Remanufacturing Processes, Planning and Control

Jianzhi Li and Zhenhua Wu

Abstract This chapter provides a summary of critical issues in remanufacturing process and its planning and control. The chapter starts with an introduction of the special characteristics and the associated problems in remanufacturing. Typical remanufacturing processes such as cleaning, testing, and disassembly are then discussed in details. The chapter also provides a discussion of process sequencing for product disassembly to minimize cost and energy consumption. Due to stochastic nature in the material arrival process, production planning represents another main challenge for remanufacturers. Based on a case study of a business in Austin TX, a simulation model with a prioritized stochastic batch arrival mechanism, considering factors that affect the total profit, is also discussed. The chapter also presents a genetic algorithm (GA) algorithm to optimize the production planning and control policies for dedicated remanufacturing.

1 Introduction

Product remanufacturing develops rapidly in recent decades due to intensified environmental legislations and growing economic concerns. Through remanufacturing, products/components that would otherwise head to land-fill or incineration will instead go through a set of value and material recapturing processes, including collection and distribution, inspection,disassembly, cleaning, testing, repair,

J. Li (✉)
Manufacturing Engineering Department, The University of Texas–Pan American, Edinburg, TX 23834, USA
e-mail: jianzhili@utpa.edu

Z. Wu
Department of Engineering, Virginia State University, Petersburg, VA 23806, USA
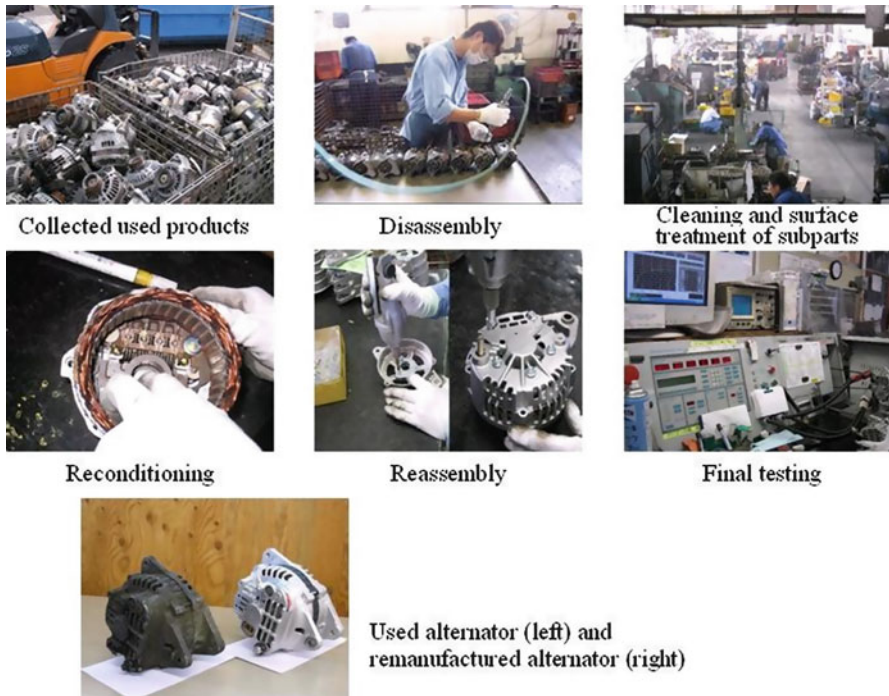
Fig. 1 Remanufacturing processes of alternators [8]

reassembly, redistribution, and remarketing or recycling. Remanufacturing allows for reusable components and recoverable materials reenter the supply chain for future reuse or new product fabrication.

Although there are numerous definitions of remanufacturing, Lund [5–7], describes remanufacturing as "... an industrial process in which worn-out products are restored to like-new condition. Through a series of industrial processes in a factory environment, a discarded product is completely disassembled. Usable parts are cleaned, refurbished, and put into inventory. Then the product is reassembled from the old parts (and where necessary, new parts) to produce a unit fully equivalent and sometimes superior in performance and expected lifetime to the original new product." Note that remanufacturing differs from simple repair or recovery in that a remanufactured product should meet the same customer expectation as new products in quality, warranties, life span, and functions.

Generally, the production processes of remanufacturing are comprised of following stages: product arrival, inspection, disassembly, cleaning, testing, repairing (reconditioning), reassembly, final testing, labeling, packaging, and shipping. The typical remanufacturing processes are demonstrated in Fig. 1.

Material arrival process for remanufacturing is a typical compound stochastic batch arrival process with varied product types and conditions. Thus, in receiving,

incoming product to be remanufactured have to be classified according to its type and condition. Received products will then be briefly inspected to collect related information, and sent to inventory. For received products, cleaning processes are required to separate undesired dirt, coating, or other contaminants from the parts to be remanufactured. Following this, the testing process is carried out to investigate the condition of the product and assign appropriate remanufacturing processes, which include refurbishing, repair, reuse and material recycling. Finished goods will be labeled, packed and shipped for resale. Components that cannot be reused will be further disassembled and classified according to their material contents, and then shipped for material recycling.

2 Key Remanufacturing Processes

A research survey of remanufacturers [1] proved the importance of the cleaning process. As the graph illustrates, 29 % of the remanufacturers' highest expense is the cleaning process. The cost of the cleaning process is a significant factor for remanufacturers. Survey results are shown on the figure below (Fig. 2).

Part refurbishing process is generally different for different types of products, so our discussion of remanufacturing will focus on cleaning, testing and inspection, and disassembly/reassembly.

2.1 Cleaning Processes

Cleaning process of mechanical parts can be grouped into two categories: liquid based cleaning process and mechanical based processes. In liquid based processes, parts are cleaned by solutions through mechanisms such as wetting and other
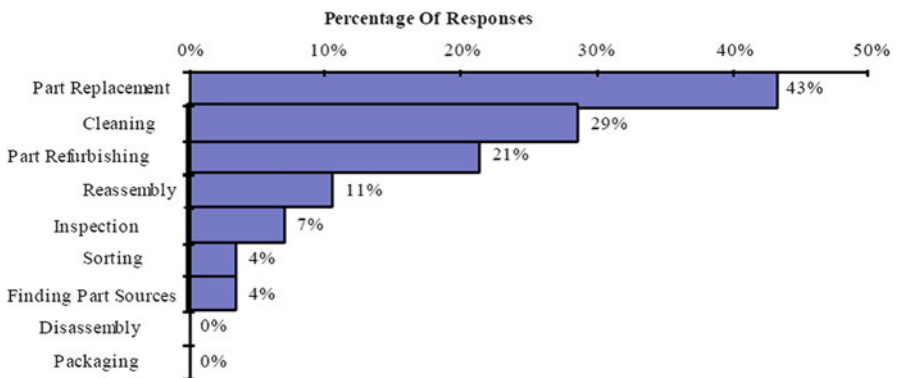

Fig. 2 Which is more costly in remanufacturing processes? [1]

chemical reactions. While in mechanical processes, external force is applied to the part being cleaned to separate undesired layers from the parts. It should be noted that liquid based cleaning can also employ mechanical energy to achieve a better cleaning effect.

2.2 Liquid Based Cleaning Process

2.2.1 Cleaning Mechanism of Liquid Based Cleaning Method

Most of the liquid based cleaning techniques rely on following mechanisms to achieve effective cleaning: wetting; emulsification; solubilization; saponification; deflocculation; and sequestration.

