceding generation products can be processed in a demanufacturing system to save net production cost of next generation products. Figure 4.3 shows product lifecycle stages on the horizontal axis and cost invested on the vertical axis. The cost associated with collection and redistribution of discarded products and inspection are common to all recovery options in addition to their specific process costs. The recovery hierarchy is reuse, remanufacture and reengineering for recovery basic materials. The cost invested in reuse option with the cost just before the use stage will be the net production cost for next generation application. Similar costs (B and C) are associated with remanufacturing and reengineering options. Table 4.1 lists all the cost invested after end of useful life from the graph shown in figure 4.2.

Table 4.1 Cost Invested for Next Generation Application

Costs Invested	**Purpose of Investment**
A	Recovery for reuse
B	Recovery for remanufacturing
C	Basic material recovery by reengineering
DF	Cost invested just before use stage of 2nd lifecycle with reuse
DG	Cost invested just before use stage of 2nd lifecycle with remanufacturing
EH	Cost invested just before use stage of 2nd lifecycle with reengineering
DE	Cost invested just before use stage in conventional lifecycle

The effectiveness of recovery process will reflect a lower profile cost curve for the next generation products. The net savings from the recovery can be observed just before the use stage by comparing the manufacturing cost at a typical life cycle cost curve of a product with production cost including the recovery cost for the next generation product. Table 4.2 summarizes the net savings observed from the graph.

Table 4.2 Summary of Cost Savings in Demanufacturing System

Savings in Cost for Different End-of-life Options	
(DE- DF-A)	Savings in Cost by Reusing the Product
(DE- DG-B)	Savings in Cost by Remanufacturing the Product
(DE- DH-C)	Savings in Cost by Reengineering the Product for recovery of basic material.

4.2 Cost Classification

A variety of classifications have been developed to support lifecycle cost and economic analysis. The classifications are based on the source and effect of costs that will have a bearing on the output of a demanufacturing activity [51, 53 and 54]. Some of the classifications are listed below

- *Investment Cost*: The initial cost of getting an activity started is an investment cost. Ordinarily, this type of cost allocation is limited to costs that occur only once for any given undertaking. In demanufacturing facility, facility installation, material handling and disassembly equipments and tools is an investment for succeeding activities.
- *Operation and Maintenance Cost*: Operation and maintenance cost will be experienced over an expected life of the product. These costs are dependent on the number of different activities performed in a facility. The timings of these costs vary substantially and are related to activities in their scope. Various categories comprising

this cost, for demanufacturers include labor, energy, material, inventory holding, internal as well as external transportation, communication and residual disposal costs.

- *Fixed and Variable Cost*: Fixed cost are costs involved in an on-going activity and whose total value will remain relatively constant throughout the life of that activity. Fixed costs result from the decisions of past and are not subject to rapid changes. Variable costs are related to variation in operational activity. For example, energy consumed by the conveyor is proportional to the weight conveyed over a precalculated distance. In general, all costs that can be easily allocated to each unit of product are variable cost. The type of activities such as disassembly, transportation, staging and inspection performed in facility are variable costs. A graphical representation of fixed, as well as variable cost, per product is shown in figure 4.4.

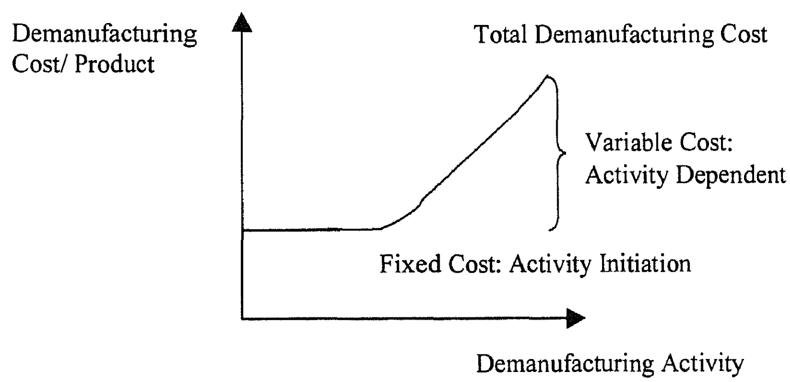


Figure 4.4 Fixed, Variable and Total Cost
[Source 52]

It is apparent form figure 4.4 that the cost incurred in disassembling a product is divided into fixed and variable cost. Variable costs incorporate the activities performed, while fixed costs include the investment required for initiation of activities such equipment cost, facility capital cost and administration cost. The total demanufacturing cost increases with the increase in disassembly activities.

- *Direct and Indirect Cost*: The direct cost consists of costs associated with the demanufacturing of a product. Direct costs are direct labor cost and direct expenses associated with demanufacturing such as cost of tools, material handling and testing equipments. Where as, indirect cost consists of indirect labor cost pertaining to disassembly, supervision and engineering consultation cost and indirect expenses such as heating, lighting, insurance and office personnel cost.

The process of classifying cost and expenses may begin by relating cost to the operations/activities of the demanufacturer. To better understand the demanufacturing business requires a cost model that generates a relation between these variables and activities that incur cost for a demanufacturer. A model that relates the cost in dollars per product disassembled will provide an insight to a demanufacturer for scheduling and improving his operations.

4.3 Cost Identification

Upon review of the classifications, an activity based cost model can be developed by identifying fixed and variable cost. The cost per product is the summation of variable costs per product representing the activities and fixed costs per product representing the investment cost for initiation of activities.

$$\textbf{Total Cost} = \sum_{i=0}^{m} \left(\sum_{j=0}^{n} \text{Cost of activity } j * \begin{array}{l}\text{Quantity of activity}_j \\ \text{for product}_i\end{array} \right) * \begin{array}{l}\text{Number of} \\ \text{products of type } i\end{array} \qquad (4.1)$$

Where, m = different types of products.

n = number of activities associated with product i

The identification of the cost sectors for the fixed as well as variable cost categories require information on different types of the of activities performed the facility.

4.3.1 Relationship of Activities with Cost Categories

The overall activities in a demanufacturing facility are disassembly, material transport, shipping, repairing, staging and inspection. The activities involved in each type of variable cost are summarized in Table 4.1.

Table 4.3 Identification of Activities for Cost Categories

Activity Conducted	Cost Category Involved
Disassembly of Products	1. Labor Cost 2. Work Center Operational Cost
Tool Setup for Disassembly	1. Labor Cost 2. Work Center Operational Cost
Loading of the Material or Products	1. Material Handling Cost 2. Labor Cost
Unloading of the Material or Products	1. Material Handling Cost 2. Labor Cost
Movement from Loading Dock to Warehouse	1. Material Handling Cost 2. Labor Cost
Movement from Warehouse to Inspection/ Staging Area	1. Material Handling Cost 2. Labor Cost
Movement from Inspection/ Staging area to Workstation	1. Material Handling Cost 2. Labor Cost

Table 4.3 (Cont.) Identification of Activities for Cost Categories

Movement in between Workstations	1. Material Handling Cost 2. Labor Cost
Movement from Workstation to Collection/Shipping Area	1. Material Handling Cost 2. Labor Cost
Disposal of Fluff Bins	1. Material Handling Cost 2. Labor Cost 3. Residue Disposal Cost
Repair and Maintenance of Disassembly Workstations	1. Work Center Operational Cost
Management and Business activities	1. Equipment Cost 2. Facility Installation Cost 3. Admin and Business Expenditure Cost

Specific management and business activities cost include:

- Transportation Equipment Cost: Purchase of materials handling equipment
- Work Center Equipments Cost: Purchase of machines and tools
- Capital Cost: Installation of facility and layout cost
- Administration Cost and Business Expenditure: The supervisor, disassembly consultation and office administration

4.3.2 Variable Cost

Variable costs result from the demanufacturing activities performed on products. These activities cut across different cost incurring groups such as labor, material handling, residue disposal and disassembly cost. Total cost incurred by an activity performed on a product is summation of cost groups (variable costs) participating, for completion of that activity.

4.3.2.1 Labor Cost: Labor cost is the cost allocated as an expense for the services provided by the operators. This cost is normally specified in terms of dollars per hour and attributable to disassemble a product as a function of time required for the disassembly and total direct and indirect handling. The labor rate for that particular type of activity is:

$$\textit{Labor Cost} = (\text{Labor Rate for Activity}_i \text{ in Dollars/hr}) * (\text{Activity Time for Activity}_i \text{ in hrs/Product}) \qquad (4.2)$$

4.3.2.2 Material Handling Cost: There are several different activities for handling/lifting materials/products in a demanufacturing system depending up on the size, weight and volume of the material or product. The material handling in demanufacturing can be divided into four major categories and the cost associated with them can be calculated from respective controlling variables.

- *Internal Transport by Transporter*: The transporter here means a power driven vehicle such as a fork lift truck. The cost associated with the operation of this truck can be calculated as summation of operational and maintenance cost for a specific period of time. Since the ratio of volume to weight of electronics products is high, this cost is then divided in a ratio by volume of products being transported, which will give a cost associated with different types of products and can be called as *transporter cost*. Therefore, the transporter cost per product will be as follows

$$\textit{Transporter Cost} = \text{(Total Annual Transporter Cost)} * \text{C. S} * \frac{\text{(Distance Traveled)}_i}{\text{Velocity of Transport}} * \frac{\text{Volume per Product}}{\text{Total Volume Transported per hr.}} \quad (4.3)$$

Where, C. S = Conversion Scale = 1/8760 per hr.

- *Internal Transport by Conveyer*: The conveyer cost is also calculated from the amount of power consumed over a specific time period. The weight/size of material or product influence the conveyer cost. A cost associated with conveying activity performed on a product can be calculated by allocating the overall cost for that period in the ratio obtained from weight/size of product.

$$\textit{Conveyer Cost} = \text{(Total Annual Conveyer Cost)} * \text{C. S} * \frac{\text{(Distance Conveyed)}_i}{\text{Velocity of Conveyer}} * \frac{\text{Weight per Product}}{\text{Total Weight Conveyed per hr.}} \quad (4.4)$$

Where, C. S = Conversion Scale = 1/8760 per hr.

- *Handling by Cranes*: The same approach is maintained for calculating craning activity cost for moving a product by using crane. The individual cost can be determined by dividing the accumulated cost in a ratio of weight of products being lifted or moved. Hence, the craning cost of the activity can be calculated as below

$$\textit{Craning Cost} = (\text{Total Annual Craning Cost}) * \text{C. S} * (\text{Number of Craning hrs}) * \frac{\text{Weight per Product}}{\text{Total Weight Lifted per hr.}} \quad (4.5)$$

Where, C. S = Conversion Scale = 1/8760 per hr.

- *Material movement by the operator*: This cost incurs when the worker itself carries material. In earlier cases may be a separate operator is employed but in this case the person involved in disassembly himself or a separate operator moves the material keeping the workstation idle. The cost can be calculated by the equation (4.2) used for labor cost by using handling time as the activity instead of disassembly time.

4.3.2.3 Residue Disposal Cost: The cost associated with the disposal of the residue (fluff) is an expense to the company. The disposal cost per product is the summation of cost associated with the disposed items. This disposal cost is normally calculated by pounds of material or items to be disposed. Therefore, the total disposal cost per product can be calculated as

$$\textit{Residue Disposal Cost} = (\text{Dollar Rate per Pound of Specific Disposable Item}) * (\text{Weight of That of Specific Disposable Item in Pounds}) \quad (4.6)$$

Note: Accounts for different disposal cuts for toxic vs. non-toxic materials.

4.3.2.4 Work Center Operational Cost: This cost is combination of operational cost of machines and tooling. An additional factor of safety is included for maintenance and repair costs. The machine cost is the power consumed over a time period and related to disassembly times of different types of products. Considering disassembly as an activity the work center, operational cost can be divided in a ratio of disassembly times for individual product.

Keeping the same approach, the total tooling cost is also divided into a ratio by disassembly times of individual products and called as tooling cost. The total cost for this activity is calculated as below

$$\textit{Work center operational cost} = \text{(Total Annual Machine Cost + Tooling Cost)} * \text{C. S} * \text{(Disassembly/ Tooling time in hours)}_i \quad (4.7)$$

Where, C. S = Conversion Scale = 1/8760 per hr.

4.3.3 Fixed Cost

The fixed cost is normally calculated as a depreciation cost depending on the expected life, salvage value and purchase cost. This depreciation is then the cost per year for that category which can be broken down to per product basis.

General cost formula for calculating the annual cost of facility investment and equipment cost is given below:

$$\text{Depreciation Cost} = \frac{\text{Capital Cost - Salvage Value}}{\text{Years of Expected Life}} \quad (4.8)$$

4.3.3.1 Facility Capital Cost: The initial investment required for establishment of a facility covers the capital cost. It includes land cost, construction cost and all other cost except equipment cost. This lumpsome amount is distributed over a given period, which is called as the expected life. The depreciation cost calculated from equation (4.8) is then allocated in a ratio by volume to assign and distribute the facility capital on per product basis. Therefore,

$$\text{Facility Capital Cost} = (\text{Annual Capital Cost}) * \frac{\text{Volume of Product}}{\text{Total Volume of products handled per year}} \quad (4.9)$$

4.3.3.1 Equipment Cost: The equipment cost is allocated to purchase cost of the equipments, machines, and tools. These cost are also distributed over a period of time. The expected life of these constituents is dependent of their usage and wear rate. The investment in machine tools from demanufacturing point of view may be less as compared with any manufacturing facility. These cost are calculated on annual basis using equation (4.8). This annual cost is then distributed in a ratio of total number of products of specific category to total number of products disassembled.

Therefore,

$$\text{Equipment Cost} = (\text{Annual Equipment Cost}) * C.S * \frac{\text{Total Number of Products of a Specific Category}}{\text{Total Number of Products Disassembled per hr.}} \quad (4.10)$$

Where, C. S = Conversion Scale = 1/8760 per hr.

4.3.3.3 Administration Cost: The administration cost is found over a time period and that cost then may be broken down per product basis by allocating it into a ratio by number of products disassembled over that period.

$$\text{Admin Cost} = (\text{Total Annual Admin Cost per Year}) * C.\,S * \frac{\text{Total Number of Products of a Specific Category}}{\text{Total Number of Products Disassembled per hr.}} \qquad (4.11)$$

Where, C. S = Conversion Scale = 1/8760 per hr.

4.4 Summary of Cost Categories

Notice that all costs are dependent upon one or more number of product properties. The properties are physical characteristics, as well as, run time properties or the activities through which products flow. The run time properties are the times related to disassembly activity and material handling activity. Variation of run time properties affects the operational cost, while variation of physical properties affects the fixed as well as variable costs.

Thus cost incurred by the disassembly activities is the summation of labor cost and work center operational cost. Table 4.2 outlines the activities, including parameters required to calculate the cost associated with that activity.

Table 4.4 Activities and Cost Generating Parameters

Activity Conducted	Cost Generating Parameters
Disassembly of Products	Disassembly Times
Tool Setup for Disassembly	Disassembly Times
Loading of the Material or Products	Material Handling Times, Type of Material Handling System, Times for Labor used
Unloading of the Material or Products	
Movement from Loading Dock to Warehouse	Material Handling Times, Type of Material Handling System, Times for Labor used
Movement from Warehouse to Inspection/ Staging Area	
Movement from Inspection/ Staging area to Workstation	
Movement in between Workstations	
Movement from Workstation to Collection/Shipping Area	
Disposal of Fluff Bins	Material Handling Times, Type of Material Handling System, Times for Labor used, Weight of Disposed Item, Type of Disposed Item
Repair and Maintenance of Disassembly Workstations	Down Times

4.5 Revenue from the Facility

From a business perspective, profit is affected not only by the number of products disassembled, cost per product and also the market value for the basic materials, subassemblies and individual components. The following are major revenue categories for a demanufacturer.

