Design Methodologies Towards a Sustainable Manufacturing Enterprise

Tariq Aljuneidi

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ABSTRACT

Design Methodologies Towards a Sustainable Manufacturing Enterprise

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Sustainability is increasingly becoming a crucial concern in many aspects of life. Even though, there is a relatively growing interest from both academic researchers and practitioners in various design aspects of sustainability, one can see that design issues of sustainable manufacturing systems have not received adequate attention. Through an extensive literature review on design for sustainability and sustainability issues, it is observed that, attaining sustainability in manufacturing needs a huge amount of effort and needs to take into consideration many aspects from different perspectives. These include considering the sustainability in both the closed loop supply chain (CLSC) and the manufacturing system levels simultaneously, considering Cellular Manufacturing Systems (CMSs), considering reconfigurability for the production systems, considering Hybrid Manufacturing-Remanufacturing Systems as well as considering the recovery options such as recycling and remanufacturing. This research presents a simultaneous investigation of Reconfigurable Cellular Manufacturing Systems and Hybrid Manufacturing-Remanufacturing Systems (HMRSs), and proposes an integrated approach in design optimization, analysis, and process planning aspects as an attempt to address to a large number of design issues for Sustainable Manufacturing Systems, while the options of

remanufacturing, recycling, and disposing are introduced. Four mathematical model have been developed.

Third part cellular remanufacturing systems design are considered within the first model, which is initially formulated as a mixed integer non-linear program that incorporates multi-period production planning, dynamic system reconfiguration, and workforce management with deterministic production requirements. It consists the costs of machines maintenance and overhead, relocation costs for machines installation and removal, part holding cost, workers' costs of salary, hiring, and firing, part intercellular movement cost, machine procurement cost, internal production cost, machine operating cost, the cost of acquiring the returned products, setup cost for disassembly operations, disassembly cost, the inventory cost of the returned products, parts disposal cost. Linearization procedures are proposed to convert it into a linearized mixed integer programming formulation. This linearized mixed integer program is solved using an exact solution (ES) procedure through the simplex-based branch and cut procedure of CPLEX software.

The second model considered the design of cellular hybrid manufacturing-remanufacturing system, where manufacturing new products using an outsourced parts and remanufacturing using returned products are performed in the same facility by using shared resources. The overall objective of the model is to minimize the total cost of the three main categories of costs; 1) Machine cost: maintenance and overhead costs, relocation costs of installation and removal of machines, machine procurement costs, and machine operating costs, 2) Costs associated with manufacturing and remanufacturing: production costs for both new and remanufactured components, holding cost for new components, holding cost for remanufactured components, setup cost for new components, setup cost for

remanufactured components, 3) Costs associated with returned products for remanufacturing: cost of acquiring the returned products, setup cost for disassembly operations, disassembly cost, and inventory cost of the returned products. Computational results and sensitivity analysis for an important design features are also reported.

The third model addresses the same attributes as the second one but an important extension is the introduction of recycling (for the end-of-life parts) and disposing of the parts with no further use. In addition, the new parts production in the third model are totally depends on the recycled parts coming from the recycling center, wherein the second model it depends on the raw material purchasing from outsourcing.

As the third model is the most comprehensive one, which considers a closed loop supply chain starts from a cellular hybrid manufacturing-remanufacturing system and ends with the customer zone, through the introducing of different centers like, collection, disassembly, and recycling centers, and in order to have one more step toward the design of sustainable closed loop supply chain, the fourth model are formulated. The fourth model is designed to minimize the carbon foot prints and the total cost which contains the opening costs for different centers and the transportation costs between these centers

Keywords: Sustainability, Sustainable manufacturing system, cellular manufacturing systems design, Reconfigurable manufacturing system, mixed integer programming, Hybrid manufacturing-remanufacturing system, Closed loop supply chain, Reverse logistics, Carbon footprints, Facility location.