Wetting mechanism is essential to any liquid based cleaning. It delivers the cleaning chemistry to contaminants to be separated. Through wetting, substrate-soil bonds are broken, so that mechanical energy can be delivered to displace and remove the contaminants. Wetting can also reduce undesired surface and interfacial tensions, allowing cleaning agent to penetrate between the contaminant and the substrate.

Emulsification is the dispersion of oils to be removed in the solvent. The main factors of emulsification include types of oil and the surfactants selected. The pH level and temperature can also affect the level of emulsification. Mechanical energy, such as vibration, ultrasonic, and turbulence are generally employed to enhance the emulsion effect. Note that emulsification does not change the chemical characters of the contaminants, however it is essential for most cleaning process in effective separation of the contaminates from the substrate.

Solubilization is a process to enhance the solubility of the contaminants in a particular solution using surface-active agents. Solubilized contaminants are then dissolved into the solution. In a typical cleaning process, cleaning agents generally solubilize a certain amount of contamination while additional contaminant is held in suspension by emulsification.

Saponification is the reaction of any organic oil containing reactive fatty acids with free alkali to form soap. Alkaline cleaners containing saponifiers rely on this process to remove some oils, including vegetable and animal fats and their derivatives. The soaps that are generated are easily removed by subsequent rinsing with water.

Deflocculation causes the breakdown of contaminants into very small particles that are then dispersed in the liquid cleaning medium and swept away. This process is similar to emulsification except it happens on a larger scale.

Sequestration is a process where undesirable ions, such as Ca^{+2} or Mg^{+2}, and heavy metals are de-activated; preventing them from reacting with material that normally would form insoluble products. The classic example is the hard water scum formed when soaps are used. The scum formed is the reaction between the

Ca^{+2} or Mg^{+2} ions in hard water with soap. When the water is softened, the Ca^{+2} or Mg^{+2} ions become tied or sequestered and are unable to react.

For any cleaning processes, proper cleaning equipment is required to implement the cleaning mechanisms described previously. The cleaning equipment provides not only the site for accomplishing the cleaning process; it can also provide other desired functions such as separation and collection of removed coating or dirt. In addition, most of the cleaning equipment integrates heating or mechanical vibration to provide external agitation that enhances the cleaning effectiveness.

The goal of agitation of the cleaning solution is to apply external energy to the part surface so that the cycle time and effectiveness of the cleaning process can be enhanced greatly. Agitation can be achieved by simply stirring solution with rotary stirrers. Similar effect can be achieved by rotating parts inside the solution. Stirring agitation is gentle in general and does not significantly improve cleaning effectiveness unless the chemistry is very aggressive. Nonetheless, due to its simplicity and easy to implement, it can be applies in most processes. Ultrasonic agitation uses high-frequency sound waves to achieve mechanical agitation. Ultrasonic waves can also penetrate thin layers of metal and propagate around corners to clean work pieces inside and out. Ultrasonic cleaning is usually not appropriate for thick buildups of contaminant.

Based on the solution and external energy sources used, cleaning processes can be grouped as follows:

a) *Immersion cleaning*

Immersion cleaning refers to a group of the most applied cleaning methods for mechanical parts. It generally uses cleaners with high concentration. Convection current combined with external vibration, soils are removed from metal surface conveniently. This cleaning approach is particularly good for cleaning irregular shapes, box sections, tube and cylindrical configurations that cannot be penetrated using spray systems. The operation may vary from hand dipping a single part or agitating a basket containing several parts in an earthenware crock at room temperature to a highly automated installation operating at elevated temperature and using controlled agitation.

Several approaches of immersion cleaning are summarized below:

– Barrel cleaning: this approach is generally used for cleaning large quantities of small parts. Parts are placed and agitated inside a barrel that rotates in the cleaner solution.
– Moving conveyor cleaning: in this approach, parts are placed on a moving conveyor, which moves parts through solution flow.
– Mechanical contact: cleaner is applied with brushes or squeegees.
– Mechanical agitation: in this approach, parts are flooded with solution which is circulated using pumps, mechanical mixers, or ultrasonic waves.
– High pressure agitation: in this approach, a high pressure solution flow generated by pumps is applied to the parts to clean deep and blind holes as well as tubes with a small diameter.

b) *Ultrasonic Cleaning*

Ultrasonic cleaning employs high frequency ultrasonic waves (20–40 kHz) passing through liquid solutions to assist effective cleaning. Due to the gas bubbles created by ultrasonic waves inside the cleaners, ultrasonic cleaning can provide strong cleaning effects on the parts immersed in the solution. Ultrasonic cleaning is ideal for parts with complicated shapes, surfaces, and cavities that may not be easily cleaned by traditional immersion techniques.

The basic ultrasonic cleaning process generally is composed of following components: the cleaning tank, ultrasonic transducers, and the power supply.

Another similar cleaning technique is Megasonic cleaning. It uses a much higher frequency (700–1,000 kHz) acoustic energy to generate pressure waves in a liquid. Compared with ultrasonic, megasonic technique does not suffer from cavitations which is a typical drawback for ultrasonic. Less cavitations reduce the likelihood of surface damage.

2.3 Mechanical Cleaning

Another group of cleaning technology is based on employment of mechanical force to separate contaminants from the substrate. The mechanical force can be in the forms of air blowing or exhausting, vibration, abrasion using brushes or small hard particles blasted by air. Since no chemical reaction occurs during the cleaning process, one of the most attractive benefits of mechanical cleaning is less hazardous emissions. However, due to strong mechanical forces applied to parts to be cleaned, it is also possible to damage the substrates.

a) *Vibration cleaning*

Vibration cleaning utilizes high frequency rotary oscillation to create strong vibration that overcomes the adhesive force so that dirts are separated from the parts. The dirts separated can be exhausted to a special container and can be reused. Additional abrasive bush can be combined with the vibration movement to enhance the cleaning effectiveness and reduce cycling time

b) *Abrasive cleaning*

Abrasive cleaning use high speed propelling blade shot small hard particles on the part surface, thus cleaning contaminants by impact force. The particles used as abrasive media vary in types and sizes to meet specific cleaning scenarios. Abrasive cleaning is most commonly used method to remove heavy scale and paint on large easy to access parts. Major components of the Centrifugal blast machines include: blast wheel, work conveyor, abrasive recycling system, and a dust collection device.

c) *Dry-Blast cleaning*

Dry-blast cleaning is also called abrasive blasting cleaning. Dry blast cleaning is considered as the most efficient and environmentally effective method for abrasive cleaning. It generally employs a 685 kPa air supply system to propel

abrasive particles to separate contaminants from the parts. Different replaceable air-blast nozzles are developed with different shape and wear resistant materials. Although all metals can be cleaned abrasive blasting processes, one should carefully select suitable abrasive medium for soft and brittle metals such as aluminum, magnesium, copper, zinc, and beryllium, to avoid damage to the part itself.

With respect to the equipment available for dry blast cleaning, people developed several types based on different material handling approach:

d) Cabinet machines: A cabinet is used to contain the abrasive-propelling mechanism, holds the work in position, and confines flying abrasive materials and dust. Cabinet machines may be designed for manual, semiautomatic, or completely automated operation to provide single-piece, batch, or continuous-flow blast cleaning.

e) Continuous-flow machines: compared with cabinet machine, continuous flow machine uses proper conveying devices to continuously clean parts in the cabinets. These machines are used to clean coils and wires as well as castings and forgings at a high production rate. Combined with a abrasive particle recycling system, it can reuse the blast particles.

f) *CO_2 dry ice blasting*

CO_2 dry ice blast is a special dry blasting method in that it uses frozen CO_2 particles or snow as abrasive media. Some parts may be sensitive to thermal changes from the pellets and should be tested first. While particles can be clean the surface at a faster rate, it can also damage the surface being cleaned. The advantage of the CO_2 dry ice blasting is that they sublimate on contact with the material to be cleaned.