- Resale of Products (reuse)
- Sale of Remanufactured Products: The Category basically involves sale of subassemblies and components
- Sale of reengineerable materials: The category involves sale of basic materials such as plastics like ABS, PVC, HDPS, PC, glass and others.
- Sale of recyclable metals to smelters: The category involves metals like aluminum, steel, copper, gold and silver

The salable items are kept in bins after they are recovered from a disassembled product. The number of bins of basic materials, components and subassemblies multiplied by the market value in dollars for each bin is the trade of that firm. The term "Resale" is included here for those products that pass testing and have secondary market for sale. The repairable products are reworked and send back to the secondary market as remanufactured (or refurbished) products. Such products are normally sold at 65 to 85 percent of their invoice price [55]. These products again go back into the use stage of their lifecycle as reusable or remanufactured products.

The failed products are disassembled and placed in sort bins for different types of materials and components. The number of sort bins is decided by the disassembly plan and market demand for the basic material and products. These are valued on the weight basis and the rate is described as dollars per unit weight of respective fate category.

$$\text{Recovered Value per Product} = \sum_{i=0}^{n} (\text{Dollar Rate per Pound of Specific Item})_i * (\text{Weight of Specific Material/Subassembly in Pounds})_i \qquad (4.12)$$

Where, n = number of valued items.

The specific items include steel, aluminum, copper, plastics, other metals, wires, circuit boards, motors, transformers, CRT's, computer drives and hard disks. The bins also include commingled materials such copper mix and aluminum mix that incorporate impure material extracted from the disassembly operation. Table 4.5 shows the recent market prices for the recovered materials. The prices of metals are average prices for the month of October 1998 reported on internet web site *scrap.org*, where as the prices of polymers are quoted by the suppliers and cited on internet web site *recycle.net* [56].

Table 4.5 Current Market Prices of Recovered Materials (October 1998)

Pure Metals	Price ¢ per lb.	Polymers	Price ¢ per lb.
Aluminum	60.4¢	ABS (Medium Impact Grade)	25-50
Copper	73.0¢	LDPE	12-18
Nickel	$1.79	PVC	5 -40
Zinc	43.6¢	HDPE	14 -21
Lead	22.9¢	PolyCarbonate	15-42

The total cost obtained from the equation (4.1) and the trade figures obtained for different products are compared for determining management issues and increased profitability of the facility.

CHAPTER 5

SYSTEM SIMULATION TOOL VALIDATION

The objective of panel development is to build an interface between the user who knows the demanufacturing operation and a software engine, which performs the simulation, collects detailed operational data, and displays results. To verify the accuracy and validity of the simulation logic running behind the modules in the panel, model validation was performed using data collected from a typical small demanufacturing facility.

5.1 Case Study Definition

The facility under study is a small electronics demanufacturing firm. The objective of the facility is the disassembly of electronics equipment with intent to ship the disassembled parts to outside vendors for further processing. Electronics products coming into the facility range from televisions, computers and monitors, microwaves and vacuum cleaners to large machines like medical equipment, photocopy machines and mainframes. The following describe the general details about the facility under study:

- 10000 sq. feet floor area out of which approximately 500 sq. feet area is actually used for disassembly.
- Staff includes a manager and two workers
- Material handling equipment includes a fork truck and manual movements.
- Disassembly work stations are arranged in parallel operations
- Out of total products 35 % are televisions, 45 % are monitors and 20 % are vacuum cleaners.

The facility performs primary disassembly of a range of electronic products at single-person workstations working in a parallel batch operation method. Parallel batch operations includes the following activities performed by the operator:

- Fetching of the batch from the storage
- Visual inspection for potential reuse or remanufacturing operation
- Disassembly of the products and separating parts and subassemblies into bins
- Delivery of the bins containing disassembled parts to collection and shipment area

Figure 5.1 shows the facility layout identifying locations of different activities.

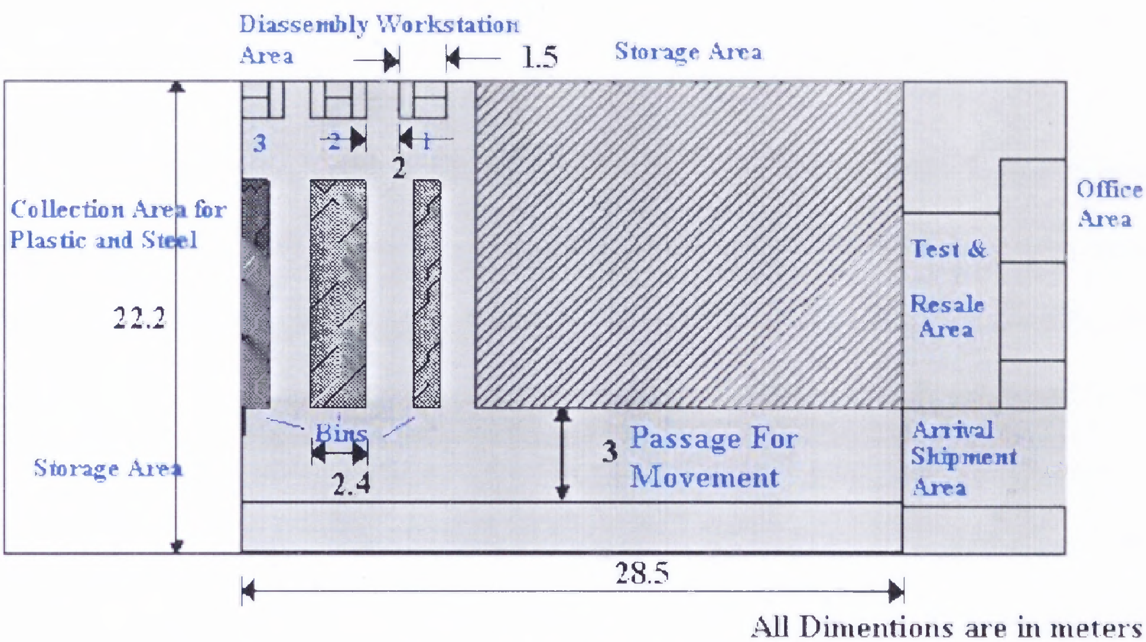


Figure 5.1 Facility Layout

The facility is divided into three major sections: Storage/collection area, disassembly area and office and resale area. The disassembly area contains three disassembly workstations. Each operator has a workstation and a set of tools. The majority of the tools are pneumatic screwdrivers, hammer, pliers and cutters. The evaluation process before disassembly is visual inspection of the product. The reusable products are sent to resale area. Following is a list of predetermined sort bin types:

- Aluminum
- Copper
- Motors
- Capacitors
- Plastics
- Steel
- Circuit Boards
- Wires
- CRT's

The facility operates in a batch process, where each operator gets the batch from storage using the fork truck. The batches are received from two types of sources: discarded by electronics manufacturing companies and local/household collection network. With the electronics manufactures group, products are already disassembled to some level at their internal demanufacturing unit to recover proprietary components or labels attached to the product. These products are fairly uniform. The products arriving through the local/household collection system or distributors normally form batches with great variability in product type and condition. For example one shipment contained twenty-two to forty-four boxes depending up on the method of stacking and size. These boxes from the specific companies may contain 20 to 24 items of only one type of products such as vacuum cleaners or microwaves. The boxes received from local distribution centers contain a range of household electronics products such as televisions, stereos, microwaves, vacuum cleaners and personnel computers.

The received batches are moved to the storage areas and, with exception of monitors, are brought directly to the disassembly workstations without prior inspection. Before starting the disassembly process at the disassembly station, a quick visual inspection of the products is carried out. Each disassembly workstation is composed of a table surrounded by four small bins and a large bin for scrap materials and subassemblies. Tools are arranged before disassembly of the first product in the batch. For large products, the disassembly operation is performed on location where it is stacked or on the floor near the workstation if possible. The disassembly process involves recovery of easily accessible components and materials. The operation can be defined as a "first stage" recovery and separation of materials into bins such as plastics, steel, aluminum, copper, main circuit boards, motors and capacitors. The remanufactured (repair operation) products and bins of recovered materials and components are sent to the collection and shipment area where they are sold to outside vendors for specific recovery processes and/or resold as refurbished products. Figure 5.2 shows the disassembly process flow chart followed by electronics products.

An operator working at the disassembly station performs the entire process described in the flowchart in Figure 5.2 on a batch.

From simulation perspective, the process flowchart can be considered as the model boundaries. The disassembly operator is a moveable resource and the workstation is a server, which actually processes the batch. The resources as well as servers are assigned predetermined states. A state is a condition characterized by the resource or server as

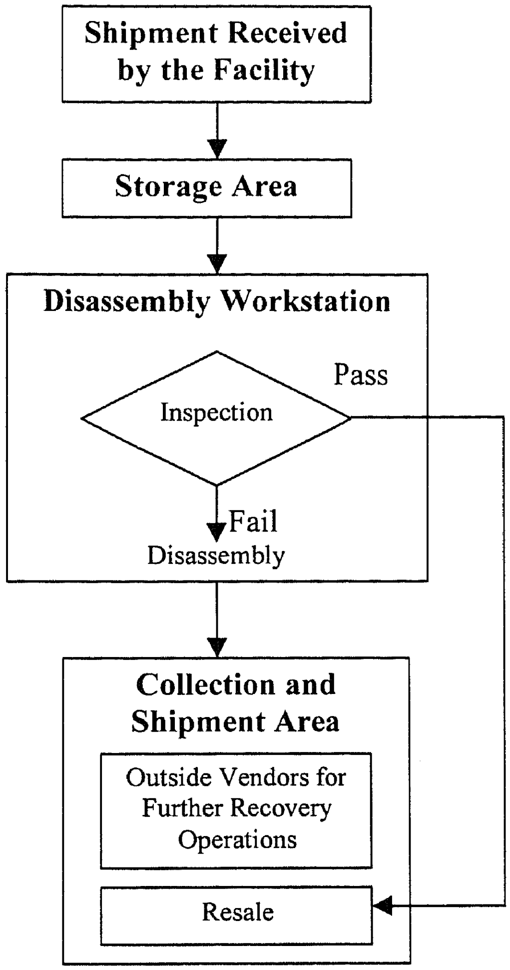


Figure 5.2 Operations Flowchart Followed by products

consequence of an activity. Based on the activities performed, four states such as *Fetch*, *Process* (disassembly), *Deliver* and *Idle* are assigned to resources. Similarly, three activity-based states are allocated to servers: waiting for operator (*Op_wait*), *Process* (disassembly) and *Idle*. If operator is getting the batch from staging/storage then the resource is in *Fetch State*. If the operator is delivering the batch then it is in *Deliver State*. Whenever resource is in *Fetch* or *Deliver State*, the server is in *Op_wait State*, which can be explained because of the method of operation described in preceding paragraphs. Figure 5.3 and Figure 5.4 shows the logic that operates behind the simulation. The complete logic for the validation model is a combination of the logical sequences shown in the Figures 5.3 and 5.4.

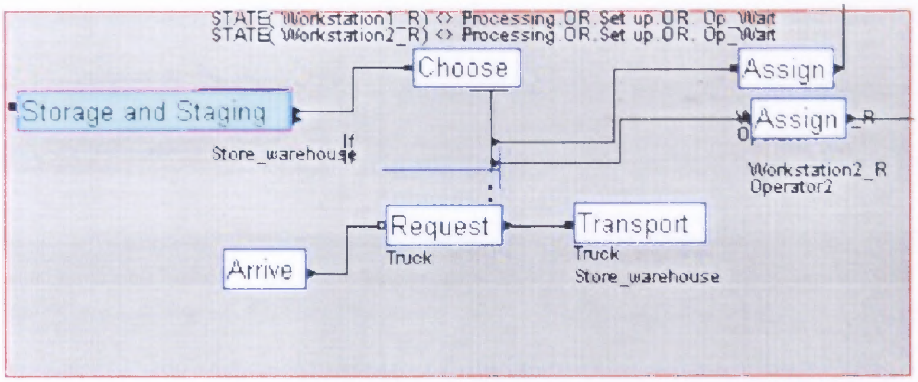


Figure 5.3 Logic for Product Arrival and transfer to Storage

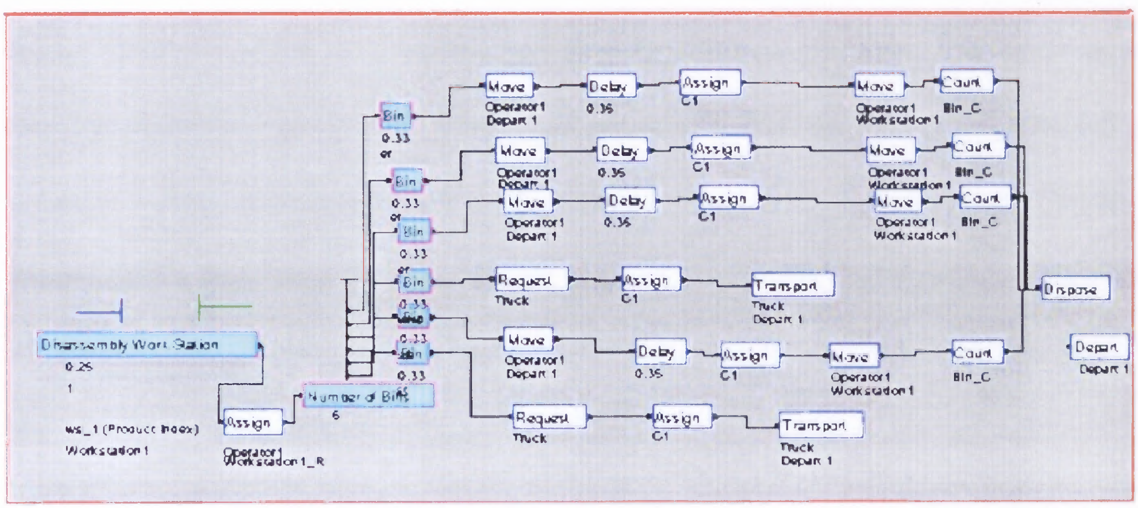


Figure 5.4 Logic for Product Disassembly and Transfer to Collection Bins

Setting up the distributions for inter-arrival times for the batches, number of batches to be created for each arrival and a distribution for generating different types of product batches create the batch using the arrival module. After creating the batch and assigning indices to the generated batch entities to identify types of product batch, the active entities request for a transporter to move into the storage and staging area. The storage and staging area module receives the entities and stores them and sends to the disassembly workstations depending upon the state of workstation. A "*choose*" module is used to check the states and directs the batch (entity) to the respective workstation.

At the disassembly workstation template, the user inputs unload, tool set up and disassembly times for the batch and name of workstation. The active batch entity undergoes a delay for all the times and proceeds to the number of bins module where batch is decomposed into specified number of branches equal to number of bins selected. For each bin the user specifies the capacity of bin and time required for loading the filled bin on a transporter. An operator then moves the bins to the collection location manually or using a truck. The logic that incorporates manual movement requires a positional resource such as operator, move and delay module as shown in Figure 5.4. The product entity before depart in case of transporter, or *dispose* in case of manual handling, increases the individual counters from a counter set for number of different types bins disposed of for final value of total number of bins of components and parts generated after disassembly. These counters are necessary to calculate the throughput and revenue generated from the operations.

5.2 Data Collection Process

The data collection process was performed for two different days and eight hours per day. The data is collected for vacuum cleaners and televisions. Table 5.1 gives the data sheet of disassembly times for the same products. The disassembly time also includes the time required to transfer the disassembled part to appropriate bin within 4 feet of the workstation table.

The data on products arriving into facility was also collected for a period of three months starting from May to July 1998 from the report sheets in the facility. The data sheet is attached as Appendix E. In a real system the time required to disassemble a product is undeterministic and dependent upon a number of variables such as condition of the product, structure of the product and depth of disassembly. So these variations appear by chance and cannot be predicted by the modeler. To model such a stochastic system, the modeler then selects a known distribution form, makes an estimate of parameters and then tests the distribution for its accuracy in prediction. These distributions with random number generator programs are used within the model for estimating times.