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LIST OF ACRONYMS

DFSME	__	Design for Sustainable Manufacturing Enterprise
CMS	__	Cellular Manufacturing System
RMS	__	Reconfigurable Manufacturing System
CM	__	Cellular Manufacturing
RCMS	__	Reconfigurable Cellular Manufacturing System
SCM	__	Supply Chain Management
RL	__	Reverse Logistics
EOL	__	End-Of-Life
GHGs	__	Green House Gases
OEM	__	Original Equipment Manufacturer
TPR	__	Third Part Remanufacturer
HMRS	__	Hybrid Manufacturing-Remanufacturing System
CLCS	__	Closed Loop Supply Chain
SMSs	__	Sustainable Manufacturing Systems
PFI	__	Part Families Identification
MGI	__	Machine Groups Identification
PF/MG	__	Part Families/Machine Grouping
AI	__	Artificial Intelligence
LP	__	Linear Programming
LQP	__	Linear and Quadratic Programming
DP	__	Dynamic Programming
GP	__	Goal Programming
GCA	__	General Cognitive Ability

RMTs	__	Reconfigurable Machine Tools
AHP	__	Analytical Hierarchical Process
RS	__	Reconfiguration Smoothness
H-RS	__	Hybrid Reconfigurable System
DfRem	__	Design for Remanufacturing
SBD	__	Sustainable Business Development
GAMS	__	Generalized Algebraic Modeling System
DCRS	__	Dynamic Cellular Remanufacturing System
RCHMRS	—	Reconfigurable Cellular Hybrid Manufacturing-Remanufacturing System
MILP	__	Mixed Linear Integer Programming

Chapter 1

1. Introduction

1.1. Introduction

Sustainability, which is a widely used term today, has been attracting an increasing attention during the recent years. However, there is no one precise definition for the term sustainability. One of the definitions is given as: '***Sustainability means the arrangement of technological, scientific, environmental, economical, and social resources in such a way that the resulting heterogeneous system can be maintained in a state of temporal and spatial equilibrium'*** (Ron, 1998). The most widely used definition is the one which is provided by the United Nations' Brundtland Commission: '***development that meets the needs of the present without compromising the ability of future generations to meet their own needs'*** (Jayal et al. 2010), this definition is the one that will be used in this dissertation.

There is a definite need of achieving sustainability in manufacturing sectors, since product manufacturing has an essential part among the whole supply chain network. However, there is no globally accepted definition for sustainability in manufacturing enterprises. The U.S. Department of Commerce defines sustainable manufacturing as: ***'the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe employees, communities, and consumers and are economically sound'*** (Jayal et al. 2010). Another definition for sustainable production is: ***'the creation of goods and services using processes and systems that are: non-polluting; conserving of energy and natural resources; economically viable; safe and healthful for workers, communities, and consumers; and, socially and creatively rewarding for all working people'*** (Veleva et al., 2001).

External pressures (e.g. government regulations, profit, and non-profit organizations) and internal pressures (e.g. strategic objectives, top management vision, cost savings, productivity, and quality) have been forcing companies to determine their actual situations with respect to sustainability and to reset their goals (Gunasekaran and Spalanzani, 2012). The concept of *Design for Sustainable Manufacturing Enterprise* (DFSME) has recently become an important issue, which it defines the significant aspects of sustainability and how they can be aggregated concurrently taking into consideration the globalization issues (Gabrie, 2013).

In order to design sustainable manufacturing enterprises, Cellular Manufacturing System (CMS) and Reconfigurable Manufacturing System (RMS) designs are highly recommended (Gabrie, 2013). A functional or process layout (a job shop) does well in the case where the variation among the products is extremely high and the production volume for each product is low. On other hand, the line layout (a flow line) deals with the high-volume production but low variety mix. Such a system has low flexibility to deal with the customization products. CMS does well in the case of mid volume and mid variety demand, and it has high flexibility in dealing with customization and short term life cycle products. Cellular Manufacturing (CM) is an application of group technology in manufacturing in which similar parts are classified into part families and different machines are assigned into machine cells (Ahkioon et al., 2009b). There are many benefits of CM for a manufacturing facility, if applied correctly. Processes become more balanced and productivity increases since the manufacturing floor has been reorganized and tidied up. Part movements, set-up times, and waiting times between operations are reduced, resulting in a reduction of work-in-process inventory freeing idle capital that can be better utilized elsewhere (Ahkioon et al., 2009a). Figure 1 – 1 shows the design layout formulation of the CMS. Figure 1 – 2 presents a comparison between the three systems (flow line, cellular, and job shop) when perform with regard to the products variety and the demand volume.