2.4 Testing and Inspection for Remanufacturing

After parts are cleaned, inspection and testing procedures are followed to check if repair is required. Since parts to be remanufactured are always in different conditions, testing is generally unavoidable. Since the purpose of remanufacturing is to reuse the parts, most of the testing methods are not intended to create any damage to the part being tested. As such called, *nondestructive* testing is a commonly used technique to reveal flaws and defects in a material or device without damaging or destroying the test sample.

Since nondestructive testing (NDT) is a wide group of analysis techniques used in science and industry to evaluate the properties of a material, component or system without causing damage, currently commonly used NDT methods are summarized below.

2.4.1 Methods for Nondestructive Testing

NDT methods employ techniques such as microscope, electromagnetic radiation, sound, and combined with the inherent properties of materials to detect flaws in the parts to be remanufactured. Microscope method is generally used to examine external surfaces of the part being tested. To test the inside of the part, methods such as electromagnetic radiation and liquid penetrant testing are generally used to examine fatigue cracks. For liquid penetrant methods, a certain liquid is applies to penetrate and reveal the cracks. For non-magnetic material, fluid with fluorescent or non-fluorescing dyes is commonly used. For magnetic material, an externally applied magnetic field or electric current through the material is used. When parts have cracks, magnetic flux will leave at the area of the flaw, resulting in leakage of magnetic field at the flaw area. This leakage can be captured and used as an indication of flaws.

NDT can be further classified in to various methods and techniques. It is important to select the right method and technique for a specific part or material to ensure the performance of NDT.

Liquid Penetrant Inspection method usually takes following test procedure:

1. Pre-cleaning: cleaning methods discussed earlier are used to remove any dirt, oil, grease or any other contaminants to ensure that any defects are open to the surface, dry, and free of contamination.
2. Application of Penetrant: After parts are cleaned, penetrant is then applied to the surface. A certain period of time (5–30 min) is required to allow the penetrant to immerse into any flaws. The length of the penetration time depends on the penetrant being used, the type of material being testing, and the size of flaws being examined. Generally, smaller flaws require a longer penetration time. Excess penetrant has to be removed from the surface of the part being tested.
3. Application of developer: A developer is a chemical that draws penetrant from defects so that defects can be identified. From the stains that show up in the developer one can identify the positions and types of defects on the surface under inspection.
4. Inspection: In inspection, visible light is applied for visible dye penetrant. In contrary, for fluorescent penetrant, ultraviolet radiation is applied to the part surface being examined.
5. Post Cleaning: Cleaning is required to remove penetrant after inspection and recording of defects are finished.

As to magnetic penetrant testing, fine iron or magnetic particles, held in suspension in a suitable liquid, are used as penetrant. For better performance of the inspection, the particles are usually colored and coated with fluorescent dyes visible under ultraviolet light. To apply the penetrant, the liquid suspension is sprayed or painted on to the part, which is magnetized. Due to magnetic leakage at the defect area, the magnetic particles are attracted in the area of the defect. When UV light is applied, the location and size of the defect can be easily identified. Magnetic

penetrant testing method is generally a low cost inspection method and is much faster than ultrasonic testing and radiographic testing.

Radiographic testing (RT) methods use short wavelength electromagnetic radiation to penetrate materials and reveal defect. Typical radiation source is an X-ray machine. Since the amount of radiation emerging from the opposite side of the material can be detected and measured, variations in the intensity of radiation are used to determine thickness or defect of material.

3 Disassembly Analysis and Disassembly Process Planning

One important step of remanufacturing is product disassembly [4]. A proper disassembly procedure can increase residual value recovery and reduce the environmental impact resulted in recycling processes. Disassembly analysis and planning in this regard, addresses three issues: (1) Optimal disassembly strategy that recovers maximum residual value, (2) Disassembly sequence planning, and (3) evaluation of disassembly time, cost, and disassembly difficulty rate, with component information provided.

The disassembly relationships among the components of a product to be remanufactured include component-fastener relationships and precedence relationships. Therefore, two types of graphs are needed in order to fully represent the relationships among the components of a product, namely, component-fastener relationship graph and precedence relationship graph.

Fasteners are used to attach one component to another for the purpose of assembly. Examples of fasteners include screws, rivets, inserts, etc. In a component-fastener graph $G_c = (V, E)$, The components are represented as the vertices $\mathbf{V} = \{v_1, v_2, \ldots, v_n\}$, where n is the number of components. Their relationships are represented as the edges $\mathbf{E} = \{e_1, e_2, \ldots, e_m\}$, where m is the number of edges. If two components vi and vj ($i \neq j$) are joined by fasteners, then $(vi, vj) \in \mathbf{E}$; otherwise $(vi, vj) \notin \mathrm{E}$. The graph Gc is an undirected graph. Vertices and edges in graph Gc are modeled using object-oriented techniques. While the object vertex consists of component information including its name, weight, material type, etc., the object edge consists of fastener information including the number of fasteners, fastener type, etc. For example, Fig. 3a. shows component-fastener graph of a personal computer.

Precedence graph represents the precedence relationship among the components of a product, namely, a component cannot be disassembled before certain components. Figure 3b shows the precedence relationship graph.

Disassembly tree can then be constructed based on the component-fastener graph and precedence graph. The disassembly tree consists of vertices representing an assembly or a component and information such as its name, material type, weight/volume. A vertex is decomposed into child vertices representing its child sub-assemblies or components. An edge, linking a child vertex with its parent vertex, represents the disassembly relationship between two components and information about assembly method.
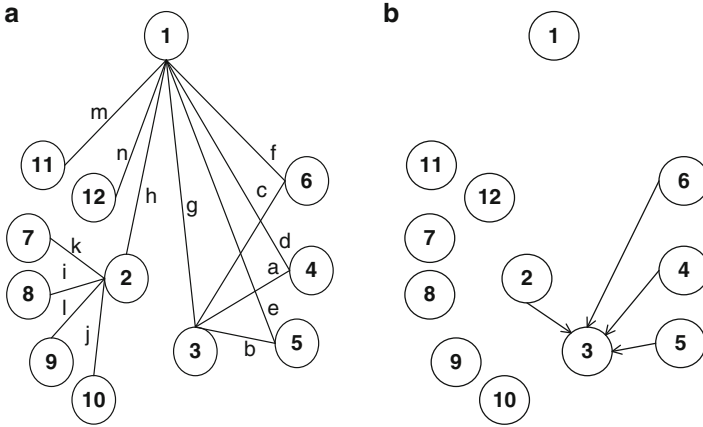
Fig. 3 (**a**): Component-fastener graph for the assembly, (**b**): Precedence relationship graph for the assembly
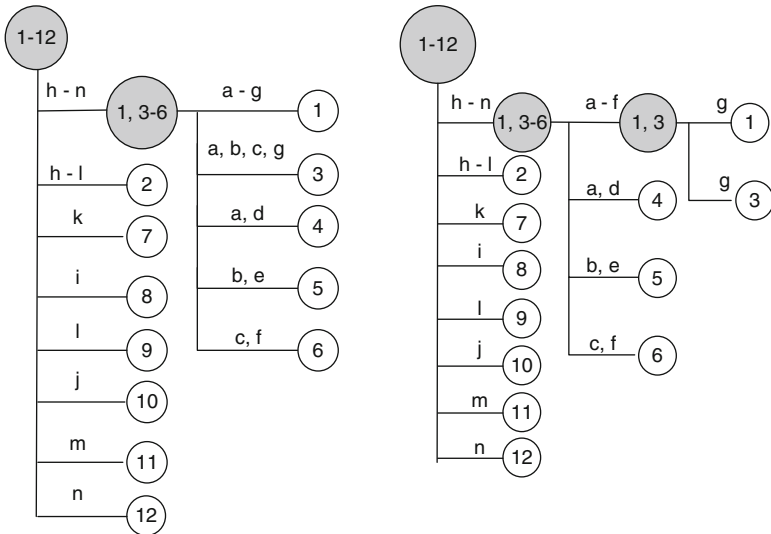
Fig. 4 (**a**): Pseudo-disassembly tree. (**b**): Disassembly tree for the assembly