Table 5.1 Disassembly Times in minutes for Vacuum Cleaners and Televisions

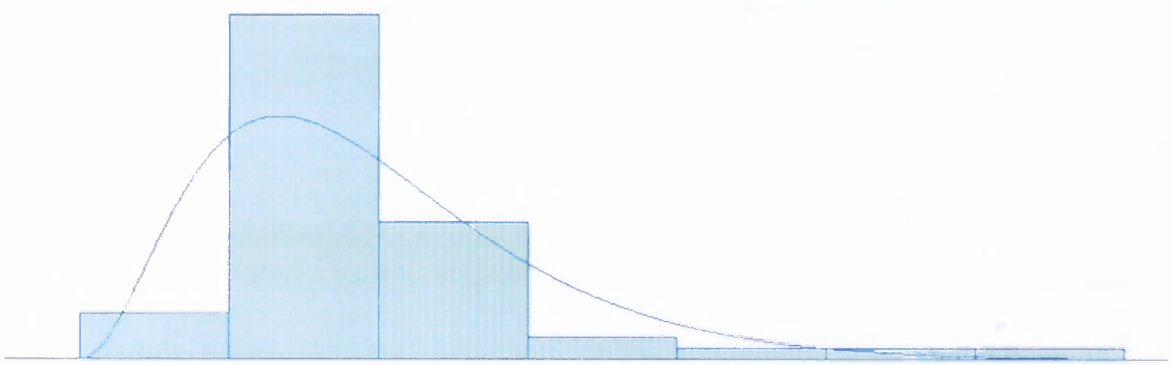
Vacuum Cleaners								
Disassembly Times in minutes	2.58	1.55	1.19	1.79	3.13	2.58	1.75	1.52
	2.25	1.33	1.1	0.91	1.17	1.36	1.14	0.92
	5.16	1.3	1.59	1.33	1.19	1.4	2.08	1.87
	0.8	1.49	1.38	4.3	1.44	1.47	1.52	1.98
	1.36	1.4	1.11	1.66	1.63	1.7	1.63	1.84
	2.24	1.51	1.33	1.66	1.83	1.36	1.83	1.87
	1.78	1.26	2.16					

Televisions								
Disassembly Times	5	6	6	5	4	7	4	4
in minutes	25	4	5	3	11	4	7	15

With the above data the distributions were created using *Arena's Input Analyzer.* The input analyzer provides continuous theoretical distributions such as exponential, normal, triangular, uniform, beta, gamma, lognormal, and Weibull. The Poisson distribution is a discrete distribution used to generate the integer valued quantities. The following steps are followed to fit distribution via analyzer

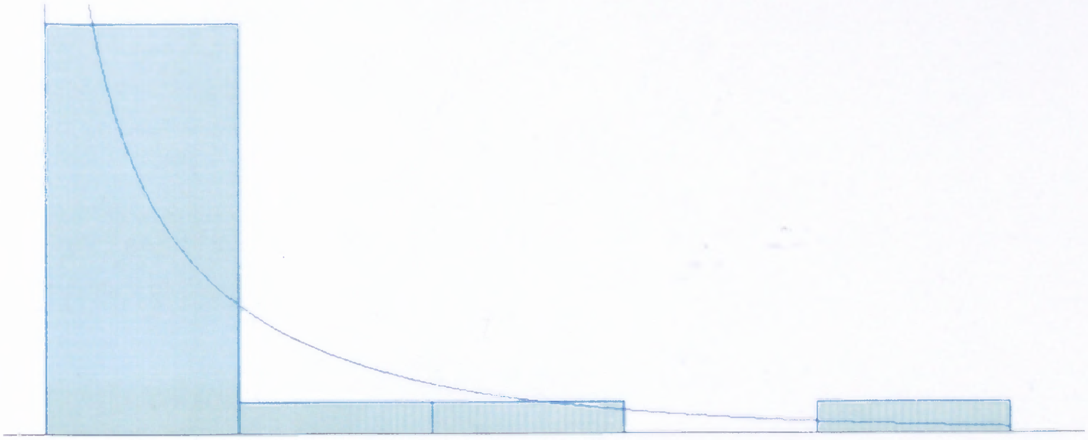
- Create a data file in an editor.
- Open the input analyzer and import the data file.
- Fit one or more distributions, select which one is most appropriate. Analyzer performs chi-square and Kolmogorov-Smirnov tests and returns the test results for each distribution fitted.
- Copy the expression and import it into Arena's model design window.

Figure 5.5 and 5.6 show the input distributions selected for vacuum cleaners and televisions. Appendix E includes the distribution for products arriving into the facility with associated data sheet.



```
Distribution Summary

Distribution:   Gamma
Expression:     7 + GAMM(9.07, 3.15)
Square Error:   0.054950

Chi Square Test
  Number of intervals   = 4
  Degrees of freedom    = 1
  Test Statistic        = 11.4
  Corresponding p-value < 0.005

Kolmogorov-Smirnov Test
  Test Statistic        = 0.152
  Corresponding p-value > 0.15

Data Summary

Number of Data Points   = 51
Min Data Value          = 7.38
Max Data Value          = 108
Sample Mean             = 35.5
Sample Std Dev          = 16.5

Histogram Summary

Histogram Range         = 7 to 109
Number of Intervals     = 7
```

Figure 5.5 Distribution Fit for Vacuum Cleaners



Distribution Summary		Data Summary	
Distribution:	Weibull	Number of Data Points	= 16
Expression:	63 + WEIB(72.9, 0.704)	Min Data Value	= 63
Square Error:	0.027020	Max Data Value	= 525
		Sample Mean	= 151
		Sample Std Dev	= 119
Kolmogorov-Smirnov Test		Histogram Summary	
Test Statistic	= 0.278	Histogram Range	= 63 to 525
Corresponding p-value	= 0.141	Number of Intervals	= 5

Figure 5.6 Distribution Fit for Televisions

5.3 Analysis and Results

The distributions in Figure 5.5 and 5.6 are input for disassembly times into server modules, which are the disassembly stations. The data is collected on a typical operations day. The purpose of validating a model is to evaluate the correctness of simulation logic with the environment. The simulation results should reflect the data collected for a typical operations day. Figure 5.7 shows a snap shot of animation screen of the validation model and Table 5.2 shows summary of observed and simulated data.

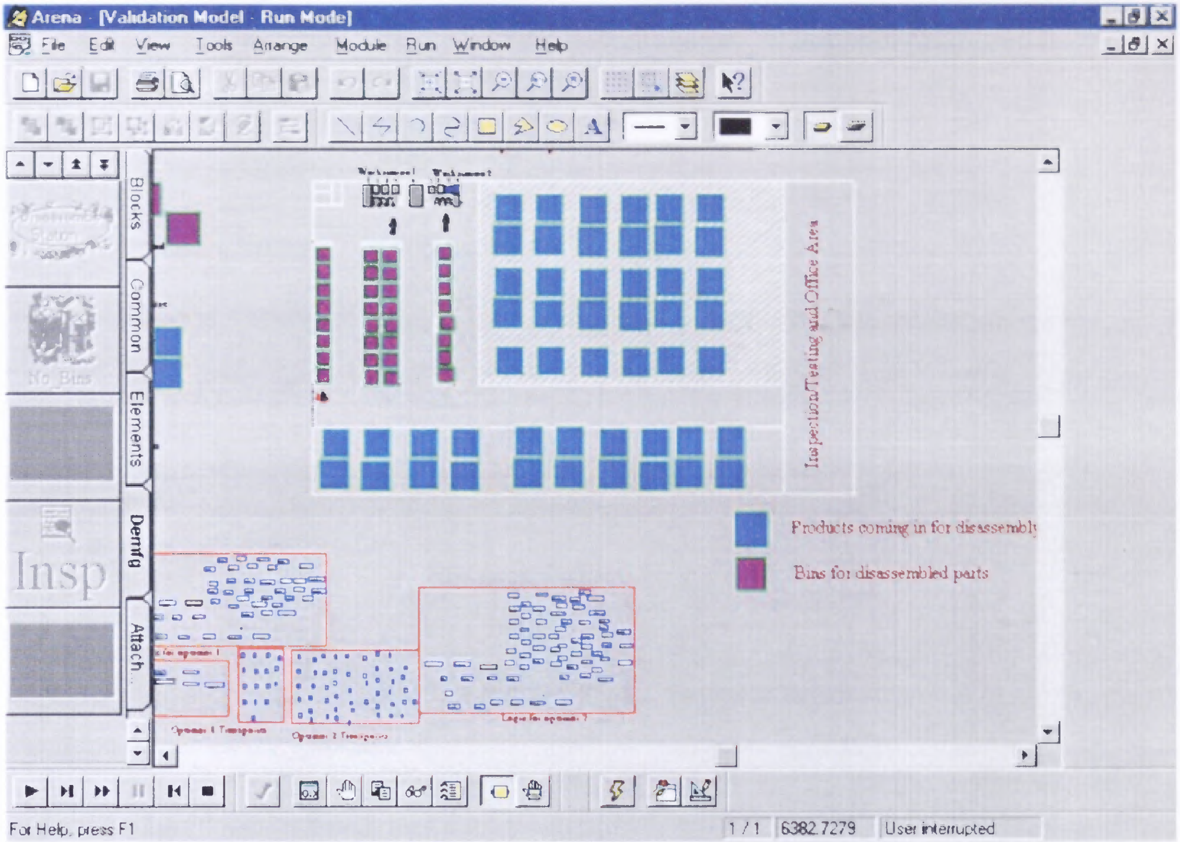


Figure 5.7 Animation Snapshot of Validation Model

Table 5.2 Summary of observed and simulated data

Pallets Coming into Facility per Month		Pallets Processed in Four Days	
Observed	Simulated	Observed	Simulated
129	127	15	17
113	249	17	19
226	114	14	12

Validation demonstrates that the simulation accurately models the existing operation consequently is capable of handling "what if" scenarios such as:

- Equipment and operational changes
- Staging in work volume
- Increase in work flow
- Layout modifications

Figure 5.8 shows the workstation time allocation statistics for the validation model. From the figure, it can be observed that most of the time the workstation is waiting for operator and approximately twenty-six percent of time is utilized for disassembly operation.

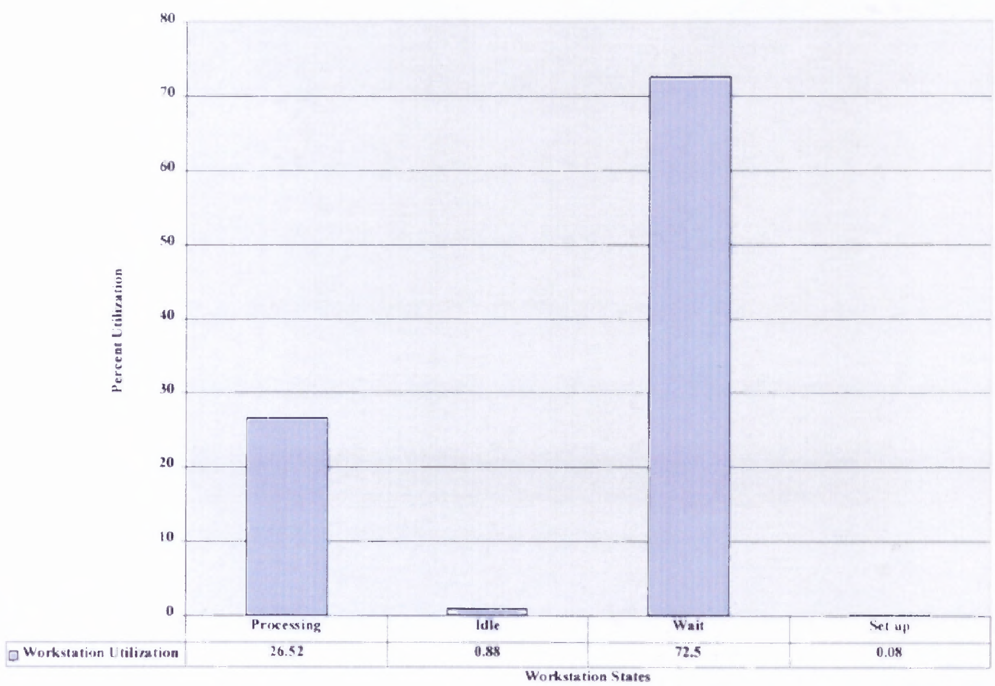


Figure 5.8 Results on Workstation Time Allocation

Figure 5.9 shows Operator (resource) time allocation statistic. The preliminary simulation results show that workers are involved in actual disassembly operation approximately nineteen percent of the time, while they are delivering the bins filled with recovered material to the collection/shipment area approximately forty-four percent of the time.

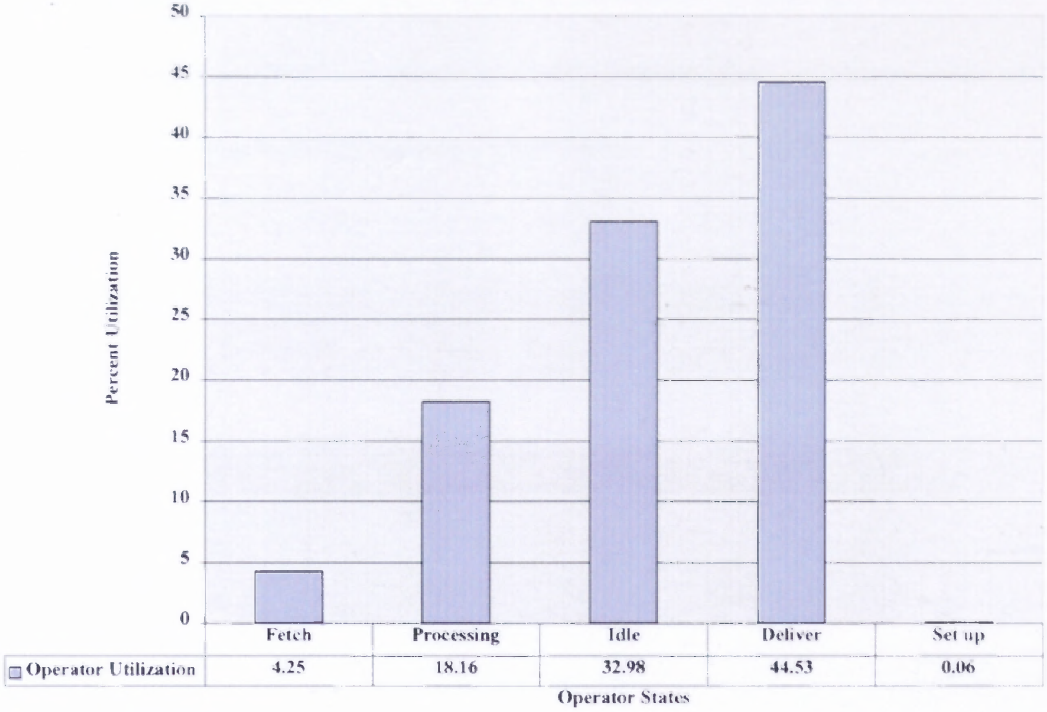


Figure 5.9 Results on Operator Time utilization

From Figure 5.9, it can be observed that approximately fifty percent of the time operator was involved in material handling activity and that is why the workstation utilization figure indicates more time allocated to operator-wait period. The observations and results suggest that the material handling activity could be improved to reduce net transportation time. Indicated few bottlenecks in the operations can be cites as:

- Operator idle time is greater than the processing time. The potential cause may be unavailability of transporter for the operator because of dispatching and unloading of the products at the storage area.
- Too few numbers of operators or allocation of this available time causing increase in transfer times.
- Material handling time is greater than actual processing time suggesting reevaluation material handling activity.

The current operations statistics and above observations reveal the inefficiency and bottleneck in existing method of operation and also suggests improvements in the current operation. These options are discussed in Chapter six.

CHAPTER 6

FACILITY AND OPERATIONAL IMPROVEMENT ANALYSIS

6.1 Alternative Operational Strategies

Examining the results from simulations performed for validation of the software tool, some suggestions for improvement can be drawn:

- Revising the layout of the facility to reduce time for moving filled bins to the collection/shipping area.
- Increase size of the sort bins to hold more material leading to fewer trips by workers.
- Assign a separate worker to move bins while others continue to disassembly products.
- Addition of material handling equipment to reduce waiting for availability of the transporter.