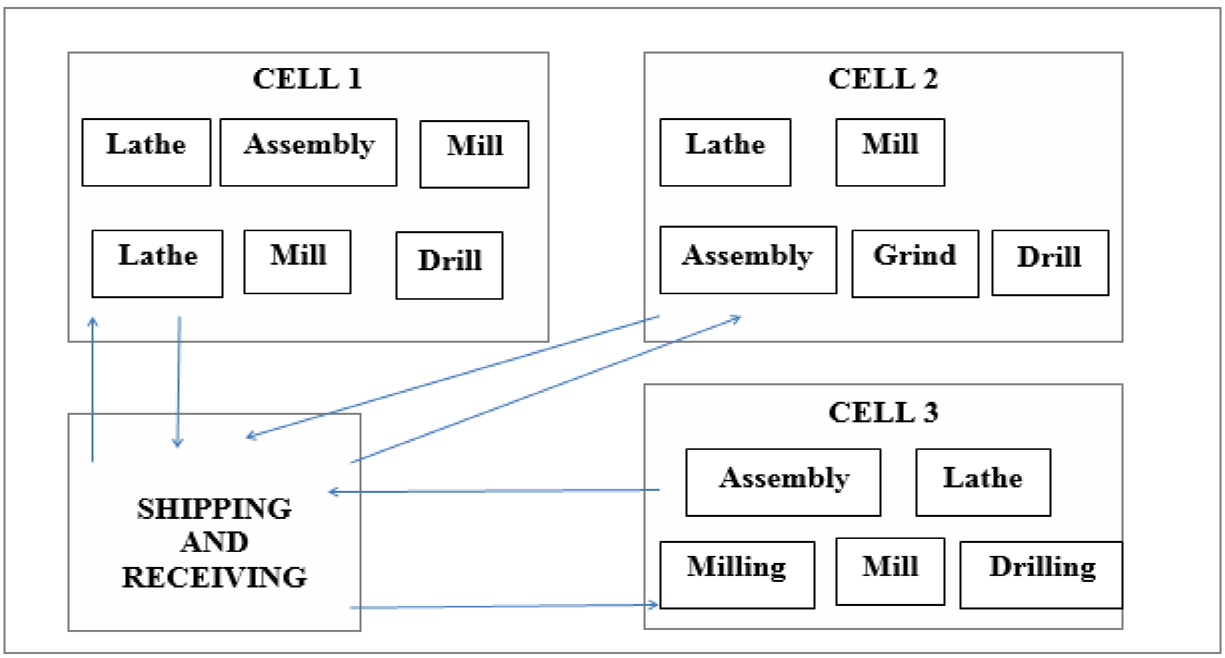

Figure 1-1 CMS layout

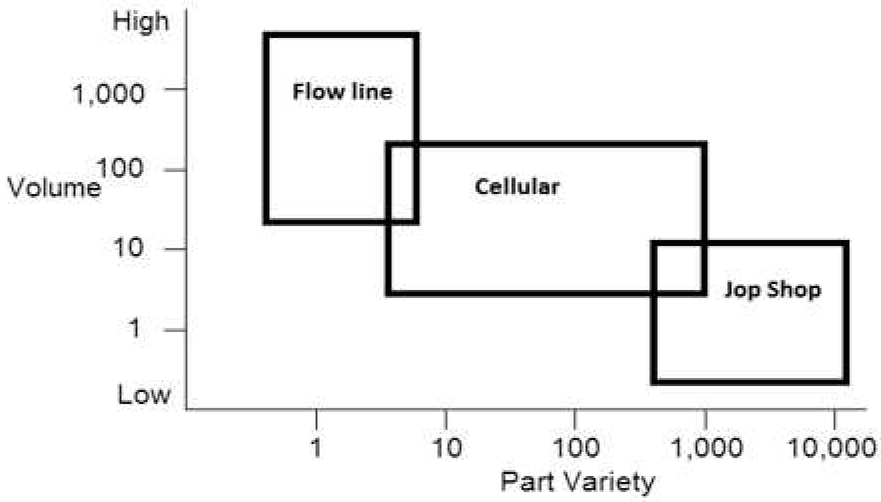

Figure 1-2 Systems comparison

Shorter product life-cycles, higher product variety, unpredictable demand, and shorter delivery times have caused manufacturing systems to operate under dynamic and uncertain environments, as a result of dynamic deterministic demands within the planning horizon, a CM configuration for a period might not be optimal or even feasible for other planning periods. In this matter, a RMS that has the ability of rapid response to market changes and customer requirements is needed. Koren and Shpitalni (2010) define the reconfigurability as "***a novel engineering technology that facilitates cost effective and rapid responses to market and product changes***". Therefore, RMS allow the user to obtain the best configuration within each planning period in terms of the types and number of machines assigned to cells, part types assigned to cells and part routings. This is achieved when machines are added and/or removed (relocation) and when new process routings for parts are chosen from one period to the next. The presence of such a dynamic system reconfiguration feature enhances the flexibility of the CMS to respond to variations in part mix demands and machine availabilities (Ahkioon, 2007). RMS can be classified into three main parts: production system design, material handling systems, and plant layout systems, as shown in figure 1 – 3 (Gabrie, 2013). RMSs own numerous advantages representing in reconfigurable components and machines, material handling systems, and easily changing physical layouts to secure sustainability (Garbie 2013). Thus, a Reconfigurable Cellular Manufacturing System (RCMS) design is a highly powerful system in order to achieve a sustainable enterprise.