The disassembly tree is constructed through searching of cut-vertices in the component-fastener graph. A cut-vertex is a vertex whose removal disconnects the graph. If a cut-vertex is found, the graph is split into two or more sub-graphs. The same procedure is repeated until no cut-vertices can be found. In this way, a pseudo-disassembly tree is generated which is showed in Fig. 4a.

Fig. 5 Optimal disassembly termination analysis

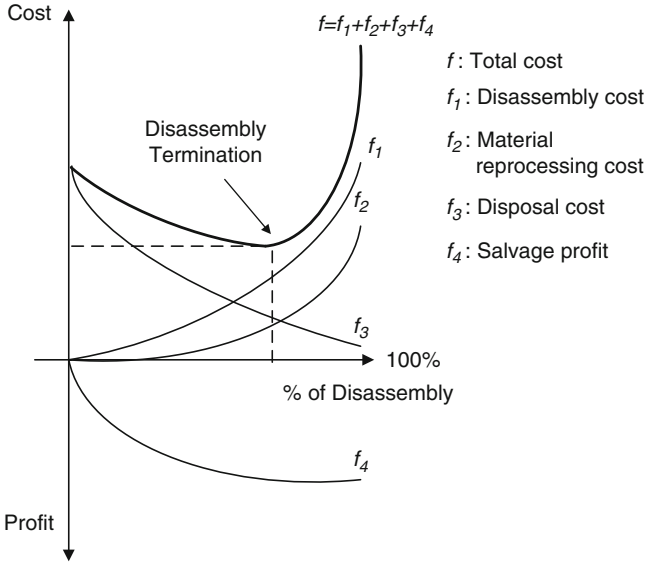The pseudo-disassembly tree is then modified by the precedence of the disassembly according to the precedence graph, and a disassembly tree can be obtained as illustrated in Fig. 4b.

In disassembly sequence planning, a popular assumption is that end-of-life products should be disassembled to the fullest extent possible. However, based on discussion with the recycling industry, such assumption is not practical in many cases due to the high cost of disassembly. It is very important to find the optimal level for disassembly where the benefit of reverse manufacturing is maximized and the cost is minimized. The disassembly sequence planning can be determined after such a termination point.

Optimal disassembly planning is determined based on the cost and profit. Three types of costs and one type of profit are addressed: (1) disassembly cost which includes labor and tooling cost, (2) material reprocessing cost, i.e. cost of recycling (3) disposal cost, which includes transportation fee and landfill cost, and (4) salvage profit, which is the profit gained by means of component reuse or recycling. The cost model for determining the termination of disassembly is illustrated in Fig. 5.

The total cost is calculated as the sum of disassembly cost, material reprocessing cost, disposal cost, and salvage profit. The lowest point of the curve (f) representing the total cost determines the termination of disassembly where the cost is minimized, in other words, the benefit of disassembly is optimized. Note that the obtained disassembly plan is optimized just from the viewpoint of economy and the plan is not always optimal from the environmental viewpoint.

4   Remanufacturing Production Planning and Optimization

The most significant characteristic of remanufacturing production system is its unstable and uncertain incoming flow [2]. The returned products generally have a high uncertainty in arrival pattern and high variation in product type with disparate residual value. Quantity, year of model, and quality of returned products are also subject to high uncertainty. For example, the product might come from a software company that updates its computers every 3 months or they might come from a family replacing its 10-year-old home computer. The consequence of high uncertainty and variation of the return flow is the difficulty associated in production planning and control of the remanufacturing, which leads to increased production cost and poor economic performance [3].

Another major challenge of remanufacturing comes from the distinct role of the receiving inventory. On one hand, it differs from traditional ones in that customers return their post consumer products to the inventory instead of taking the product away from the inventory. In this regard, inventory is used to meet the product return demand. A redistribution cost, which does not exist in a forward manufacturing system, is incurred when the remanufacturer finds no inventory space to handle the returns. On the other hand, receiving inventory can still act as a buffer to dampen the randomness of material arrival process, thus providing a relatively stable material flow for the reverse production. However, replenishment of stocks (post consumer products) is a stochastic process with high uncertainty, while remanufacturer has little control over it. This generally results in huge safety inventory for the remanufacturers.

As in forward manufacturing, operations and processes of remanufacturing should also be aligned and optimized to maximize the total profit. This leads to following three production planning problems that need to be addressed:

1) First of all, remanufacturing system has to handle substantial number of product types. Generally these different products share one production line. Therefore, a priority based switch rule has to be developed for production planning to determine how and when to switch between different production types. The priority mechanism is generally based on following concerns. The first concern is the depreciation rate of the products or components received. Products with the highest depreciation rate should be given first consideration. The second concern is the residual value of the product. Generally, products with a high residual value should be processed first. The third concern is the environmental impact. If the product has in-transition environmental impact, it should also be processed early. The fourth concern is the market demand. If the secondary-market demand for a certain remanufactured product or component is higher, these products should be handled first. In determining when to switch, production lot size for different products with different priorities have to be determined and optimized to reduce total holding cost, set up cost and redistribution cost.

2) The second issue for remanufacturing planning and control is determination of the optimal receiving inventory capacity and safety stock level. On one hand,

receiving inventory capacity set a constraint of safety stock level and the possible production run size (that is, the number of products to be produced in one run without changing the production configuration). It also has significant impact on both stability of production and redistribution cost. With more receiving inventory space, a higher level safety stock can be allocated to improve the stability of reverse production system. This could result in better efficiency. More receiving inventory space will also reduce the chance of redistribution and associated cost. Nonetheless, excessive inventory capacity also has shortcomings—large inventory capacity increases the space cost, while higher safety inventory results in higher inventory cost.

3) The third problem is to determine the optimal workforce level and production capacity. The unstable and uncertain incoming flow of the dedicated model requires workforce level and production capacity respond to the product return demand so that excessive capacity can be avoided. However, changing capacity of any production system will always incur costs.

Obviously, effective modeling and analysis of the production model of remanufacturing system is critical to attack the problems discussed. Approaches such as Queuing networks or other mathematical modeling techniques are possible options. However, due to the special stochastic characteristics of the arrival process and the priority based switching rules in production planning, the Queuing model has to consider both the compound bulk arrival and the priority Queuing. Analysis of priority queue with compound bulk arrival has shown to be very hard to solve. Optimization with simulation methods proved to be an effective approach and can be used in optimization of a system that possesses the characteristics described in a remanufacturing system [3].