The key point driving most of these suggestions is to reduce net percentage of transfer times. The increase in bin capacity has limitations of available bin sizes, transporter capacity and handling and location space. The present capacity of bins is matches size and place available. Increase in bin size will reduce the number of delivery trips but time required to move the larger bins is much more than time required to move smaller capacity bins. The total time required for loading, unloading and transport together for moving a bin from disassembly workstation to collection/shipment area can be calculated as:

Total Transport Time per Trip = Loading Time + Transport Time + Unloading Time

Assuming constant velocity operation, transport time can be calculated as:

Transport time = Distance Traveled (m) / Transporter Velocity (m/min) = 8 / 25 = 0.35

From twenty observations made during the data collection process, the average time required to load the bin on a truck is 0.33 minutes, to unload a bin from truck is 0.35 minutes and to manually move the bin is 0.33 minutes.

Total Truck Transport Time per Trip = 0.33 + 0.35 + 0.35 = 1.03 minutes.

This time difference of 0.70 minutes is because, collection bins are located eight meters apart from disassembly workstation. Instead of increasing bin size, increase in operator and increase in number of transporters alternatives are simulated and the results are presented in next section

6.2 Results of Simulated Alternatives

The improvement options selected for simulation and evaluation of throughput, worker and workstation time allocation are:

1. An additional operator to receive the batches after their arrival. This operator is not used for delivering the filled bins because the operator at disassembly workstation has to wait until the bins are located back in their place. If the additional operator is used to deliver the bins and disassembly operator is sent for getting new bins the time can be reduced by few seconds but not by significant amount. This operator can be used for staging and inspection operation other than transporting the batches for his effective time utilization.
2. An additional operator and an additional fork truck are incorporated for efficient movement of materials and less transfer times.

6.2.1 First Improvement Option

The first improvement option keeps the set up of existing two operators, however employs an additional operator to receive batches from the facility.

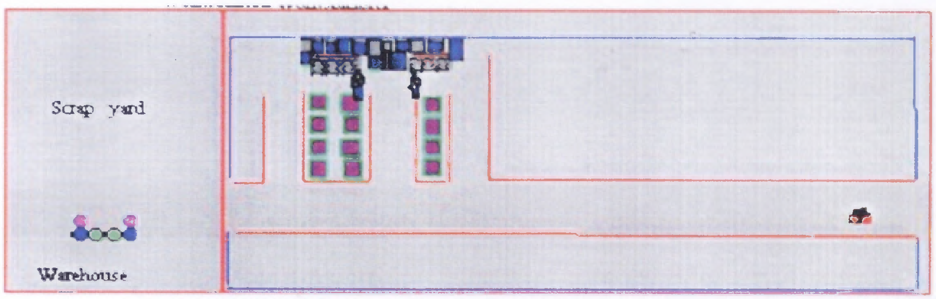


Figure 6.1 Animation Snapshot of first Improvement Option

The logic running behind the disassembly operators is the same as explained in Chapter 5. The additional operator is assigned to move batches from unloading location to storage area Figure 6.1 shows the animation snapshot of simulation. The additional operator description uses the same definition of other two operators as a part of its logic in model development.

The arrival module creates the batches, which are transferred to the storage and staging area. The highest priority of allocating truck is given to movement of products from unloading dock; i.e. arrival dock to storage area. The next priority is given to movement of batches from storage area to disassembly workstation and then the delivery routes are prioritized. A lower the priority number relates to a higher is the priority of the activity. Figure 6.2 and figure 6.3 show graphs along with the data sheet of the time utilization of disassembly workstation and operator respectively. The simulations are performed in three runs of five replications per run and a simulated period of four days per replication.

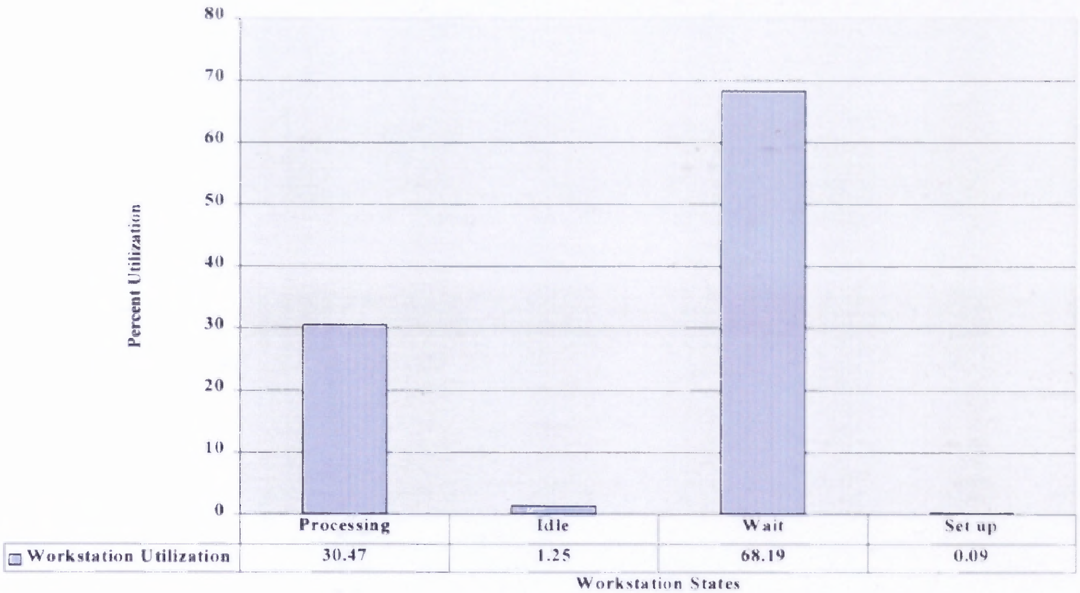


Figure 6.2 Time Utilization of Disassembly Workstation (1)

The data sheet attached to the graph in Figure 6.2 shows the average percentage of time consumed by the disassembly workstation and operator.

On comparison with the results from existing operation (validation model), the improvement option reduces the net operator-waiting period to sixty-eight percent and net processing time is increased to thirty percent.

Similarly, percent time spent in delivery of filled bins is reduced to forty percent increasing the processing time to forty nine percent. The results show that higher percentage of time are utilized by operator and consequently by the workstation in "Deliver" and "Wait" process states respectively. The potential cause of these higher percentages may be unavailability of truck immediately after the request. The sharing of truck by the two operators at disassembly workstation and one additional operator can support the above caused relationship.

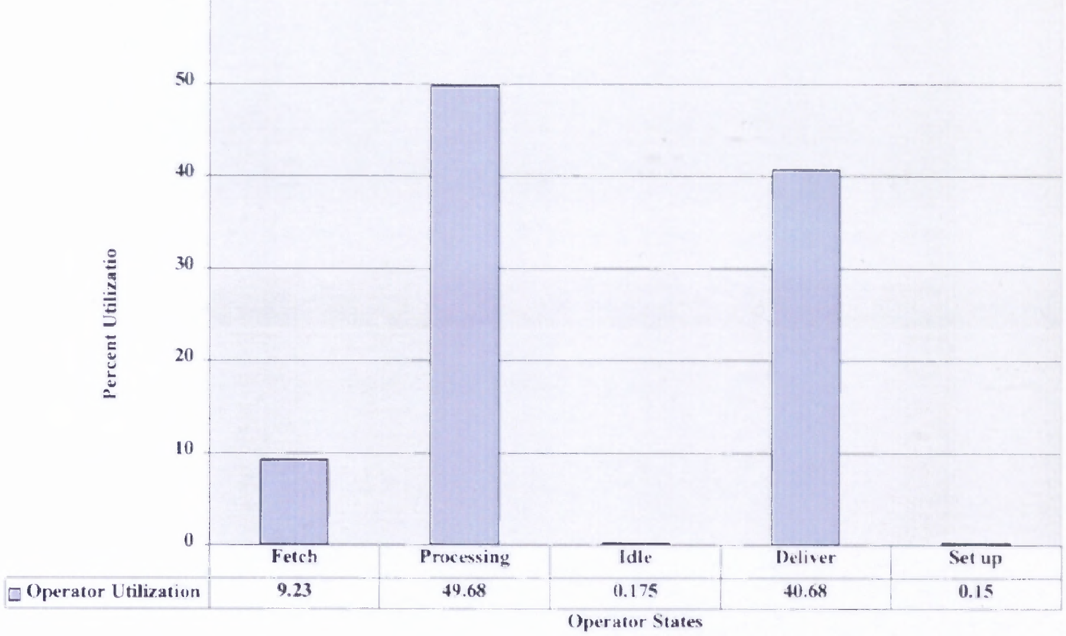


Figure 6.3 Time Utilization of Operator (1)

The operation can be evaluated again by introducing an additional forklift truck (5000 lb capacity), in addition to, three operators and forklift truck. The second improvement scenario describes and discusses the results of these changes.

6.2.1 Second Improvement Option

This improvement option simulates both the operator and equipment changes for improving the throughput and time utilized by the resources. Both the trucks are allocated on a "preferred order" basis, in which the routes are prioritized by the analyst. Keeping the priorities of material movement the same as explained in scenario one the simulations are performed. Figure 6.4 shows the animation snapshot of the simulation showing two transporters.

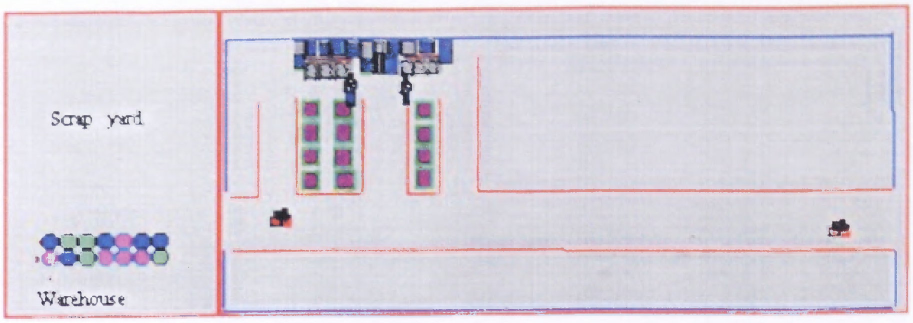


Figure 6.4 Animation Snapshot of Second Improvement Scenario

Histogram along with the data sheet, for the time utilization of disassembly workstation and operator are shown in Figure 6.4 and Figure 6.5 respectively.

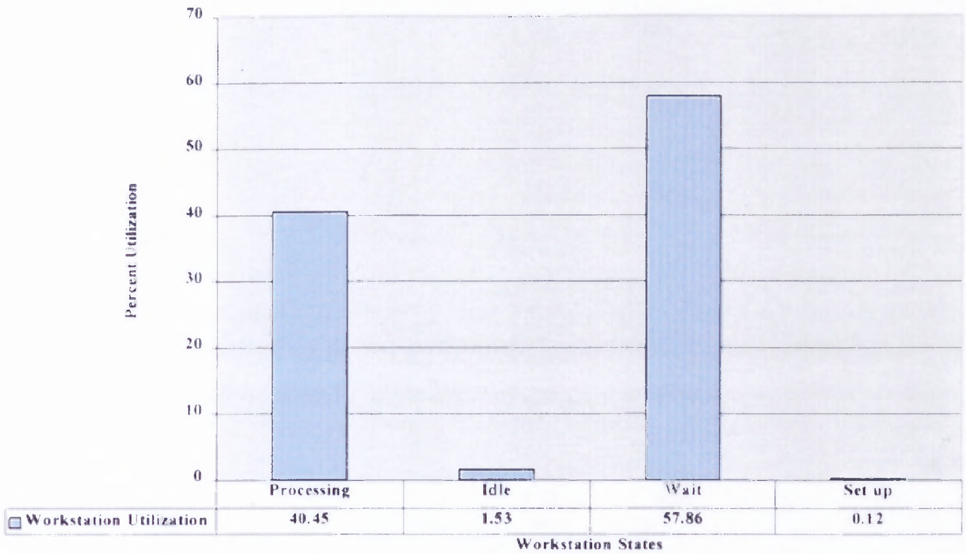


Figure 6.5 Time Utilization of Disassembly Workstation (2)

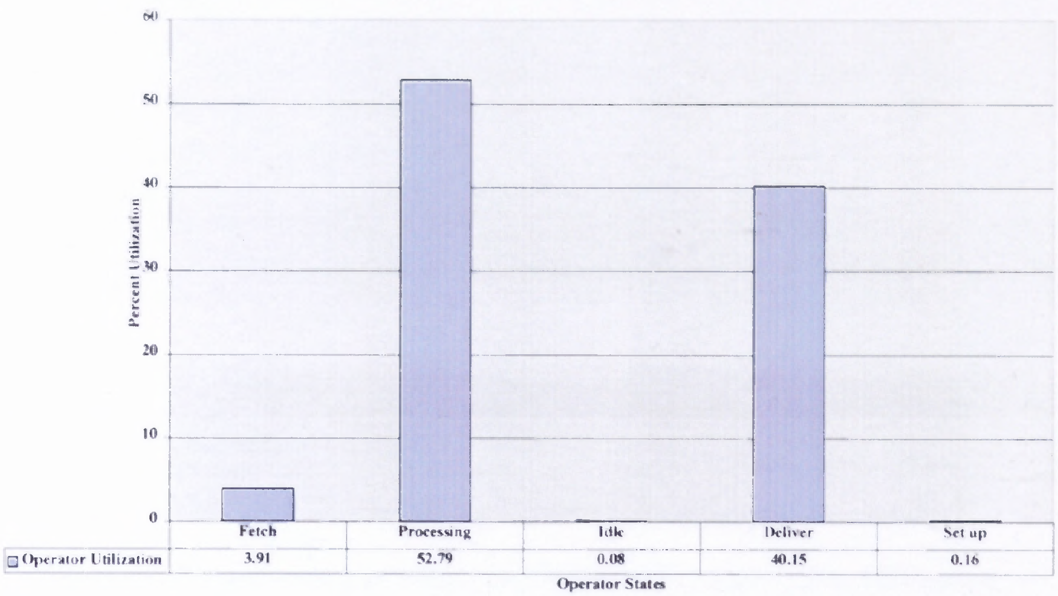
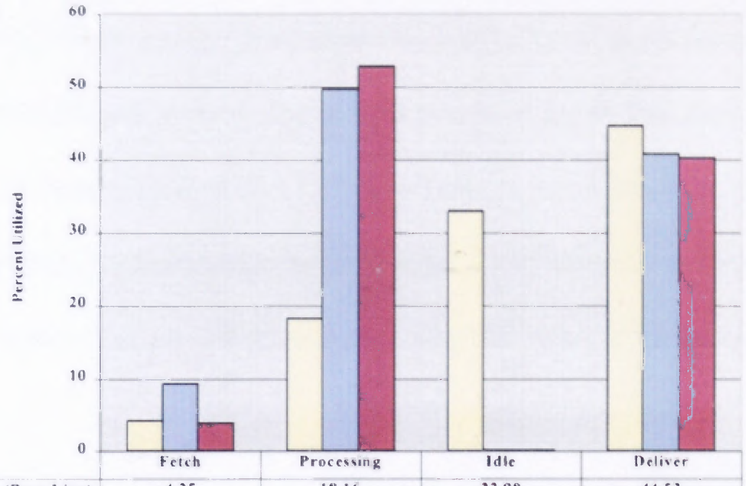


Figure 6.6 Time Utilization of Operator (2)

In comparison with first scenario there is a ten percent increase in processing time and approximately ten percent decrease in operator-waiting time at the disassembly works station. Also there is a marginal increase in processing time of disassembly workstation. The next section describes in details, the comparative study of the two improvement scenarios with base line "as is" scenario.

6.3 Comparative Study

This section describes deals with comparison of results obtained from simulating two different improvement scenarios with the base line scenario in terms of time allocation for the activities, cost of improvement and revenue from the improvement. Figure 6.7 and Figure 6.8 show comparative time utilization of operator and disassembly workstation.