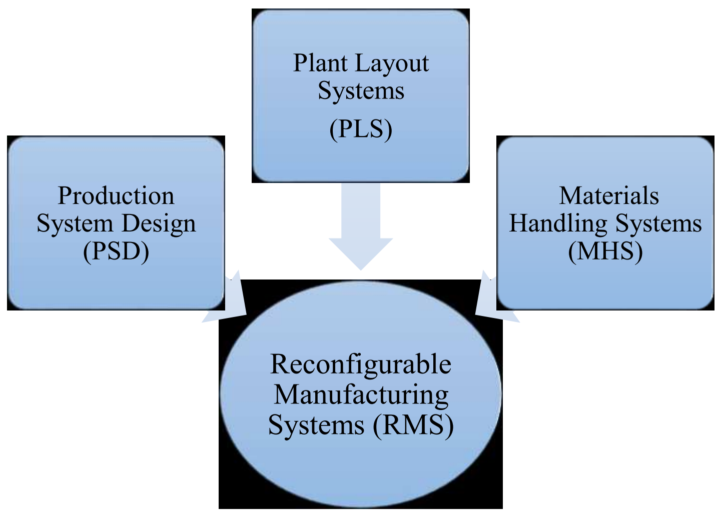

Figure 1-3 Reconfigurable Manufacturing Systems (RMS)

Achieving sustainability in manufacturing requires a holistic view spanning not just of the product and the manufacturing processes involved in its fabrication, but also the entire supply chain including the manufacturing systems across multiple product life-cycles (Jayal et al. 2010). Thus, it is critical that a sustainable supply chain be integrated with sustainable manufacturing processes, design, and systems in order to fulfill the sustainable manufacturing philosophy (Haapala et al. 2013). Manufacturing processes, reprocessing operations, and inspection/ disassembly are considered plant level processes that interact with system level aspects, such as process planning, production scheduling, the forward supply chain, and the reverse supply chain (Haapala et al. 2013). Badurdeen et al. (2009) defines the sustainable Supply Chain Management (SCM) as "***Involvement of the planning and management of sourcing, procurement, conversion and logistics activities involved during premanufacturing, manufacturing, use, and post-use stages in the life cycle in closed-loop through multiple life-cycles with seamless information sharing about all product life cycle stages between companies by explicitly considering the social and environmental implications to achieve a shared vision***".

Supply chain sustainability focuses on two aspects: the design of sustainable enterprises and closing the production loop (reverse supply chain) (Haapala et al. 2013). Reverse Logistics (RL) can be defined as "***RL is the process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal***" (Rogers and Tibben-Lembke, 1999). RL starts from end users where used products are collected from customer zone and then attempts to manage End-Of-Life (EOL) products through different recover options including recycling (to have more raw materials or raw parts), remanufacturing (to resale them to second markets or if possible to first customers), repairing (to sell in the second markets through repairing), and finally, disposing of some used parts (Govindan et al. 2015). In supply chain networks, a number of actors will influence business costs and corresponding environmental impact: suppliers, manufacturers, consumers, logistic operators, third parties operating in testing, refurbishing, recycling, and energy production for the EOL products (Quariguasi Frota Neto et al. 2008). As explained by Quariguasi Frota

Neto et al. 2008, the decisions regarding these activities will therefore determine the supply chain configuration, as well as the costs and the environmental impact. These decisions are strategic (e.g. location of manufacturing plants or warehouses), tactical (e.g. product flows through the chain, choice of suppliers), and operational (e.g. vehicle routing, day-to-day production scheduling).

Sustainable SCM has evolved from the traditional green supply chain management, which in general, focuses on environmental aspects (Haapala et al. 2013). Emission of CO2 has the most significant impact on the earth's ecology since it drastically affects the environment and could potentially lead to complete disaster on earth (Govindan et al., 2016). Thus, carbon footprint measurement provide a good estimate of the total amount of Green House Gases (GHGs) emitted during the life cycle of goods and services, from the extraction of raw materials, production, transportation, storage and use to waste disposal (Plassmann et al. 2010). Hence the minimization of its emission at every stage should be the desired objective of each and every firm (Govindan et al., 2016).