4.1   General Simulation Model

The general simulation model developed for the remanufacturing is illustrated in Fig. 6. The remanufacturing system receives the products with stochastic, compound and batch arrival. It is assumed that a batch of n different products with random quantities $(x_1, x_2, \ldots, x_n)$ is transported via the same truck. It is also assumed that there is one production line that is capable of producing each of the different product types. The production line has N stations (or stages), with a queue in front of every station. Every station has one or more identical servers with a stochastic service time. There is a transit time between any two consecutive stations, which is assumed to be exponentially distributed. The production line does not have any coordination of job movement between stations. An available operator starts a job as soon as it is available and, upon completion, the job leaves the station provided there is room at the next station. This mode of operation may cause starvation and blocking of servers. A bulk of returned products will be accepted to the receiving inventory if enough receiving space is available to hold the entire load. Otherwise,
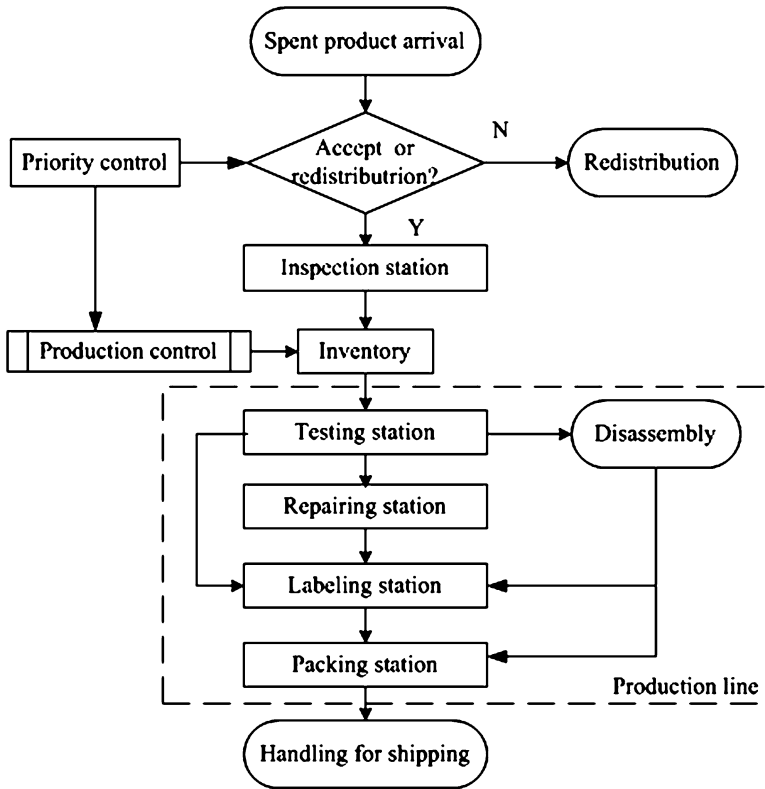
Fig. 6 General remanufacturing production flowchart

as many products as possible will be accepted and products with higher priority will be considered first. The rest of the load would be refused and a redistribution cost would be incurred.

4.2 Production Switch Rule

Since the production line is shared for processing different product types, a control mechanism is required to switch the line from one product type to another considering a specific run size and specific priorities. The switch rule can be either based on production batch or based on the product type. Production based switch is launched only when the inventory of products currently being processed is totally depleted. A variation of this rule is switching the production line after a certain period of time without referring to the current inventory level. For either case, all product types sharing the same production line implicitly have the same priority.

Another rule strictly follows the priority of each product type. Priority based rule could be impractical because it could switch the production line too frequently raising the setup costs. Consequently, it is rational to combine the product priority rule with the batch production rule. A pseudo code for the priority based batch switch control rule developed for the simulation model is given as follows:

Assume there are N types of products with distinct priority level, $N = 1, 2, 3, \ldots,$ n, where the smaller number means higher priority. Let I_i denote the inventory level of product type i, *current* denote the type of product currently being processed, and q_i denote the run size of product i, where $i = 1, 2, 3, \ldots, n.$, then we have the following switch rule:

if (Production line is running and receiving inventory station is requested to send more products to the production line) or (production line is idle and a new bulk arrives) **then**

for $i=$ 1 to n
      begin
      if $i < current$ (i.e. product i has priority over current product) and $I_i > q_i$ **then**
              current = i
              switch production line to product i
              break
          else if $i > = current$ and $I_{current} > 0$, **then**
                  continue sending current type of product to production line
                  break
          else
              idle period begins, waiting till more spent products arrival
              break
          end if
      end
end if

4.3   Optimization Problem Formulation

The control variables in the optimization model of the remanufacturing system are categorized into four types: inventory capacity, run size of each product type, number of workers in each manufacturing cell, and the buffer size of each manufacturing cells. The objective of the analysis is to find the optimal value of these decision variables that maximize the total net profit. The objective function of the remanufacturing system can be expressed as follows:

$$\max_{I \in D_I, W \in D_W, B \in D_B, Q \in D_Q,} f\,(I, W, B, Q) = TR - TC \qquad (1)$$

Where

$I =$ available inventory space for the receiving area.
$W = (w_1, w_2, \ldots, w_p)$ is the vector representing number of workers in manufacturing cell 1 to p,

$\boldsymbol{B} = (b_1, b_2, \ldots, b_p)$ is the vector representing buffer size of each manufacturing cell,

$\boldsymbol{Q} = (Q_1, Q_2, \ldots, Q_n)$ is the vector representing run size of product type 1 to n,

(D_I, D_W, D_B, D_Q) represents the feasible domain of $(\boldsymbol{I, W, B, Q})$.

Total expected profit can be derived as the difference between the expected total revenue (*TR*) and the expected total cost (*TC*) of a dedicated remanufacturing system. Total annual revenue is assumed to be

$$TR = \sum_{i=1}^{n} R_i \times V_i \tag{2}$$

where R_i is the residual value of product type i and V_i is the total volume (number) of product type i processed per year. The total cost is broken down into five major cost categories:

$$TC = C_c + C_L + C_M + C_H + C_F \tag{3}$$

Where

C_c: product collection cost. This includes the purchasing cost of used products from customers and the transportation cost during the collection process.

C_L: logistics cost. This is incurred during distribution and redistribution of the collected products. When the receiving inventory is full, redistribution cost is incurred in the re-transportation of returned products to other remanufacturing facilities.

C_M: remanufacturing processing cost. This includes labor cost, materials cost and utility cost, which are incurred in machine operating, line switch and setup, and line and operator idling.

C_H: inventory holding cost, which is incurred by holding received products in the inventory area and the production line.

C_F: fixed cost of running the factory regardless of the production level. This includes general utility, air-conditioning, insurance, and facility depreciation.

4.4 Hybrid GA Simulation Optimization Approach

Based on the objective function and the simulation model, a hybrid GA approach which combines the Fractional Factorial Design (FFD) with the GA method was developed.