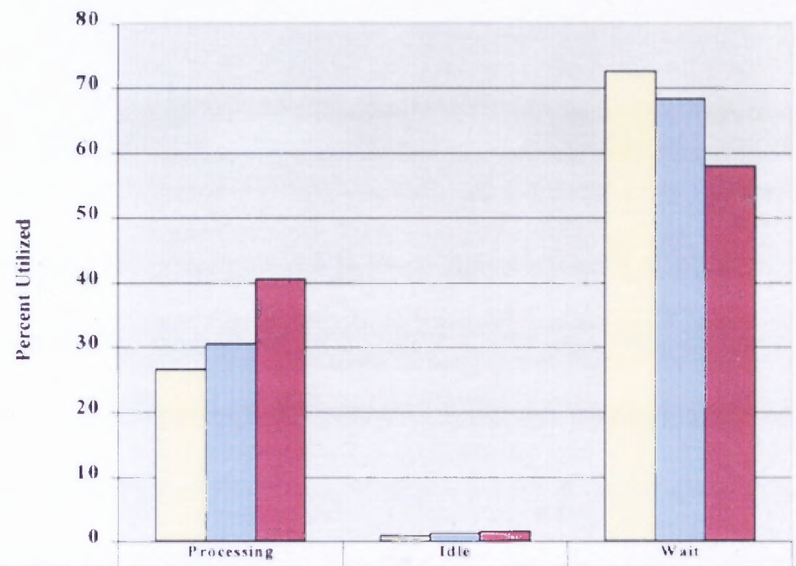


	Fetch	Processing	Idle	Deliver
Operator Time Allocation (Base Line)	4.25	18.16	32.98	44.53
Operator Time Allocation (1)	9.23	49.68	0.175	40.68
Operator Time Allocation (2)	3.91	52.79	0.08	40.15

Operator States

Figure 6.7 Comparison of Three Scenarios on Operator Time Utilization

It can be observed from the Figure 6.7 that there has been successive reduction in the idle time as well as increase in the processing time. The time consumed in delivering the batches has also been reduced by four percent compared with base line scenario.



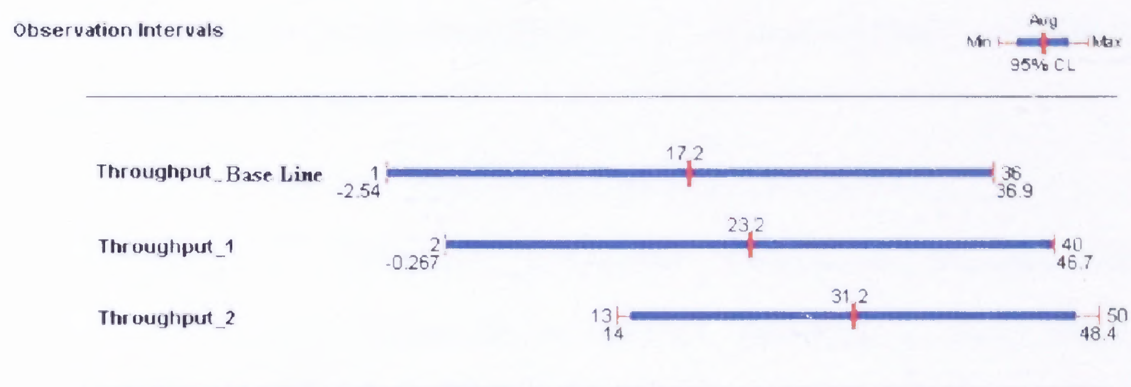
	Processing	Idle	Wait
Workstation Time Allocation (Base Line)	26.52	0.88	72.5
Workstation Time Allocation (1)	30.47	1.25	68.19
Workstation Time Allocation (2)	40.45	1.53	57.86

Workstation States

Figure 6.8 Comparison of Three Scenarios on Disassembly Workstation Time Utilization

It can be observed from Figure 6.8 that the utilization of the disassembly workstation has increased by successive reduction in operator-wait time. This wait time incorporates the total waiting period for the workstation in receiving as well as delivering the batches.

The improved allocation to disassembly activities directly leads to an increase in the throughput of the facility. Figure 6.9 shows that the variation, at 95 percent confidence level, in total number of product batches disassembled during the simulation period of four days.



Classical C.I. Intervals Summary

IDENTIFIER	AVERAGE	STANDARD DEVIATION	0.950 C.I. HALF-WIDTH	MINIMUM VALUE	MAXIMUM VALUE	NUMBER OF OBS.
Throughput_Base Line	17.2	15.9	19.7	1	36	5
Throughput_1	23.2	18.9	23.5	2	40	5
Throughput 2	31.2	13.9	17.2	13	50	5

Figure 6.8 Confidence Interval on Total Number of Products Disassembled

The total number of batches disassembled in the base line scenario is 17 with a standard deviation of nineteen batches. The average number of batches disassembled in first scenario is twenty-three with a standard deviation of eighteen products and the second scenario disassembles an average thirty-one batches in four days with a standard deviation of thirteen batches, which is significantly less than the other two scenarios. From this observation, that total number of products disassembled in baseline and first scenarios have a higher variation than observed for second scenario.

To compare the economic viability of the improvement scenarios, Table 6.2 shows comparative cost changes due to improvement options assuming base line cost as zero. Using labor rate of 8 dollars per hour and 8000 dollars as capital cost of forklift truck the cost incurred from improvement options is calculated. The information is obtained from private discussion with small demanufacturing facilities.

The net labor cost incurred can be calculated using equation (4.2) for both the scenarios.

Labor Cost = 8 * (4*8) = $ 256 ...(6.1)

The labor cost per product for simulation period of four days and twenty-one products per batch is calculated as follows:

Table 6.1 Labor Cost per Product for Three Scenarios

Scenario	**Labor cost per Labor ($)**	**Number of Labors**	**Throughput (Batches)**	**Net Labor Cost per Batch ($/Batch)**
Base Line Scenario	256	2	17	31
First Scenario	256	3	23	34
Second Scenario	256	3	31	25

Similarly, Using equation (4.8) depreciation cost of fork truck assuming salvage value of $1000 and life of 8 years can be calculated as:

(8000-1000)/8 = $ 875 per year = 0.09 $ per hour ...(6.2)

The truck fixed is independent of the activities performed by the truck Therefore, for calculating the truck cost in three scenarios total time consumed by one or more transporter is the same and corresponds to simulation time of 4200 minutes. Table 6.2 shows the truck cost on per product basis for three scenarios.

Therefore, from eq. (6.2)

Truck Cost for simulation period of four days = 0.09 * 5760= $ 8.64 ...(6.3)

Table 6.2 Truck Cost per Product for Three Scenarios

Scenario	Truck cost er Truck ($)	Number of Trucks	Throughput (Batches)	Net Truck Cost per Batch ($/Batch)
Base Line Scenario	8.64	1	17	0.50
First Scenario	8.64	1	23	0.38
Second Scenario	8.64	2	31	0.55

The facility capital cost and administration cost, being cost throughout the study are not considered. Also, the truck operational cost is also not included because of insufficient data on truck operational efficiency and fuel consumption. Table 6.3 summarizes the total cost of operation including the labor cost and truck cost. In addition to, total cost on per product basis, the table also provides total cost incurred from three scenarios.

Table 6.3 Summary of Total Cost Incurred

Scenario	Net Labor Cost per Batch ($ per Batch)	Net Truck Cost per Batch ($ per Product)	Total Cost per Batch ($ per Batch)	Total Cost of Facility ($)
Base Line Scenario	31	0.50	31.50	535.50
First Scenario	34	0.38	34.38	790.14
Second Scenario	25	0.55	25.55	792.05

The net value recovered from disassembling the products from the scenarios can be calculated using the value of recovered materials minus the residual disposal cost. The cost effectiveness of the improvement scenario is ratio of net value recovered to net disassembly time required for value recovery. Using the thesis work of Devendra Badwe [57] Table 6.4 shows the dollar value of recovered materials. Since both monitors and televisions are disassembled to the same level of recovering CRT, they are clubbed together.

Table 6.4 Value of Recovered Materials for Monitors and Televisions
[Source 57: page 185]

Type of Bin	**Weight per Batch (lb)**	**Value ($/lb)**	**Value of Recovered Materials ($ per Batch)**
Dirty Steel	30.87	0.02	0.62
Aluminum	0.21	0.4	0.08
Dirty Copper	15.92	0.5	7.96
Mixed Plastic	103.47	0.005	0.52
PCB's	1.89	0.10	0.19
CRT	239.8	0.10	23.98
Total Value Recovered per batch			**33.35**

The landfill cost can be calculated as shown below [57]:

Total Weight of Fluff = 0.084 tons per batch ...(6.4)

Therefore,

Landfill Cost = Tipping Fee ($ per ton) * Total Weight of Fluff (tons)

= 75 * 0.084 = $ 6.30 per batch ...(6.5)

Net Revenue = Value Recovered - Landfill Cost)

= 33.35 - 6.30

= $27.05 per batch ...(6.6)

Assuming forty-seven percent of dirty copper and remaining dirty steel in a motor of a vacuum cleaner, the total value of materials recovered using Table 6.4 is $ 1.23 from one motor of five pounds. Therefore, the value recovered from vacuum is calculated by assuming resale value of 25 cents per pound for motors and 0.005 dollars per pound for the remaining mixed plastic from Table 6.4.

Table 6.5 Value of Recovered Materials for Vacuum cleaners

Type of Bin	**Weight per Batch (lb)**	**Value ($/lb)**	**Value of Recovered Materials ($ per Batch)**
Motor	105	0.25	26.25
Mixed Plastic	157.5	0.005	0.79
Total Value Recovered per batch			**27.04**

Fourteen out of seventeen batches in base line scenario, eighteen out of twenty three batches for first Scenario and twenty-six out of thirty-one for the second scenario were of televisions and monitors. Using Table 6.4 and Equation (6.6) total revenue is calculated as shown in Table 6.6 and Table 6.7 summarizes cost and revenue from the facility

Table 6.6 Total Revenue from the Facility

Scenario	Revenue from Televisions and Monitors ($)	Revenue from Vacuum Cleaners ($)	Total Revenue ($)
Base Line Scenario	378.7	108.16	486.85
First Scenario	486.9	135.02	622.10
Second Scenario	703.3	135.02	838.50

Table 6.6 Summary of Cost and Revenue Analysis

Scenario	Total Cost of Facility ($)	Total Revenue ($)	Profit/ (Loss) ($)
Base Line Scenario	535.50	486.85	(48.65)
First Scenario	790.14	622.10	(168.04)
Second Scenario	792.05	838.50	46.45

6.4 Recommendation Suggested

From observations on time utilization and total number of batches disassembled, cost and revenue analysis reflects that the *scenario one* has higher throughput from the facility, but cost and revenue study does not provide promising results. Actually it increases the loss by approximately $120.

The throughput and cost-benefit analysis shows that *scenario two* not only produces higher throughput of thirty-one batches, but also provides gains to the facility. The cost-benefit results in Table shows that the facility improves its economical status by approximately $86 on implementation of second scenario. The scenario two can be implemented in the facility to improve overall efficiency of the facility by increased throughput, lower cost per product disassembled and higher gains for the facility.

CHAPTER 7

SUMMARY AND CONCLUSION

The chapter summarizes the results and draws conclusions from the research presented in this thesis. The first section summarizes results obtained by using the demanufacturing simulation tool and presents the general conclusions from this entire research. The second section presents recommendation further development of the system simulation tool.

7.1 Summary of Demanufacturing Model and System Simulation Tool

The demanufacturing systems model reflects all the activities and prcesses performed on discarded products. The generic model includes:

- The reverse collection/distribution system: To assess the impacts from transportation of discarded products and recovered materials, a truck transportation model is developed. The transportation model evaluates the energy requirements and emissions from transportation.
- The demanufacturing activity: This module reflects the logical flow of products through the demanufacturing facility from unloading, storage and staging to inspect, disassembly, sorting and collection for shipment.
- The products of the demanufacturing activity are represented as outputs from the demanufacturing facility incorporating all end fate categories such as reuse, remanufacturing, reengineering, smelting and residue disposal. The disposal option sends the residue to landfill or incineration for energy recovery.

The generic demanufacturing systems model developed in this thesis is implemented as a computer based system simulation tool specifically designed for evaluating demanufacturing facility layouts and operational strategies. The simulation tool is developed using commercially available simulation software **Arena** by **Systems modeling Corporation**. The demanufacturing simulation tool is developed to model various scenarios configurations and evaluate the following functions:

- Analysis of operational strategies
- Evaluation of facility layout options
- Evaluation of machine/worker utilization and material handling equipment changes.

The simulation tool is integrated with an activity based cost model to assess the economic performance of current operations and evaluate cost-benefit tradeoffs from improvement options. The cost model presents the cost incurred on per product basis. It incorporates and allocates the fixed cost as well as variable costs. The total cost per product is calculated using the equations developed in chapter four, which give the cost of each activity associated with processing products through the demanufacturing facility.

7.1.1 Summary Demanufacturing System Simulation Tool and Conclusion

The simulation is developed to assess and evaluate overall efficiency and operations in a demanufacturing facility. The tool incorporates the following customized modules and simulation logic for a demanufacturing facility:

- Storage and staging area
- Disassembly workstation
- Number of Bins

- Bins
- Inspection and Testing area

The current modules in the software are sufficient to model for material-handling systems used by demanufacturers. Validation of simulation system was performed based upon data collected by observing the operation of a small electronics demanufacturing facility. The model structure and operational logic of the customized modules have verified by comparing simulation output with observed data. The summary of base line scenario and two improvements scenario is given below:

- The *base line scenario* simulates the facility incorporating two operators and a truck, in addition to, manual movements for material handling. The simulation results showed that the facility was not efficiently utilizing the workers, as only eighteen percent of the time the operator was actually disassembling products. Since an additional eight percent of time was consumed in materials handling activities, the disassembly workstation was disassembling for twenty-six percent of the time. The cost analysis (Chapter 6) showed that the operations incur higher cost than revenue creating a loss of approximately $48 for the simulated four days of operation.
- To improve operations, two improvement scenarios have developed and simulated. In *scenario one*, an additional operator was introduced to receive batches from the unloading dock to storage area. The results reflected increase in throughput from seventeen batches to twenty-three batches. Also, the percent time utilization of both operators and workstation improved by twenty-seven and four percent, respectively. But, the cost-benefit results showed that there has been increase in loss by $120. This

additional in loss was due to the less than expected throughput and higher percent transfer times compared to the increased cost of adding a new operator.

- In order to reduce the material handling transfer time an additional truck was introduced for the *second improvement scenario*, keeping same number of operators as with scenario one. The results showed that both workstation and operator utilization improved by approximately fourteen and thirty percent, respectively. The simulations have increased the throughput from seventeen batches seen in the base line scenario to thirty-one batches for this scenario. Similarly, The cost-benefit results showed that this improvement scenario has generated a profit of $46 by improving the net gains of $90 as compared with the base line scenario.

The results demonstrated the usefulness demanufacturing simulation tool in evaluating overall improvement in the operations of actual demanufacturing facilities. The following section draws the general conclusion of this research.

7.1.2 General Conclusions

- Commercially available Simulation softwares are complex and require extensive training, however the customized tool developed provides a bridge (interface) between rigorous simulation nomenclature and terminologies used by demanufacturer.
- The simulation tool was accurately validate based on actual data collected as part of this thesis research and used to evaluate alternative improvement options.
- From the observation of the simulation results material-handling time was a key activity that significantly influences the worker and machine utilization time.

- Throughput from the facility is depends upon disassembly times, transfer times and facility layout and planning. Therefore, extensive data on above decision variables is necessary and important for fitting distributions. The more data helps analyst to fit the most appropriate distribution.
- Lastly, while dealing with simulation, there are several issues, which restrict and slow the pace of development. Some of these are lack of sufficient information on product disassembly times, variability of products incoming stream, inconsistent performance of operators resulting in lower throughput.

7.2 Future Recommendations

- There are still areas in the software tool that should be extended to provide for more robust application development. Some of the suggestions for the demanufacturing tool are the following:
  - Improvement in Visual Basic interface for the cost model to link costing data with Life cycle Assessment (LCA) Software developed at the research center
  - Incorporation of "Transfer In" options in disassembly workstation module to incorporate the releasing options for material handling system.
  - Development of special functions and algorithms for generating and evaluating more complex decisions in scheduling and planning to provide more flexibility in batch forming and sequencing operations.
- More specific data on product disassembly and number of bins for different products is necessary for generating more extensive database for a variety of products. In addition, data on dollar values of recovered components and subassemblies and

market trend for different recovered materials is needed on a frequently updated basis.