Remanufacturing can take place by either the Original Equipment Manufacturer (OEM); where manufacturing and remanufacturing operations occur simultaneously or by a Third Part Remanufacturer (TPR) (remanufacturing facility) (Parkinson and Thompson, 2003). However, Companies should consider returns as a value to be maximized rather than a waste to be minimized (Difrancesco and Huchzermeier, 2016). A system where manufacturing and remanufacturing operations occur simultaneously with shared resources is called a Hybrid Manufacturing-Remanufacturing System (HMRS) (Chen and Abrishami, 2014).

HMRS is recommended while designing a Closed Loop Supply Chain (CLSC), which is the network that considers forward and reverse supply chains simultaneously, in order to achieve an efficient network design (Govindan et al. 2015). Figure 1 – 4 illustrates such a CLSC and how it relates to HMRSs.

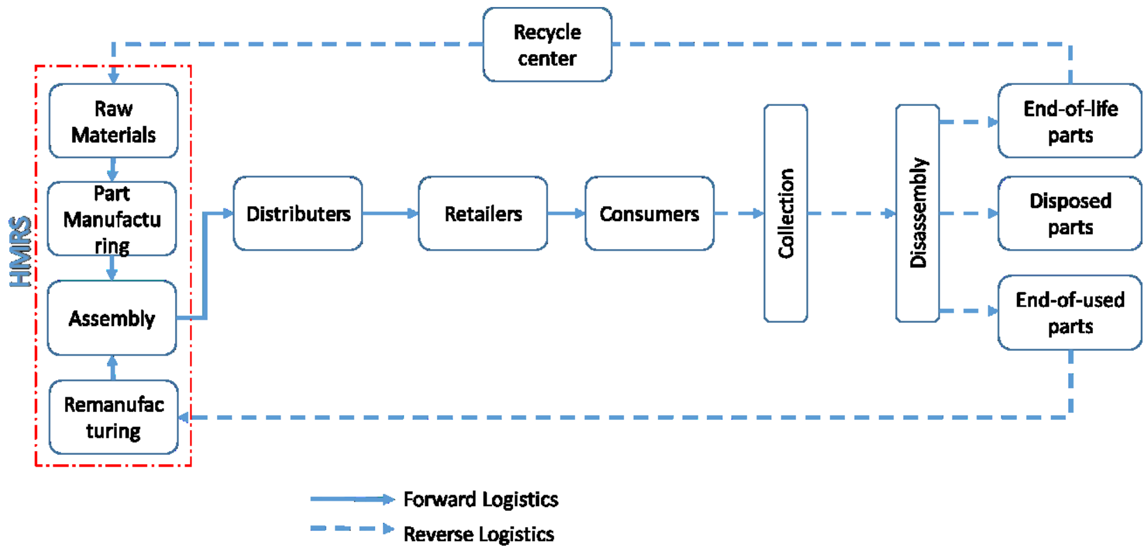

Figure 1-4 CLSC and HMRS relationship

1.2. Problem Definition, Scope, and Framework

Design for sustainable manufacturing enterprise (*DFSME*) is considered to be a new ideologue regarding survival of manufacturing enterprise and it can also be considered as one of the most important solutions to deal with the existing global financial crisis (Garbie 2013). In order for an enterprise to be qualified as a "sustainable manufacturing enterprise" requires simultaneous considerations of a large variety of issues from diverse perspectives; including international/national regulations, business strategies, innovative product designs, manufacturing strategies, manufacturing system designs. The major steps, as reported in different published articles [Haapala et al., 2013; Jayal et al., 2010; Gunasekaran and Spalanzani, 2012; Garbie, 2013; Difrancesco and Huchzermeier, 2016], are considerations of the recovery options, Cellular Manufacturing Systems, Reconfigurable Manufacturing Systems, Hybrid Manufacturing-Remanufacturing Systems, Green Closed Loop Supply Chains as well as considerations of sustainability in both the closed loop supply chain and the manufacturing system levels simultaneously (as also depicted in figure 1 – 5).