As shown in Fig. 7, the optimizationprocedure starts with dividing the solution space into subspaces called cells. Each cell is considered as the local solution space of the FFD. The FFD is used to find the extrema of each cell. The results of the FFD provide the solution candidates for the GA. Based on the corresponding extrema of each cell produced by the FFD the GA will continue the search process until the termination condition is met. It is important that a well thought out fraction of the design be selected when the FFD is used to coordinate both efficiency and accuracy. A high fraction will increase the efficiency while losing accuracy as a trade-off.
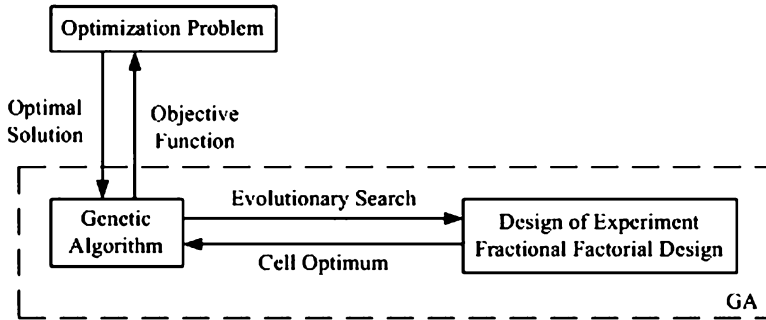
Fig. 7 The hybrid GA approach

Similarly, low fraction will increase the accuracy but will take more time to find the extrema. In general, the FFD will not only make sure that the output is the local optimum in the cell thereby improving the searching accuracy of the GA by considering all solutions in a subspace instead of a unique point, but also improve the searching efficiency due to its fractional runs. On the other hand, the GA can guarantee promising solutions due to its effective global searching performance. For a more thorough explanation of fractional factorial designs please refer to Montgomery [9].

4.5 Case Study

A case study is conducted based on a remanufacturing plant located in Austin Texas. The plant recovers, reuses, and recycles used laptops and desktops. The two types of products share the same reproduction line.

4.5.1 Model Parameters Assumptions

A number of parameters were obtained and assumptions were made in this case study based on conversations with the plant managers.

Truck arrivals are assumed to follow a Poisson process with the mean time between arrivals of 4 h per 8 h a day. Both laptop and desktop are contained in the same truck load. However, the proportion of desktop and laptop in a truck is not fixed and is a random number. The number of desktops and laptops in a single shipment satisfy the following equation: $0.5 \times$ (number of Laptops) $+ 1 \times$ (number of Desktops) $= 260$.

The number of laptops is a random integer variable with a uniform distribution between 0 and 520. The number of desktops is also a random number, which is complementary to the number of the laptops and equals $260 - 0.5 \times$ (number of laptops).

Based on the interview with the plant manager, we assume that 10 % of received computers will pass testing and be labeled directly; 10 % of them, which cannot be remanufactured, will be torn down for further recycling; the remaining 80 % of computers have to be fixed and labeled after repair.

The capacity of the receiving inventory was initially set to 500 sq. ft. If the returned products find no space available in the receiving area they will be redistributed. The redistribution fee is $450 each time regardless of how many computers are re-transported. It is assumed that all of the finished products will be immediately shipped and sold out after packaging. Hence, there is no inventory for finished goods.

There is only one production line that is shared by laptops and desktops. Based on the aforementioned production priority rule, the production line will switch with a setup time of 30 min. Letting q_L and q_D be the run size of laptop and desktop respectively, and assuming that the current production line is processing desktops. The priority based switch control can be stated as follows:

g) If I_L (number of laptops in the inventory) $> q_L$, the production line will be switched to process laptops.
h) Else if the I_D (number of desktops in the inventory) is greater than zero, the production line will keep processing desktops.
i) Otherwise, it will wait for the arrival of more computers, which causes an idle period.

The selling price of the remanufactured desktops is assumed to be $250 per unit and the selling price of the remanufactured laptops is assumed to be $400 per unit. Other parameters, assumptions and factory profile are summarized in Table 1 below.

4.5.2 Cost/Profit Evaluation

Based on the analysis outlined earlier, the costs for all related operations are summarized in Table 2.

The total inventory cost can be derived by summing all of the costs:

$$TIC = C_{space} + C_{utility} + C_{handling} + C_{equipment} \tag{4}$$

The fixed cost of the whole plant includes utility cost, as well as building and equipment expense that includes machine depreciation, building rental, taxes, insurance, fire protection, and general maintenance cost. The total building and equipment expense is $811,000 per year.

The total profit for the remanufacturer is the difference between gross revenue and total costs which is given by following equation: Profit = (Finished Desktops) × (Desktop Sell Price) + (Finished laptops) × (Laptop Sell Price) − Total Cost.

Table 1 Model assumptions

Labor	Working time	8 h per day	350 work days per year = 2,800 h per year
	Work efficiency	90 %	
Factory	Space	3,200 sq. ft.	
Truck	Arrival rate	Poisson (4 h)	
	Bulk capacity	260 sq. ft.	
	Returned products	Desktop	0.5 sq. ft. per unit, random # units per truck
		Laptop	1.0 sq. ft. per unit, random # units per truck
Inventory	For receiving	500 sq. ft.	
	For finished goods	0	
Production line	One production line shared by laptops and desktops		
	30 min setup time per switch		
	Run size	Laptop	q_L
		Desktop	q_D
Sale price	Laptop	$400 per unit	
	Desktop	$250 per unit	

4.6 Simulation Model

The simulation model for the remanufacturing operation is developed using Arena™ Software. The flowchart module is demonstrated in Fig. 8. The general purpose of the model is to analyze the effect of operational changes on the profit performance of this dedicated reverse manufacturing system. The ultimate goal of the simulation model is to find the optimal configuration of the production system resulting in maximum profit.

The distribution of the time for each operation modeled in the simulation model is assumed to be an exponential distribution, where the normal time listed in Table 3 represents the expected value. An exponential distribution is used for all service times in order to simulate the large range of possible values.

4.6.1 Optimization

In order to optimize the remanufacturing system, ten control variables are identified as important to the performance of the system under study. These parameters include: (1) receiving inventory capacity (I), (2) run size of laptops (q_L), (3) run size

Table 2 Cost analysis

Collection costs	Desktop	$150/unit
	Laptop	$250/unit
Logistic costs	Transportation cost from the supplier to the remanufacturer's site is included in the collection cost	
	Redistribution cost	$450 per redistribution
Manufacturing costs	Labor costs	Operators	$9/worker/h
		Inspectors	$12/worker/h
		Supervisors	$15/worker/h
	Material costs	$1.6/day	
	Utility costs	Electricity	9 kWh/day
		Maintenance	$4/day
	Setup costs	30 min/switch	
Inventory holding cost	Space costs	$277.74/h/ 1,000 sq.ft.	
	Utility costs	Electricity	1 kWh/day
		Maintenance	$8/day
	Handling costs	$72/day	
	Inventory opportunity costs[a]	0.00882 %/h	
	Depreciation costs	Laptop	$4.8/h/unit
		Desktop	$3.2/h/unit
Fixed cost	Utility costs	21 kWh/day	
	Building	$277.74/h/ 1,000 sq.ft.	