- The tool should be extended further for incorporation additional modules for other recovery options and other specific demanufacturing activities such as shredding.

APPENDIX A

TRANSPORTATION MODEL

The energy requirement for road transport system can be divided into three parts: fuel energy, tuck production energy and truck maintenance energy. The energy consumed as fuel accounts for more than 55 % of the total.

Energy Associated with Fuel Consumed by Vehicle

Fuel consumption is sensitive to a number of factors such as vehicle size and payload. The table given in Appendix b summarizes oil fuel requirements in Mega-Joules per mile (MJ/mile) on the basis of load carried by the truck.

Production of Truck

This category contains energy associated with the construction of vehicle, lubrication, tires and batteries. The energy required for a truck to keep on road covers energy required for lubrication at about 0.6 % of fuel energy, tires at about 1.5% of the total fuel energy, Garaging energy at about 32 % of the fuel energy and spares at about 0.2 % of the total fuel energy [45]. The essential component of the garaging is the provision of the facilities for servicing and repairing vehicles. The data obtained is from a number of fleet operators who themselves maintain the whole of their fleet and typically consumption of kerosene for space heating and electricity of space lighting and powered machines. Apart from tires, which have been considered separately, the only significant components are engine and transmission. The differential mat last about 300,000 miles and gearbox for about 150,000 miles. Assuming mass of gear box 123 kg and gross energy of steel of 50

MJ/kg, the energy requirement of gear box is about 0.1 % of the direct fuel energy requirement or 0.04 MJ/mile. The same consideration is given for batteries which normally last for 100,000 miles. Assuming they consume 0.01 MJ/mile or 0.03 % of the direct fuel energy requirement of the vehicle.

The energies required for production of truck is given in Appendix c and table 3.1 gives the energies for other options in terms of Direct Energy of Fuel.

Table A.1 Calculating energy for rest of the options
[Source: 45]

Other components of second phase	% of the Direct Energy of Fuel
Lubrication	0.6
Garaging	32
Tire	1.5
Spares	0.2

Total Energy in Transportation

Eco balance [36] proposes a formula to calculate the Direct Energy of Fuel in terms of gallons of fuel required.

$$\text{Fuel} = \frac{\text{Distance}}{\text{Sp. Consumption}} * \left(\frac{2}{3} + \frac{1}{3}\left(\frac{\text{Actual Load}}{\text{Maximum Load}}\right) + \frac{2}{3}\left(\text{for Empty Return}\right) \right) * \frac{\text{Weight}}{\text{Actual Load}} \quad \text{(A.1)}$$

Definitions of the terms with their units used in the formula are given below:

Fuel: This is the amount of fuel consumed expressed in gallons.

Distance: The miles traveled by truck.

Sp. Consumption: The fuel efficiency in miles per gallons.

Actual Load: The load carried by the truck in pounds.

Maximum Load: The maximum payload capacity of the truck in pounds.

Weight: Truck tare weight (unloaded) in pounds.

Empty Return: The phrase implies the truck tare weight in pounds, while returning from a facility with out carrying a load. Boolean value is returned. (1: for empty return and 0: for not empty return)

The Direct Energy of Fuel (DEF) in terms of kWh/mile can be expressed keeping the structure of equation (1) same as follows:

$$\text{DEF} = \frac{1}{\text{Fuel Efficiency}} * \left(\frac{2}{3} + \left(\frac{1}{3} * \begin{matrix}\text{Load} \\ \text{Ratio}\end{matrix}\right) + \frac{2\ (\text{for Empty}}{3\ \ \text{Return})}\right) * \frac{\text{Truck Tare Weight}}{\text{Actual Load}} * \begin{matrix}\text{Energy Content} \\ \text{of Fuel}\end{matrix} \tag{A.2}$$

Definitions of terms with their units are given below:

DEF: Direct Energy of Fuel in kWh per mile.

Load Ratio: It is the ratio of Actual Load carried to the Maximum Payload.

Truck Tare Weight: The weight of truck itself in pounds.

Empty Return: The phrase implies the weight of truck in pounds, while returning from a facility with out carrying any load.

Actual Load: The actual weight of products transported.

Energy Content of Fuel: This is the energy required in kWh per gallon of fuel used. (see Table A.2)

Table A.2 Energy Content Factor
[Source: 45, Table 6.13, page 126]

Fuel	Total energy in kWh/gallon
Gasoline	45.02
Diesel	48.61

Methodology Used:

As described earlier the total transportation energy can be expressed as follows:

Total Transportation energy = Direct Energy of Fuel (DEF) + Other Energies

"Other Energies" include energies necessary for truck production and operations such as garaging, lubrication, tire and spares.

Three truck sizes are defined according to different load capacities as *Light Truck, Medium Truck* and *Large Truck*. The capacities or maximum payloads for the defined categories are 8000 pounds, 24,000 pounds and 36,000 pounds respectively. To calculate total energy, the weight of the truck itself along with actual load is required because that is the constant energy required regardless of load. From Appendix c, the average tare weight of truck capacities ranging from 1 to 8 tons to get the tare weight of light truck. Similarly, for medium and large trucks, the averages of 10 to 12 and 12 to 20 respectively are calculated to get their tare weights. Table A.3 gives key characteristics for various truck types.

Table A.3 Preliminary Information of the trucks

Truck Type	**Weight in pounds**	**Maximum pay Load in pounds**	**Fuel Efficiency in miles per gallon**
Light	5100	8000	9.0
Medium	9500	24000	6.4
Large	15000	36000	6.4

Information on fuel efficiency and load ratio is required to calculate the DEF. Fuel efficiency is assumed to be constant for medium and large trucks and the load ratio can be calculated from the actual load carried and maximum payload.

As stated earlier, "Other Energies" can be represented as a percent of the DEF then we can combine these two terms in a single formula. Table A.4 summarizes energy requirement for other energies.

Table A.4 "Other Energies"
[Source: 45, Table 9.4, page 204, and Table 9.7 page 209]

Category in Other Energies	**Energy as a % of DEF**
Truck Production	8.02
Garaging	32
Lubrication	0.6
Tire	1.5
Spares	0.2
Total Other Energies as a % of DEF= 42.32	

Therefore,

Total Transportation Energy = 1.43 * DEF

$$= \frac{1.43}{\text{Actual Load}} \left(\left[\frac{1}{\text{Fuel Efficiency}} * \left\{ \frac{2}{3} + \left(\frac{1}{3} * \text{Load Ratio} \right) \right\} + \frac{2}{3} \text{(for Empty Return)} \right] * \frac{\text{Truck Tare Weight}}{\text{Actual Load}} * \text{Energy Content of Fuel} \right) \quad \text{(A.3)}$$

This is the transportation energy in kWh per mile per pound of product transported.

Validation of the Formula A.3 by Calculating Energy Requirement for All the Three Truck Types:

Assumptions:

1.Assuming the load ratio to 95 % i.e. the truck is loaded up to 95 % of its maximum payload.

2. The fuel efficiency for medium and large truck is assumed to be 6.4 gallons per mile. [46: page 40]

3.Assuming the fuel efficiency of light truck is 9 gallons per mile.

4.Assuming empty return from the delivery (Empty Return: 1).

5.Assuming that light capacity truck uses gasoline and medium and large trucks use diesel as source of energy.

Table A.5 Energy Input

Energy Input for 95 % of The Capacity				
Truck type (maximum pay load in pounds)	Direct Fuel(DF) Energy (kWh/mile)	Other Energies (kWh/mile)	Total energy (kWh/mile)	Total Energy (kWh/1000-lb of product- miles)
Light (8000)	5.54	2.34	7.88	1.04
Medium(24000)	5.22	2.19	7.41	0.33
Large(36000)	5.49	2.30	7.79	0.23

From the work of I. Boustead and G. F. Hancock (Appendix b) [45], The DEF for light truck, medium truck and large truck are 4.771, 5.762, 5.762 kWh per mile respectively.

Total energy required is more for light truck because of the assumptions made for type of fuel and fuel efficiency. If a graph [see Appendix C] of total energy is plotted against the type of truck it will show the curve sloping down as we move towards higher capacity trucks. But if the graph [see Appendix D] of DEF is plotted against the type of curve it will not show a smooth curve. One reason for such trend might be the assumption made for fuel efficiency.

Emissions from Transportation

Emissions coming from burning of fuel are of three types such as solid waste, air emissions and waterborne effluents. Air emissions primarily comprise of carbon monoxide, particulate, sulfur oxides, lead, nitrogen oxides and hydrocarbons. Similarly, Waterborne effluents consist of metal ions, acids, and suspended solids.

Emissions from the transportation are divided into two groups:

1. Fixed Emissions: Due to the tare weight truck.
2. Variable Emissions: Depend on the actual load carried by the truck.

The total emission from each category is the summation of fixed and variable emissions.

Keeping the same assumption for the tare weight of trucks, fixed emissions are calculated. Variable emissions are calculated on the basis of the actual load being transported by the truck and so they are the function of weight of product, which can be calculated as a product of individual weight to total number of products being carried.

Table A.6 Emissions summary
[Source: 46, Page 40]

Emissions	**Light Truck**		**Medium Truck**		**Large Truck**	
$* 10^{-3}$ lb. per mile	**Fixed**	**Variable**	**Fixed**	**Variable**	**Fixed**	**Variable**
Solid						
Solid	1.02	0.2 * LOAD	1.9	0.2 * LOAD	3.0	0.2 * LOAD
Air						
Particulate	3.57	0.7* LOAD	6.65	0.7* LOAD	10.5	0.7* LOAD
Hydrocarbons	8.21	1.61* LOAD	15.29	1.61* LOAD	24.15	1.61* LOAD
CO	34.94	6.85* LOAD	65.08	6.85* LOAD	102.75	6.85* LOAD
NO_2	8.26	1.62* LOAD	15.39	1.62* LOAD	24.3	1.62* LOAD
Lead	0.045	0.009* LOAD	0.09	0.009* LOAD	0.14	0.009* LOAD
Others	3.39	0.76* LOAD	7.25	0.76* LOAD	11.45	0.76* LOAD
Water						
Suspended solids	3.16	0.62* LOAD	5.89	0.62* LOAD	9.30	0.62* LOAD
Acid	0.33	0.065* LOAD	0.61	0.065* LOAD	0.98	0.065* LOAD
Others	0.01	0.0028* LOAD	0.02	0.0028* LOAD	.04	0.0028* LOAD

Note:

1. **LOAD**: It is the Actual Load being carried by the truck.
2. The summation of constant and variable emissions for each type will give the total emissions of that type

The total emissions arising from transportation by truck are then the function of number miles the truck travels and the amount of load it carries.

Sample Calculations:

Continuing with the same example and keeping the same assumptions

The emissions are written in tabulated format.

Here the value of "Load" for three different types for 95 % of the maximum payload is:

Light truck: 7600 pounds

Medium Truck: 22800 pounds

Large Truck: 34200 pounds

Table A.7 Emissions resulted for sample example

Emissions * 10^{-3} **lb. per mile**	**Light Truck** * 10^{-3} **lb. per mile**	**Medium Truck** * 10^{-3} **lb. per mile**	**Large Truck** * 10^{-3} **lb. per mile**
Solid			
Solid	2.54	6.46	6.84
Air			
Particulate	8.89	22.61	23.94
Hydrocarbons	20.45	51.99	55.06
CO	87	221.26	234.27
NO_2	20.57	52.32	55.40
Lead	0.11	0.29	0.31
Others	9.17	24.58	25.99
Water			
Suspended solids	7.87	20.03	21.20
Acid	0.82	2.09	2.22
Others	0.03	0.08	0.09

APPENDIX B

DIRECT ENERGY CONSUMPTION OF FUEL BY TRUCK TYPE

[Source: 45, page 201]

Table B.1 Direct Energy Consumption of Fuel by Truck Type

Truck type (maximum pay load in tons)	Oil fuel energy requirements in MJ/Mile			Total In kWh/mile
	Fuel Production Energy	Energy content of fuel	Total	
Rigid Vehicles				
<1	1.29	6.71	8.00	2.22
1-2	1.66	8.54	10.20	2.88
3	1.95	10.17	12.12	3.37
4	2.28	11.70	13.98	3.88
5-8	2.78	14.18	16.96	4.71
9	3.11	15.69	18.80	5.22
10-12	3.19	16.11	19.30	5.36
13-20	3.41	17.33	20.74	5.76
Articulated Vehicles				
10	3.14	15.91	19.05	5.29
10-12	3.30	16.73	20.03	5.56
13-14	4.09	20.66	24.75	6.88
15-16	4.14	20.90	25.04	6.96
17-18	4.13	21.75	25.88	7.19
18	5.42	27.42	32.84	9.12

APPENDIX C

CONSTRUCTION ENERGIES FOR DIFFERENT TRUCK SIZES

[Source: 45, page 204]

Table C.1 Construction Energies for Different Truck Sizes

Max. Load in tons	Unlade weight Tons (Note 1)	Lifetime $*10^3$ miles (Note 1)	Construction energy as if vehicle were 100 % steel MJ (Note 2)	Construction energy per mile	Total Fuel Energy (MJ/Mile)	Construction energy as a % of fuel energy
1	0.8	75	40000	0.53	8.0	6.6
2	1.75	90	87500	0.97	10.2	9.4
3	2.0	90	100000	1.11	7.53	9.2
4	2.5	90	125000	1.39	8.69	9.9
5	2.75	150	137500	1.53	10.54	9.0
6	3.0	150	150000	1.00	10.54	5.9
7	3.5	150	175000	1.16	10.54	6.8
8	3.75	210	187500	1.25	10.54	7.4
10	4.0	210	200000	0.95	11.99	4.9
12	4.5	240	225000	1.07	12.45	5.4
14	5	240	250000	1.04	15.38	4.2
16	6.5	240	325000	1.35	15.56	5.4
18	8	240	400000	1.67	16.20	6.4
20	10	240	500000	2.08	20.41	6.3

Notes (Commercial motor (1977)): 1. Based on gross energy requirement of steel of 50 MJ/kg. 2. From table of *Appendix A*