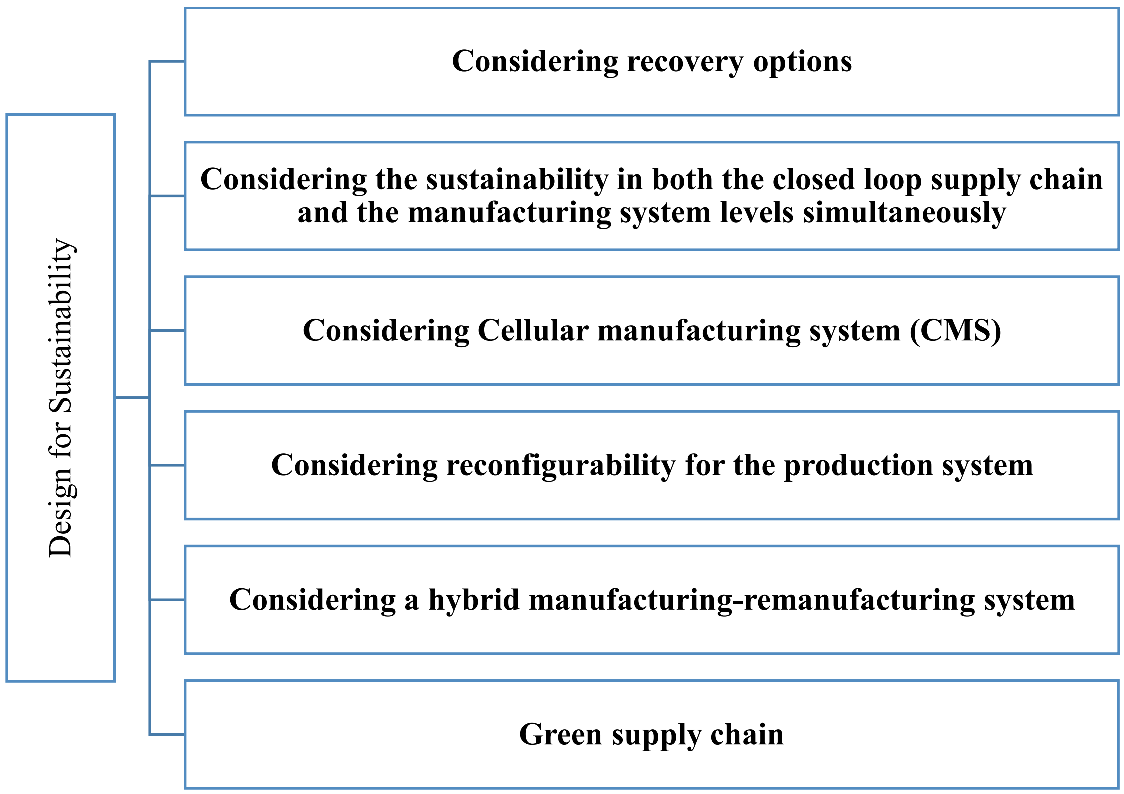

Figure 1-5 Major steps toward DFSME

Accordingly, this thesis addresses a number of interrelated manufacturing system/supply chain design problems towards achieving a Sustainable Manufacturing Enterprise within the context of the "Design for Sustainability" framework as presented above. These problems can further be elaborated as follows:

1) Remanufacturing is the most popular recovery option that is used nowadays, since it recaptures a valuable portion of the energy and value added during the

manufacturing stages of the products. Remanufacturing can take place by either the Original Equipment Manufacturer (OEM); where manufacturing and remanufacturing operations occur simultaneously or by a Third Part Remanufacturer (TPR) (i.e. remanufacturing facility) (Parkinson and Thompson, 2003). We started this research by addressing design aspects for a Third Part Remanufacturer (TPR). As recommended by Garbie (2013), in order to design a sustainable TPR system, a Cellular Manufacturing System for the TPR should be designed while considering the reconfigurability option simultaneously. Thus, in Chapter 3, a Dynamic Cellular Remanufacturing System (DCRS) design methodology is proposed. The proposed model is a nonlinear mixed integer programming model which considers a wide range of manufacturing attributes in addition to certain workforce management issues.

2) The second stage in this research is to consider design issues towards a sustainable Original Equipment Manufacturer (OEM). In an OEM, manufacturing and remanufacturing typically take place within the same facility. This type of manufacturing system is called a Hybrid Manufacturing-Remanufacturing System (Chen and Abrishami, 2014). In this context, Reconfigurable Cellular Hybrid Manufacturing-Remanufacturing Systems (RCHMRSs) are highly recommended and desired for an OEM (Garbie 2013). The design methodology of such systems can be executed in two phases. The first phase is to design a system that deals with remanufacturing option only while manufacturing new products are depends on new material procurement. In Chapter 4, a mathematical model for designing such a RCHMRS is presented.