[a]The presence of the goods in inventory means that they are not being sold, thus the opportunity of earning with the money invested in the inventory is lost

Table 3 Manufacturing cell analysis

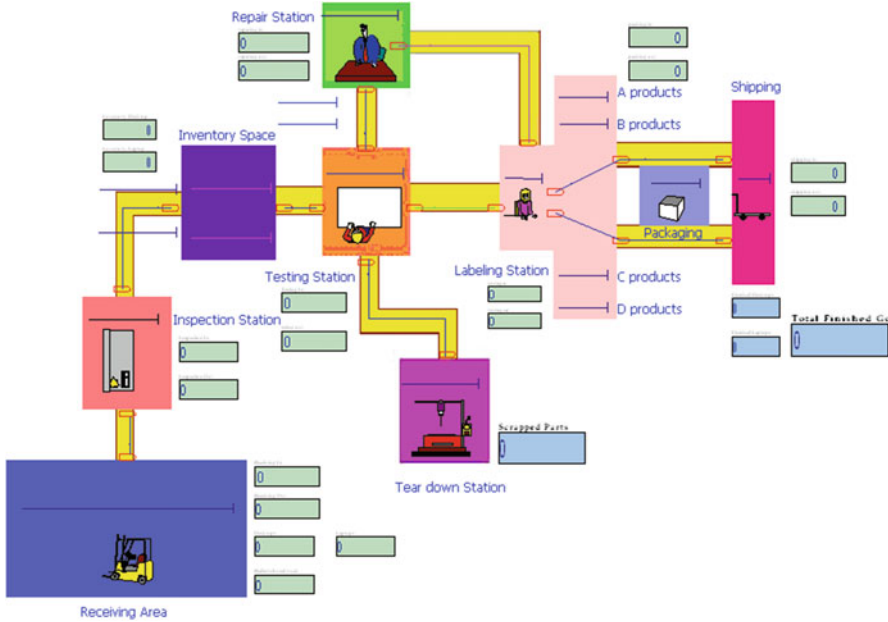| Cycle time (min)		Receiving	Inspection	Inventory handling	Testing	Repairing	Labeling	Packing	Tear down	Shipping/handling
	Laptop	3.24	1.05	0.5425	6.5	15	5.66	9.1462	5.025	1.65
	Desktop	3.24	1.23	0.5425	7.32	20	5.66	9.1462	5.725	1.65

Fig. 8 Simulation model for reverse manufacturing

of desktops (q_D), (4) buffer size of repair stations (b_r), (5) buffer size of labeling area (b_l), (6) buffer size of packing station (b_p), (7) number of workers in the testing cell w_t, (8) number of workers in the repairing cell (w_r), (9) number of workers in the labeling cell (w_l), and (10) number of workers in the packing cell (w_p). Based on the consulting from the plan manager, the reasonable range for each control variable is also obtained:

$I = \{200, 300, 400, 500, 600, 700, 800\}$
$q_L = q_D = \{30, 40, 50, 60, 70, 80\}$
$b_r = b_l = \{2, 4, 6, 8, 10\}$
$b_p = \{10, 20, 30\}$
$w_t = \{4, 5, 6, 7, 8\}$
$w_r = \{10, 11, 12\ 13, 14, 15, 16, 17, 18, 19, 20, 21\}$
$w_l = \{3, 4, 5, 6\}$
$w_p = \{5, 6, 7, 8, 9, 10\}$

In order to use the GA approach presented earlier, these ranges were decomposed into smaller cells so that the two-level FFD algorithm can be implemented. Recall that each control variable has only one or two values. In doing this, the following new segments were obtained:

$I_1 = \{200, 300\}, I_2 = \{400, 500\}, I_3 = \{600, 700\}, I_4 = \{800\}$
$q_{L1} = \{30, 40\}, q_{L2} = \{50, 60\}, q_{L3} = \{70, 80\}$
$q_{D1} = \{30, 40\}, q_{D2} = \{50, 60\}, q_{D3} = \{70, 80\}$

Table 4 Initial population

Cell index	b_r	b_l	b_p	I	q_L	q_D	w_t	w_r	w_l	w_p
7,976	[2, 4]	[6, 8]	[10, 20]	[200, 300]	[30, 40]	[50, 60]	[8]	[16, 17]	[3, 4]	[7, 8]
22,517	[2, 4]	[10]	[30]	[800]	[30, 40]	[50, 60]	[6, 7]	[14, 15]	[5, 6]	[7, 8]
25,832	[6, 8]	[2, 4]	[10, 20]	[600, 700]	[50, 60]	[70, 80]	[6, 7]	[16, 17]	[3, 4]	[5, 6]
28,314	[6, 8]	[2, 4]	[30]	[400, 500]	[30, 40]	[50, 60]	[4, 5]	[14, 15]	[5, 6]	[9, 10]
43,652	[6, 8]	[10]	[30]	[200, 300]	[70, 80]	[70, 80]	[4, 5]	[16, 17]	[3, 4]	[7, 8]
18,526	[2, 4]	[10]	[10, 20]	[800]	[30, 40]	[30, 40]	[6, 7]	[16, 17]	[5, 6]	[5, 6]
1,166	[2, 4]	[2, 4]	[10, 20]	[400, 500]	[30, 40]	[50, 60]	[8]	[14, 15]	[3, 4]	[7, 8]
66,424	[10]	[10]	[30]	[200, 300]	[50, 60]	[30, 40]	[4, 5]	[10, 11]	[5, 6]	[5, 6]
16,444	[2, 4]	[10]	[10, 20]	[200, 300]	[70, 80]	[70, 80]	[4, 5]	[18, 19]	[5, 6]	[5, 6]
4,427	[2, 4]	[2, 4]	[30]	[200, 300]	[50, 60]	[50, 60]	[8]	[20, 21]	[5, 6]	[7, 8]

$b_{r1} = \{2, 4\}$, $b_{r2} = \{6, 8\}$, $b_{r3} = \{10\}$
$b_{l1} = \{2, 4\}$, $b_{l2} = \{6, 8\}$, $b_{l3} = \{10\}$
$b_{p1} = \{10, 20\}$, $b_{p2} = \{30\}$
$w_{t1} = \{4, 5\}$, $w_{t2} = \{6, 7\}$, $w_{t3} = \{8\}$
$w_{r1} = \{10, 11\}$, $w_{r2} = \{12, 13\}$, $w_{r3} = \{14, 15\}$, $w_{r4} = \{16, 17\}$, $w_{r5} = \{18, 19\}$, $w_{r6} = \{20, 21\}$
$w_{l1} = \{3, 4\}$, $w_{l2} = \{5, 6\}$
$w_{p1} = \{5, 6\}$, $w_{p2} = \{7, 8\}$, $w_{p3} = \{9, 10\}$.

Combining the segment for each parameter, we have a total of $4 \times 3 \times 3 \times 3 \times 3 \times 2 \times 3 \times 6 \times 2 \times 3 = 69,984$ cells, which compose the original domain. Index numbers are also assigned to each of the cells from 1 to 69,984.

The population size N of each generation is set to 10. Other important parameters for the GA approach are crossover rate, P_c, and mutation rate, P_m, which are set to 0.8 and 0.78 respectively. Therefore, in each generation, 8 $(=N \times P_c)$ of ten individuals will be selected to crossover and generate eight new designs. Among these eight new designs, 6 $(=N \times P_c \times P_m)$ will be chosen for mutation.

To initialize the start population, ten random integers are generated with a uniform distribution between 0 and 69,984; they are {7,976, 22,517, 25,832, 28,314, 43,652, 18,526, 1,166, 66,424, 16,444, 4,427}. The corresponding cells are listed in Table 4.

A $\frac{1}{16}$ Fractional Factorial Design is built for each of these cells with a run size of 64 $(2^{10-4} = 64)$. The output of the simulation model is used in the FFD analysis to determine the optimum for each individual cell. The result provides the first generation listed in Table 5.

In crossover, eight of ten individuals, individuals 1, 2, 3, 4, 6, 7, 9, 10, in the first generation are randomly picked with probability P_c. Meanwhile, based on a uniform distribution U (0, 1), four random numbers, 0.46, 0.91, 0.33, and 0.78, are generated for λ. The result is shown in Table 6.