APPENDIX D

COMPARISON GRAPHS

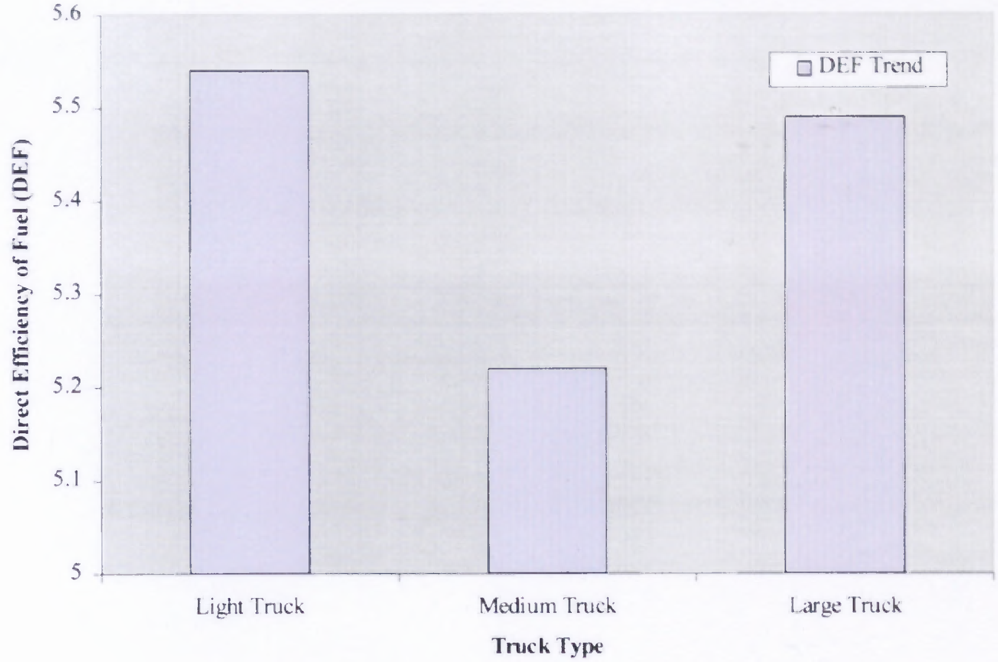


FIGURE D.1 Graph of DEF against Truck Type

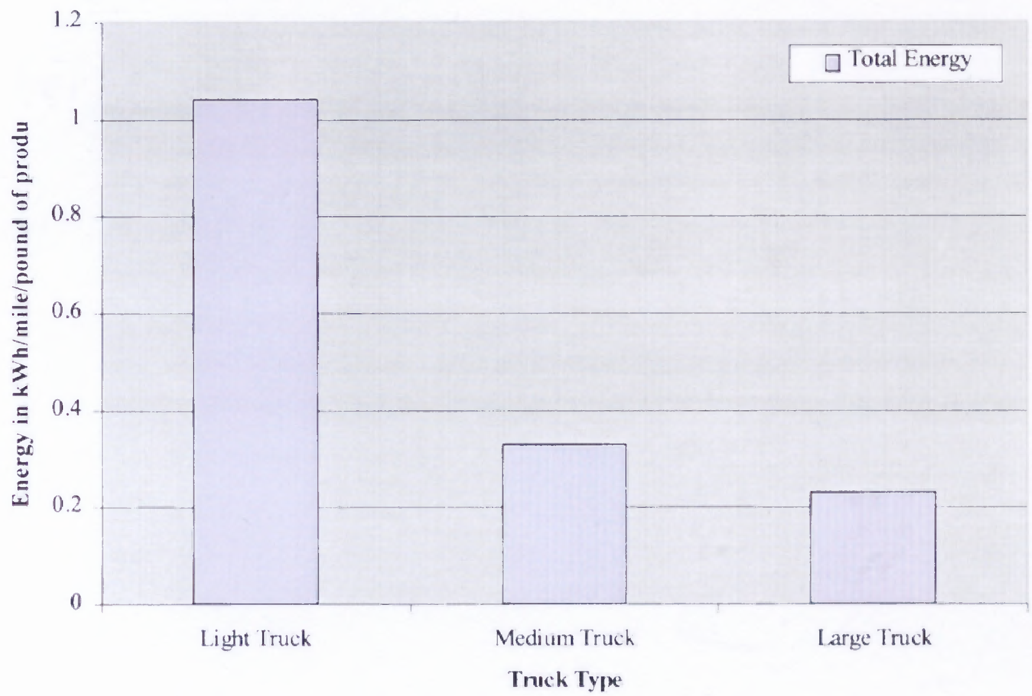


FIGURE D.2 Graph of Total Transportation Energy against Truck Type

APPENDIX E

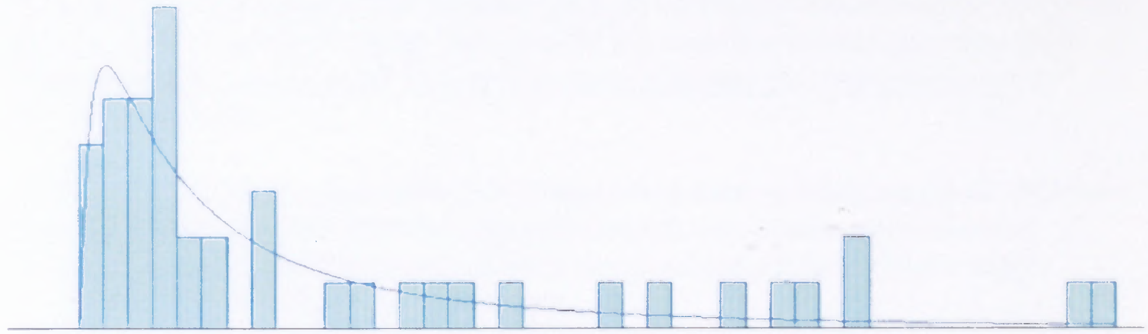
DATA AND DISTRIBUTIONS ON PRODUCT ARRIVALS

Table E.1 Data on Product Arrivals

Difference in days	No of pallets	Difference in days	No of pallets
2	1	1	4
1	3	1	4
2	2	1	3
1	8	3	3
3	4	1	30
1	6	2	3
2	6	1	8
5	1	3	1
2	15	1	4
4	12	1	14
1	8	3	4
5	5	2	4
1	42	1	2
1	1	1	3
1	16	3	2
5	32	3	32
1	41	1	2
1	27	4	2
4	11	2	22
1	18	5	5
1	24	1	29
		1	4

Pallets per month	Average Pallets
May-129 June-113 July-226	156

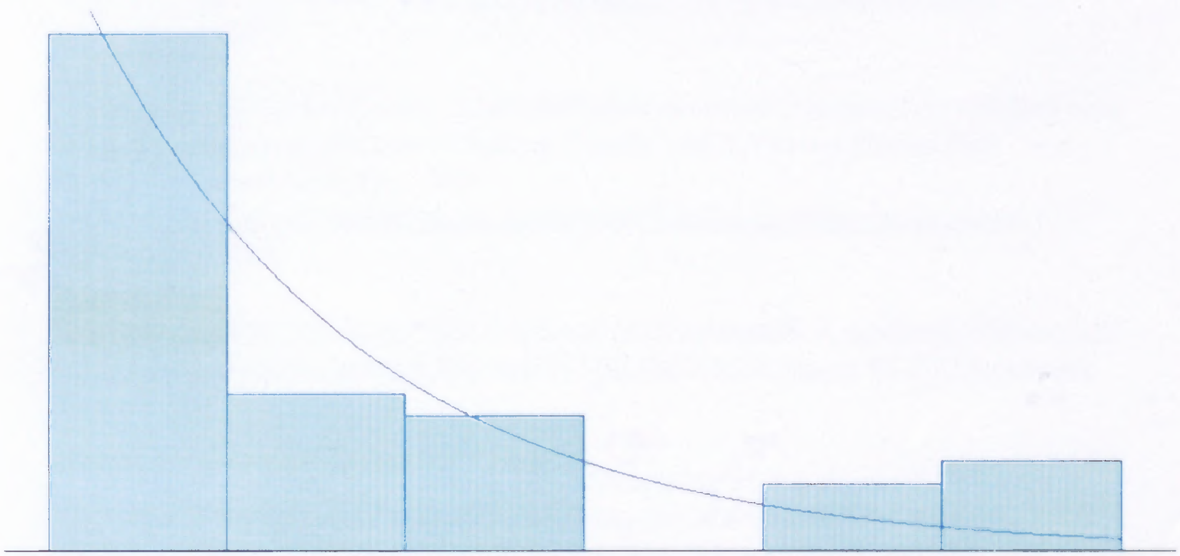
APPENDIX E (Cont.)



```
Distribution Summary

Distribution:   Lognormal
Expression:     0.5 + LOGN(0, 0)
Square Error:   0.017692

Chi Square Test
  Number of intervals    = 6
  Degrees of freedom     = 3
  Test Statistic         = 7.15
  Corresponding p-value  = 0.0713
```

```
Data Summary

Number of Data Points   = 43
Min Data Value          = 1
Max Data Value          = 42
Sample Mean             = 10.9
Sample Std Dev          = 11.6

Histogram Summary

Histogram Range         = 0.5 to 42.5
Number of Intervals     = 42
```

Figure E.1 Distribution for Number of Batches



```
Distribution Summary

Distribution:   Exponential
Expression:     1.44e+003 + EXPO(1.47e+003)
Square Error:   0.022116

Chi Square Test
  Number of intervals    = 4
  Degrees of freedom     = 2
  Test Statistic         = 2.21
  Corresponding p-value  = 0.351

Kolmogorov-Smirnov Test
  Test Statistic         = 0.161
  Corresponding p-value  > 0.15
```

```
Data Summary

Number of Data Points   = 43
Min Data Value          = 1.44e+003
Max Data Value          = 7.2e+003
Sample Mean             = 2.91e+003
Sample Std Dev          = 1.95e+003

Histogram Summary

Histogram Range         = 1.44e+003 to 7.2e+003
Number of Intervals     = 6
```

Figure E.2 Distribution for Inter-arrival Times

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CHAPTER 1

INTRODUCTION

1.1 Background

With growing concerns and increasing responsibility towards product stewardship, many companies are instituting new concepts and methodologies to improve environmental performance of their products. A key driving force is that European countries have begun to enact new laws and regulations requiring product take back and resource recovery.

In these regards, the manufacturing industry has been evaluating various options for end-of-life management. Manufacturers have come to realize end-of-life management is not a separate activity, but it is an integrative process beginning with the early stages of product innovation. The inherent complexity in life cycle management challenges researchers and engineers for a comprehensive solution, which not only strengthens competitive position but also promotes socio-ecological responsibility. The "issues" have profoundly affected electronics manufacturers because of the high production rate and rapid obsolescence of electronics goods.

In the UK, approximately 10,000 tons of domestic appliances and 80000 tons of consumer electronics waste are generated per year [1]. In the United States, 209.7 millions of tons of municipal solid waste was generated in 1996; out of which 55.5 % was landfilled, 27.3 % recovered through recycling and 17.2 % was combusted with energy recovery [2]. But the problem has intensified due to a shortage of landfill sites and waste-incineration facilities in certain regions. The search for new solutions to the increasing problem, led researchers to look for different recovery options such as reuse, remanufacture, recycle and reengineer, other than landfill and incineration. Technologically obsolete but functionally operating discarded products can be reused, where changes in technology are trivial, to retain maximum value embedded into the product. These products can also be disassembled to remanufacture by repairing and refurbishing subassemblies and components or non-remanufacturalbe subassemblies and components can be reengineered and recycled to recover the valuable materials in the product. As the depth of disassembly of increases, value recovery methods utilizes reuse, remanufacture and reengineer options progressively. In addition to support for healthy environment, recovery options promotes cost saving at different stages of life cycle. As against conventional landfill options not only reduce the agricultural sector and leaching of toxic materials into ground, but also losing of the value and energy added during material synthesis and production phase. Waste incineration with or with out energy recovery generating noxious gases, particulates and fly ash has inherent environmental impacts. Therefore, the optimal solution would be to keep materials and components flowing from a product application; maximizing the recycled content in the product, minimizing requirements for virgin materials, reengineering or remanufacturing materials time after time and minimizing the possible impact by remainder that is either landfilled or incinerated. The general idea is to retain the highest value invested for next generation application.

The amount of value and energy recovered from disposed product depends up on selection of end-of-life options. From the perspective of maximum recovery hierarchy, different end-of -life options are reuse, remanufacturing, reengineering and smelting to recover products, subassemblies or components and basic materials. The demanufacturing has been introduced as an integral part of product life cycle, which performs a set of functions to recover value from products and waste streams and ships these recovered materials and components for recycling/reengineering or remanufacturing technology [3]. The demanufacturing discards the concept of linear flow of raw materials converted into products/packages and disposed off after end of useful life. The demanufacturing activity apart from disassembly includes testing, inspection, sorting and staging and also packaging, shredding and separation and distribution of recovered materials and components. The recovered materials and components are feed stocks for next generation products and such repeated cycles will give materials an indefinite extended life.

Current demanufacturing practices include manual disassembly of discarded products (majority electronics products) using hand tools and powered tools for remanufacturing or reuse processes and shredding of non-recoverable components or subassemblies. Shredding combines with various separation methodologies for different materials prepare products for reengineering and smelting operation. The shredding operation can be a single stage or two-stage operation depending upon the product composition. Sequencing of products for faster disassembly and maximum value recovery are activities prior to disassembly. Few automated disassembly cells have been designed for specific disassembly tasks such as disassembly of camcorders, explosive gas generators [4, 5 and 6]. The technological development in demanufacturing is slow because of economical constraints in terms of revenue, variable product structures and difficulties posed by underdeveloped disassembly processes.

A number of studies addressing recovery issues have been published in research journals and conference papers. Researchers have concentrated on areas such as Design for Disassembly (DFD), Design for Environment (DFE), Design for Recyclablity (DFR) and Design for Extended Life (DEL). These research areas support demanufacturing through information on faster disassembly processes, potential reengineering materials/techniques, remanufacturing components/subassemblies and the environmental burdens associated with process residue. These areas concentrate on different methodologies of recovery process and various issues at different stages of product life cycle, however little research has concentrated on the systems aspects of demanufacturing. Facility layout is also a significant research issue for efficient operations and movement of products and equipments, which has not been fully examined. The focus of this thesis is to provide a system aspect to demanufacturing activity.

Some companies have established internal demanufacturing operations and several new firms have emerged specializing in demanufacturing; however, these operations are facing problems of efficient and economical operations. Since disassembly issues and the post disassembly options are related to effective management and operations of demanufacturing activity, overall systems perspective is necessary to provide a comprehensive understanding of demanufacturing facility management and layouts.

1.2 Aims and Objectives

A demanufacturing system that takes discarded products collected from consumers or businesses and performs following functions:

- Inspection of collected products
- Staging the workflow
- Disassembly of products
- Separation into bins
- Shipping the recovered materials and components for further recovery.

The system is aimed at maximizing value recovery in any form by using reuse, remanufacture and reengineering options while minimizing residual disposal. The system provides a higher level of abstraction to specific processes such as disassembly and shredding for overall improvement of demanufacturing operations and facility layouts. Thus, the principal aim of this research is to develop for modeling demanufacturing systems simulation tool integrated with an activity based cost model to compare operational and economic trade-offs of different facility layout, equipment and operational changes.

The demanufacturing system can be modeled as a flowchart in which connecting links represent transportation activities and nodes represent stationary activities. The tool follows the flows of discarded products that undergo different activities for system simulation tool development. Discrete event system simulation is used as a tool to improve the overall efficiency of the demanufacturing operation. This thesis aims to build an integrated tool for demanufacturers to simulate the entire facility for various possible operational strategies, machine/ worker utilization, material handling equipment changes and layout planning. The simulation part of tool will help to model and run the current operations and improvement options, while the cost model will analyze economical viability of improvement options.

1.3 Research Need and Purpose

Technology driven products, such as consumer electronics have short life times because of technology obsolescence and advanced version introduced by the competitor [7]. Rapid changes in the market create a significant amount of unsold products. Increased environmental responsibility will generate potentials of product take back to manufacturers after disposal from user. Traditionally, the general approach was to landfill or incinerate these products; however in addition to sufficient flow of discarded products and potential market for recovered materials, there are several reasons for increasing demanufacturing business:

- Avoid landfilling
- Reuse value and prospective savings at material extraction and synthesis stages
- Protect proprietary information associated with the product
- Strengthening product take back policies

Recovered materials can be feed stock for next generation products reducing use of non-renewable resources and virgin materials [3]. Many individual businesses in association with manufacturing industry are being established for demanufacturing of electronics products, for example EPA Incorporation, Envirocycle Incorporation and Hestech. The demanufacturing in its primitive stages is facing problems for its efficient operations and strategic planning.

Some of the issues that are faced by demanufacturers are listed below:

- *Variation in the in-coming stream*: The quantity of products and the type of products coming into facility are varied due to uncertainty in collection process, flexible market conditions and introduction of new technologies.
- *Condition of products*: The products range from being technologically to functionally obsolete. The number of years in service, accidental breakdown and failure of components and/or sub-assemblies affect the actual condition of the product. The staging and testing operation prioritize the disassembly operation upon actual evaluation of the recoverable value from the products. The condition plays an important role in reuse.
- *Structure of products*: The product structure from the disassembly point of view is more related towards easy accessibility to high-valued components and materials. The structure influences the disassembly effort and eventually cost of operation. The cost incurred to recover value is a business issue for the demanufacturer. The structure also influences depth of disassembly operation, which may affect selection of number of bins. Complicated product structures require higher disassembly times and may reduce throughput from the facility. Separate specialized disassembly stations may have to establish for complicated structures to separate them from rest simple structured products, which might not be economical.
- *Operational Strategies*: The strategies are related to quantity and variation in products to demanufacture. These strategies are aimed towards prioritizing high valued components and materials recovered from products. The more variation, the more manual operation is involved. The operational strategies not only include the method

of operation but also batch formulation, staging and sequencing of the products accordingly.