3) In the second phase, an essential extension for the model presented in Chapter 4 is proposed by considering the “recycling option” for the end-of-life components. End-of-Life components are the components that can no longer be used for remanufacturing processes. While the end-of-life components are sent to landfilling in many industries today, recycling is far more desirable in comparison to landfilling since the energy and resources expended in producing the raw materials are recaptured (Parkinson and Thompson, 2003). With the recycling option included, the production for the new products totally depends on the recycled parts coming from the recycling center. In addition, the “disposal option” for components with no further use is also considered. The mathematical model for designing a RCHMRS are reported in Chapter 5.

4) The material flow for the proposed model in chapter 5 as shown in figure 5 – 1 perform a closed loop supply chain with different centers allocated within this network. Correspondingly, there is a need to build this network as a green supply chain network. A green supply chain features many aspects such as carbon foot prints, plant location, and the introduction of recovery options. The material flow network design based on carbon footprints and facility location while considering a hybrid manufacturing-remanufacturing system as well as the recovery options are presented in Chapter 6.

1.3. Research Objectives

Based on Gunasekaran and Spalanzani’s (2012) article as well as based on our literature review presented in Chapter 2, one can observe that:

a) While sustainable business development has become a popular research area presently.

b) While sustainable CLSC research has become a popular research area presently,

c) While the research on product recovery; particularly research in remanufacturing as well as HMRSs, are starting to attract the interest of researchers,

d) Research in modeling and optimization challenges at the product, process, and system levels for sustainable manufacturing is still lagging behind. We observe that the published research related to remanufacturing and/or HMRSs is, in most part, focusing on specific and isolated problems; hence there is a need for research to approach Sustainable Manufacturing Systems (SMSs) design problems from a "*holistic*" system perspective.

The main objective of this research is to address to this important research gap and to contribute to the research in SMSs from the "*manufacturing system*" design and analysis viewpoint. Therefore, with regards to manufacturing system design, the following research sub-objectives are met in this dissertation:

1. Study the implications of product and service design as well as production operations on sustainable business development in manufacturing and services.
2. Identify the key manufacturing technologies appropriate for SMSs design; such as CMSs, which could possibly evolve to lead SMSs.
3. Develop mathematical models for the SMS design.
4. Develop a mathematical model for designing a RL network for allocating different centers within the network based on minimum carbon footprint and minimum distance;

while simultaneously addressing to a number of important design optimization problems of HMRS operating within these RL networks.

5. Use IBM ILOG CPLEX OPTIMIZATION STUDIO 12.2/OPL to solve the proposed integrated models and evaluate its ability by solving various design optimization problems.

1.4. Research Approach

To achieve the aforementioned research main objective/sub-objectives, the research approach consists of the following steps:

1. Identify the factors and technologies that should be considered during the design of SMSs by making a critic al review of published articles on, CMSs design, RMSs, remanufacturing system design, SMSs design, and CLSC and RL.
2. Formulate a three mathematical models for the following purposes:
    a. Design a 3rd part sustainable remanufacturing system.
    b. Design a sustainable cellular manufacturing remanufacturing system which deals with one recovery option; remanufacturing. Then, extend this model to an integrated one considering: recycling, remanufacturing and disposing issues.
    c. A Carbon footprint and facility location for designing reverse logistics network introducing a hybrid manufacturing-remanufacturing systems.
3. The mathematical models are converted into a format that can be recognized and solved by a selected off-the-shelf optimization package.

4. Generate problem instances to be used for validating the developed models. (Data will be generated in the range of the data found in published articles).
5. These problem instances are optimally solved by using the selected off-the-shelf optimization software.
6. Perform a sensitivity analysis on some important input factors, and analyze the results on the basis of the required elapsed time for solving the problem instances as the problem size increases.
7. Draw conclusions and discuss the directions for future works.

1.5. Outline of thesis

The reminder of this dissertation is arranged as follows: Chapter 2 presents review of the literature in CMSs design, RMSs design, remanufacturing systems design, SMSs design as well as CLSC and RL. In chapter 3, a nonlinear mathematical model for designing a third part cellular remanufacturing system is presented. Chapter 4 presents a mathematical model for designing reconfigurable cellular hybrid manufacturing-remanufacturing systems, with a detailed discussion of the sensitivity analysis for some important factors. A mathematical model for designing a sustainable cellular manufacturing system featuring remanufacturing, recycling, and disposal options is presented in chapter 5, solved for various numerical examples and followed by a detailed discussion of the computational results. Chapter 6 presents a mathematical model for carbon footprint and facility location for designing reverse logistics network introducing a hybrid manufacturing-remanufacturing systems. Chapter 7 presents the summary, conclusions and future research directions.