In mutation, six of the eight new designs, new designs 2, 3, 4, 5, 6, 7, 8, are randomly picked with probability P_m. Meanwhile, six random numbers, 0.86, 0.74, −0.01, −0.27, 0.42, and −0.67, are generated for ζ following normal distribution

Table 5 First generation

Individual	Control parameters										Output ($)
	b_r	b_l	b_p	I	q_L	q_D	w_t	w_r	w_l	w_p	
I_1	2	6	20	300	40	50	8	17	4	7	18,970.26
I_2	4	10	30	800	30	50	7	14	5	8	28,161.37
I_3	8	4	20	600	50	70	5	16	4	7	19,443.51
I_4	8	4	30	500	40	60	7	15	6	10	29,153.52
I_5	8	10	30	300	70	70	5	16	4	7	18,896.89
I_6	2	10	20	800	30	40	6	16	6	6	19,505.26
I_7	4	2	10	500	30	60	5	14	4	7	18,346.21
I_8	10	10	30	300	60	30	5	11	5	6	17,914.16
I_9	4	10	20	300	80	70	5	19	5	5	15,543.76
I_{10}	2	2	30	300	50	60	8	21	5	8	24,729.08

N (0, 1). The resulting mutation is listed in Table 7. The last column contains the corresponding cell indexes.

The FFDs are built for these new designs. After running the simulation model, the output is analyzed using the FFDs to find the cell optima. After eight optima are obtained, the best ten was selected from them and the second generation as the population of the first generation, which are shown in Table 8.

Similar procedures of crossover, mutation and cell analysis are followed to generate the rest of the generations until the termination condition is met. In this case, the procedure stops if the optimum does not change for two generations or the differences among individuals in a generation is less than 5 %. Under this criterion, the GA approach stops after seven generations. Figure 9 shows the outputs of each generation. In each generation ten seeds are selected for mutation and crossover which lead the next generation. These ten selected ones are demonstrated in Fig. 9. As illustrated, the profit of each generation is increasing as the generation evolves. The final optimal solution of the remanufacturing system in this case study is 700 sq. ft. for receiving inventory, 40 for run size of laptops, 80 for run size of desktops, 18 workers in the repairing station withbuffer size of 8, 6 workers in the labeling station with buffer size of 6, 10 workers in the packing station with buffer size of 20 and 8 workers in the testing station.

5 Conclusion

This chapter summarizes the critical issues involved in remanufacturing. Typical remanufacturing processes including cleaning, testing and inspection, and disassembly are illustrated. Characteristics of remanufacturing production system and problems are also introduced. A GA optimization approach based on the simulation model is also developed to obtain the optimal production policy.

Table 6 Cross over of first generation

New design	Cross over function	Control parameters									
		b_r	b_l	b_p	I	q_L	q_D	w_t	w_r	w_l	w_p
N_1	$I_1 \times 0.46 + I_2 \times 0.54$	3.08	8.16	25.4	570	34.6	50	7.46	15.38	4.54	7.54
N_2	$I_1 \times 0.54 + I_2 \times 0.46$	2.92	7.84	24.6	530	35.4	50	7.54	15.62	4.46	7.46
N_3	$I_3 \times 0.91 + I_4 \times 0.09$	8	4	20.9	591	49.1	69.1	5.18	15.91	4.18	7.27
N_4	$I_3 \times 0.91 + I_4 \times 0.09$	8	4	29.1	509	40.9	60.9	6.82	15.09	5.82	9.73
N_5	$I_6 \times 0.33 + I_7 \times 0.67$	3.34	4.64	13.3	599	30	53.4	5.33	14.66	4.66	6.67
N_6	$I_6 \times 0.67 + I_7 \times 0.33$	2.66	7.36	16.7	701	30	46.6	5.67	15.34	5.34	6.33
N_7	$I_9 \times 0.78 + I_{10} \times 0.22$	3.56	8.24	22.2	300	73.4	67.8	5.66	19.44	5	5.66
N_8	$I_9 \times 0.22 + I_{10} \times 0.78$	2.44	3.76	27.8	300	56.6	62.2	7.34	20.56	5	7.34

Table 7 Mutation of first generation

New design	Mutation function	Control parameters										Corresponding cell index
		b_r	b_l	b_p	I	q_L	q_D	w_t	w_r	w_l	w_p	
N_1	–	3.08	8.16	25.4	570	34.6	50	7.46	15.38	4.54	7.54	13, 769
N_2	$N_2 + 0.86$	3.78	8.7	25.46	530.86	36.26	50.86	8.4	16.48	5.32	8.32	20, 615
N_3	$N_3 + 0.74$	8.74	4.74	21.64	591.74	49.84	69.84	5.92	16.65	4.92	8.01	56, 976
N_4	$N_4 - 0.01$	7.99	3.99	29.09	508.99	40.89	60.89	6.81	15.08	5.81	9.72	28, 350
N_5	$N_5 - 0.27$	3.07	4.37	13.03	598.73	29.73	53.13	5.06	14.39	4.39	6.4	2, 065
N_6	$N_6 + 0.42$	3.08	7.78	17.12	701.42	30.42	47.02	6.09	15.76	5.76	6.75	13, 775
N_7	$N_7 - 0.67$	2.89	7.57	21.53	299.33	72.73	67.13	4.99	18.77	4.33	4.99	12, 445
N_8	–	2.44	3.76	27.8	300	56.6	62.2	7.34	20.56	5	7.34	503

Table 8 Second generation

| Individual	Control parameters										Output ($)
	b_r	b_l	b_p	I	q_L	q_D	w_t	w_r	w_l	w_p	
I_1	8	4	30	500	40	60	7	15	6	10	29,153.52
I_2	8	4	30	500	40	60	7	15	6	10	29,153.52
I_3	2	10	30	500	40	60	8	16	6	8	28,684.64
I_4	4	10	30	800	30	50	7	14	5	8	28,161.37
I_5	10	8	20	700	60	80	7	17	6	8	27,993.82
I_6	4	8	30	700	30	50	7	14	5	8	26,383.17
I_7	2	8	20	700	30	60	7	16	6	8	25,424.63
I_8	2	2	30	300	50	60	8	21	5	8	24,729.08
I_9	4	2	30	300	60	60	7	20	6	8	24,287.99
I_{10}	4	4	20	700	40	60	5	15	4	6	19,564.63
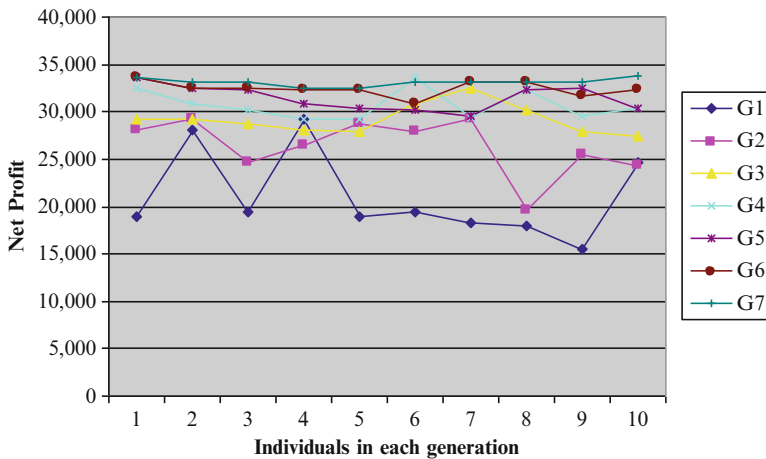
Fig. 9 Outputs of different generations

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