- *Strength of Business*: This is an important issue, which is dependent on the in-flow of products and also the market condition. The variable demand for basic materials, components or subassemblies may require a thorough planning of demanufacturing incorporating facility layout and operations planning to meet current market demands and prospective future requirement of different materials components or subassemblies and expansion of the current facility/layout.

In light of above problems, there is a need to analyze the entire demanufacturing operation. Understanding the operation from various perspectives under different conditions is needed for higher profits. The stochastic nature of the problem, because of variable in-flow, non-deterministic product conditions and disassembly timings, demands a flexible, easily understandable and interpretable method/tool. Discrete event simulation is one technique of understanding the business operations in a virtually created realistic program. Simulation is assisted by animation capabilities for graphical visualization of simulation outputs and presentation of results in form of graphs and charts.

Along with the simulation, a profit-oriented cost analysis is also required for validation of simulated scenarios from net cost of running the facility and market prices of basic materials, components and sub-assemblies perspective. The purpose of this research is to develop, validate and demonstrate the power of an integrated system simulation tool for efficient operation of demanufacturing facilities.

1.4 Research Scope

The generic demanufacturing system is divided into three sections: the collection system, demanufacturing activity and output of recovered values to next process activity. The thesis focuses on the demanufacturing activity including staging/testing, disassembly operation, material collection/handling systems and flow of products and materials into and out of the facility issues are studied. A customized system simulation tool is developed for evaluating demanufacturing system including current operation and various improvement scenarios. The tool analyzes changes in operational details and facility layout options. The simulation tool provides a new interface to an existing general-purpose simulation software package. Simulating a typical small demanufacturing facility validates the modeling and logic for the tool. Postulating and evaluating various improvement scenarios provide the demanufacturer with strategies or increasing throughput and reducing cost.

1.5 Thesis Format

The thesis formatted in seven sections and each section is a separate chapter.

Chapter 2 presents a brief overview of simulation techniques, the potential benefits occurring from simulating manufacturing systems with supporting examples and in general provides the background information in demanufacturing and disassembly area.

Chapter 3 describes development of generic demanufacturing systems model, the Arena simulation software used for developing simulation tool and develops customized simulation tool for demanufacturing businesses.

Chapter 4 develops an activity based cost model to compare economical trade-offs.

Chapter 5 validates the simulation tool and presents the results.

Chapter 6 analyzes the results presented in chapter five for improvements in current operations, simulates and presents the improvement options.

Chapter 7 concludes the thesis by summarizing the results obtained during the improvement analysis and suggests recommendations for future development of simulation tool.

CHAPTER 2

LITERATURE REVIEW

System simulation techniques have contributed towards improving operational efficiencies of manufacturing facilities by assessing process bottlenecks, evaluating machine/worker utilization rates, and supporting decisions regarding efficiency improvements, changes in physical layout and economics driving the business. However there has been little research focused on implementing similar techniques in demanufacturing systems. Past research has focused on parts of demanufacturing systems and has concentrated on design for disassembly and disassembly process planning [8]. But, today's complex demanufacturing systems require detail understanding and analysis with the same engineering rigor as been performed on manufacturing systems. No prior research work on demanufacturing systems simulation has been reported in the open literature; consequently fundamental studies with closely defined field of simulation, manufacturing simulation and demanufacturing systems development provide the scholarly basis for this literature review.

Potential benefits from manufacturing systems simulation supported with real world examples emphasize significance and importance of simulation for its future implementation in demanufacturing system simulation. A summary of current research activities in demanufacturing systems is also presented as a background information for system simulation of demanufacturing system.

2.1 Introduction to Simulation

Simulation is a numerical solution method that seeks to evaluate alternatives (strategies) by choosing and assessing various scenarios. The approach has been used to study a wide range of problems that entail uncertainty and randomness. Variability in the problem may be associated with disassembly timings or process scheduling and can be represented by a probability distribution. The simulation process requires model to represent logical and mathematical relationships among decision variables of the problem under study [9, 10,11].

The following general definitions of simulation have been proposed:

1. According to Shannon [9]," Simulation is the process of designing a model of a real system and conducting experiments with this model, for purpose of understanding the behavior (within the limits imposed by a criterion or a set of criterion) for the operation of system."
2. Naylor et al. [9] says, "Simulation is a numerical technique for conducting experiments on a digital computer, which involves certain types of mathematical and logical relationships necessary to describe the behavior and structure of a complex real world system over extended period of time."

2.1.1 Types of Simulations

Two system simulation methodologies have been used to model and evaluate manufacturing systems: discrete event simulation, where system is analyzed only after occurrence of an event and Petri Nets, which is a relative new concept of system simulation.

1. Discrete Event Simulation:

In this type of simulation one or more of the independent variables are stochastic. Discrete event simulations involve a limited number of events that can only taken on an infinite number of values. It concerns the modeling of a system as it evolves over time by a representation in which the state variables change instantaneously at separate points in time. In other words, the system can change at only countable number of points in time. These points in time are the ones at which an event occurs, where an event is defined as an occurrence that may change the state of system [14]. Following are the common elements of discrete simulation [10, 11,13]:

- *Entity*: This is a single component explicitly representing a single active terminal or operator. Entity is divided in to two type viz. permanent entities and temporary entities. Where as permanent entities remain in the model for entire duration of run, temporary entities generated in the model are disposed of after some simulation period.
- *Activities*: These are procedure followed by the entities or the procedures done on the entities. These are not isolated for any one entity. More than one entity may follow the same activity. Times of occurrence and duration of existence of activities is important from simulation from view.

- *Events*: Events are the instants in time when system changes its state. Event is the cause for start or end of an activity. A single event can start or end any number of activities. Events are classified into internal and external events. While, external events are caused from outside of the simulated system in the model, internal events are caused by conditions defined in the definition and description of the system in the model.
- *Queues*: Queues are the passive states of an entity, while it waits for the condition to change so that it can proceed through the model. The ranking rule and type of queues characterize queues. Queues are generally classified as normal queue and shared queue. The ranking rules are the various ways for releasing a job waiting a queue. Some of them are First In First Out (FIFO), Higher Value First (HVF), Lower Value First (LVF) and Last In First Out (LIFO). Queues are individual queues or shared queues. In shared queue the queue is shared by more than one number of resources.
- *Attributes*: Attributes are the characteristics of the entities. They are used to distinguish one entity from another. The selection of entity from queue depends on the attribute values of entities in the queue.
- *Sets*: It is the general term and used to combine similar modules under one single name.
- *States*: States are referred to condition of model or its entities. These are normally the criterions for evaluating performance of a system.

2. *Petri Nets:*

Petri nets is a graphical and mathematical tool for modeling, analyzing and designing discrete event systems. The model is used for analysis of behavioral properties and performs evaluation as well as for systematic construction of discrete event simulators and controllers. They can be used to model properties of such as process synchronization, asynchronous events, sequential and concurrent operations [16]. It is a network based analytical approach to solve system-related problems. Petri nets are used to model dynamic systems using combinations of places and transition. Petri nets are formed by two types of nodes viz. places and transitions [15].

In discrete event simulations, Places represent resources. The existence of one of more tokens in a place represents availability of the resource and vice versa. The transition firing represents an activity, which begins and ends with two consecutive events. The time of activity may be zero implying immediate action. Places and Transitions together represent conditions and precedence relations in the systems operations [17]. If transition times are allowed to be random variables then Petri Nets are called as stochastic timed Petri Nets. Following is the general methodology adopted using Petri Nets for modeling discrete event systems [16, 17]:

- Identification of operations and relations.
- Identification of resources.
- Petri net Design
- Petri net Modification

Petri nets require a power full and user friendly graphic editor, a behavior analyzer, a performance evaluator, dynamic graphical display for simulator and automatic Petri Net synthesizer for its effective implementation. Petri Nets have been used to present a methodology for design and implementation of disassembly strategies for remanufacturing of discarded products [58] and the research is expanded to implement disassembly Petri Net considering level of disassembly and cost of disassembly process [59]. But for simulating demanufacturing system traditional discrete event simulation techniques have used.

2.1.2 Advantages and Disadvantages of Simulation

Several *advantages* and *disadvantages* of system simulation are listed below [9, 12, 13 and 14]:

1. Simulation approach is suitable to analyze large and complex real life problems, which can not be solved by usual quantitative methods.
2. Simulation is descriptive rather than normative. This allows "what if" type questions to be evaluate. In a demanufacturing system different operational strategies can be evaluated for maximizing the throughput and utilization of resources and inventories.
3. Simulation allows decision-makers to study the interactive system variables and assess changes in these variables on the system performance in order to determine the desired one. These decision variables in a demanufacturing system will be disassembly times, transfers times, staging and sorting of products. These are dependent on the level of disassembly and revenue anticipated from the process.

4. Simulation experiments are done with the model, not on the system itself. It also allows including additional information during analysis that most quantitative models do not permit.
5. Due to the nature of simulation, a great amount of time compression can be attained, giving the analyst a feel of the long-term effects of various policies, in a matter of few minutes. The long-term simulation would help to evaluate the efficiency of current operational strategies, bottlenecks for long-term sustainability of the business and impact of variation in scrappage rate of various discarded products on time.

Disadvantages:

1. It is a trial and error process that produces different "solutions" in repeated runs. This means, in a demanufacturing system simulation an optional solution can not be guaranteed.
2. Constructing a simulation model is frequently a slow and costly process. In demanufacturing analysis, time spent on collecting information required to build model may range from few days to few months depending upon the level of modeling and objective of simulation.
3. Each application of simulation is ad hoc to a great extent.

2.2 Overview of Discrete Event Simulation Tools

2.2.1 Simulation Software Development

The desire for success has led companies to strive for new sophisticated tools and techniques to better understand their business. The following two basic requirements motivated development of simulation techniques [10]:

1. To make the software more user friendly to develop a model
2. To make the results of simulation more understandable to novice personal

These needs put forward the development in not only the language but also in the "Front-end" of the software. The front-end is a tool for users or model developers to use the jargons and nomenclature of application domain as opposed to simulation specialist. Graphic output replacing the data numbers on a computer sheet enhances clearer understanding of the result.

The development of simulation softwares was initiated by pioneering work done in the steel industry by Tocher and others [10]. With the accumulated experience, these researchers developed a generic model the first General Simulation Package (GSP), which includes common features in the industry [10]. In UK and US a series of software and code generators was initiated. Figure 2.2 shows a generic development diagram of the simulation softwares and/or code generators in the USA.

After first development of GASP (Gathering Analyzing Sorting and Presenting), a series of modifications were made for newer versions of GASP such as GASP-II, GASP-IV and GASP-V. Q-GERT introduced a network convention as a way of defining elemental behavior in the model and SLAM was a conceptual combination of Q-GERT and GASP-IV and provides event scheduling or process interaction orientation or a combination of both approaches [11].

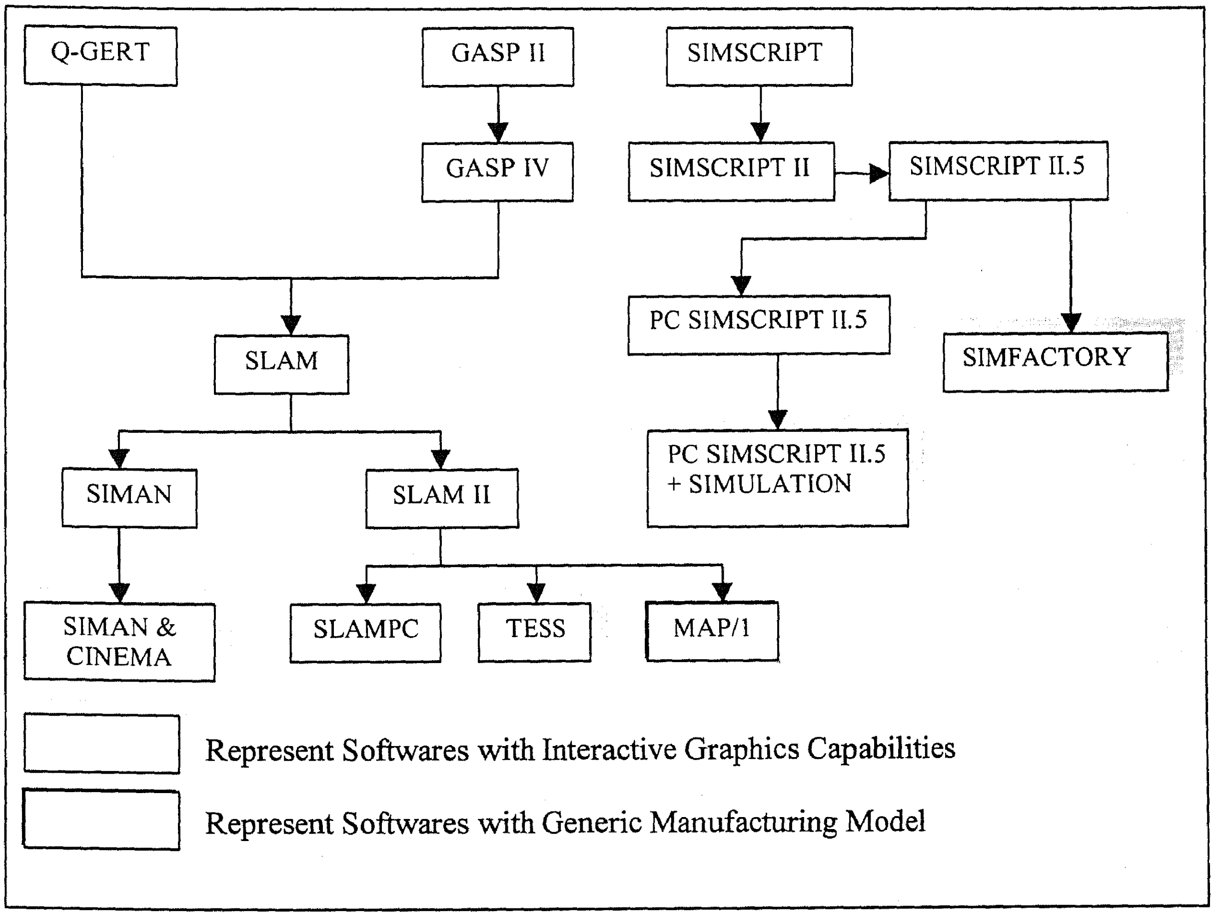

Figure 2.1 Generic Development Flow Chart of Simulation Softwares in USA [Source 15]

SLAM II emerges from SLAM and TESS provided an integrated framework for model development, data management and graphical animation of simulation models [16]. General-purpose languages such as FORTRAN, ALGOL, BASIC or Pascal use event-scheduling approach [11].

SIMAN was developed after sufficient experience with SLAM with some animated graphics through CINEMA. SIMAN provides the following features [17, 18]:

- Input capabilities for data analysis and data input flexibility (batch input or interactive input)
- Modelling facilities include on-line error handling object oriented database with FORTRAN/C interface, special purpose constructs such as conveyors, transporters, process plans, resources queues and scheduling.
- The results presented shows the statistics and frequencies on the output data. The software provides facilities of customized report generation and the statistical analysis such as point estimates, confidence intervals, variance analysis and data filtering.
- CINEMA provides dynamic animation capabilities and CAD support.

After initial development of GPSS at IBM, advanced versions such as GPSS V and GPSS/H were introduced. GPSS/H provides process interaction approach but, does not provide event-scheduling approach, so the modeler needs to program separate routines for different unique event [19]. The early version of SIMSCRIPT simulation software evolved through SIMSCRIP II, SIMSCRIP II.5, PC SIMSCRIP II.5, PC SIMANIMATION, which added a graphics capability. SIMFACTORY is a manufacturing generic model. PC SIMSCRIP II.5 and SLAM-PC provide installation and use of softwares on personal computers. PC-Model, PC-Model/GAF are some of the simulation softwares developed for personal computers only, which provide more sophisticated animation [10].