Chapter 2

2. Literature Review

2.1. Introduction

Sustainability is increasingly becoming a decisive issue in many aspects of life. While sustainability appears to be a popular research area in general, one cannot observe much emphasis on research in design issues of Sustainable Manufacturing Systems (SMSs) presently. Many aspects should be taken into account while designing SMSs. This chapter presents an overview of the relevant research that has been undertaken towards the design of SMSs. There are five main topics to be covered related to research in SMSs design:

- Cellular Manufacturing Systems (CMSs) design,
- Reconfigurability in Manufacturing Systems (RMSs),
- Remanufacturing system design,
- Sustainable Manufacturing Systems (SMSs) design,
- Closed Loop Supply Chain (CLSC) and Reverse Logistics (RL),

Recently published articles are considered to provide a general guideline for developing the conceptual and mathematical models for designing a SMSs.

2.2. Cellular Manufacturing Systems (CMSs) Design

The literature on the design of CMS is quite extensive. Figure 2-1 shows the number of articles on CMSs design from 1990 until September 2016 according to SCOPUS.

Comprehensive reviews and taxonomies of CMSs, classifications, and design techniques can be found in [Greene and Sadowski, 1984; Wemmerlov and Hyer, 1986; Kusiak and Chow, 1987; Singh, 1993; Vakharia and Slim, 1994; Joines et al., 1996; Selim et al., 1998; and Arora et al., 2013]. Reisman et al. (1997) presented a review of the literature on CM between 1965 and 1996. An excellent review articles of the recent literature focusing on the design of CMSs can be found in [Mansouri et al. 2000; Balakrishnan and Cheng, 2007; Papaioannou and Wilson, 2010].

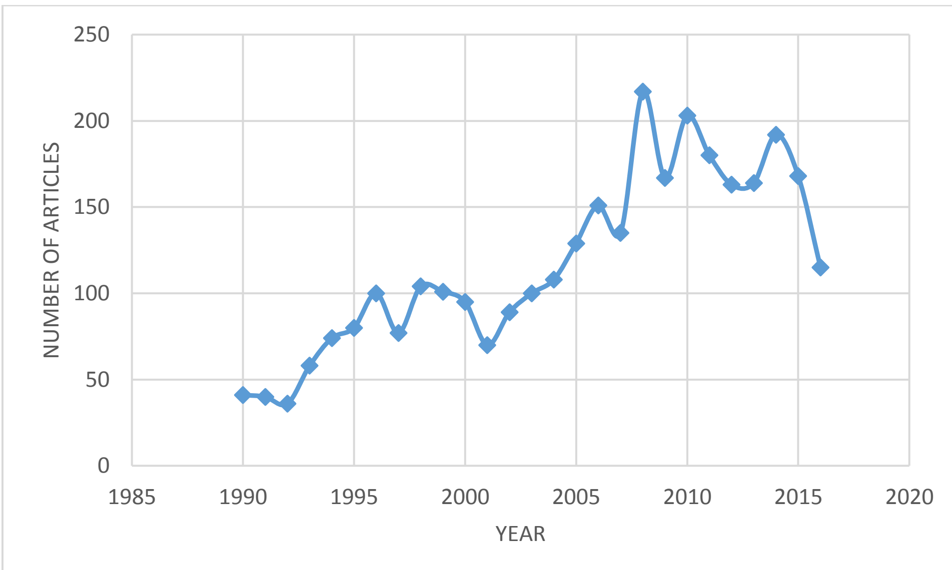

Figure 2-1 The number of scientific articles are identified by a search of "cellular manufacturing system" from 1990 to September 2016

The cell formation problem deals with the identification of part families and machine groups on which to process these parts (Ahkioon, 2007). Part family/machine cell formation can be classified into two major ways; design-oriented and production-oriented (Defersha, 2006). Based on the similarity of the design features parts will be group into families in design-oriented approach, while production-oriented techniques aggregate parts requiring similar processing (Defersha, 2006). One of the design-oriented tools is the classification and coding schemes, since part codes are assigned based upon physical geometry, parts having similar design features have similar codes providing a weak connection between part features and machine grouping. This makes the application of classification and coding to machine cell formation very limited. This can be seen by the fact that the large number of CM designed methods proposed during the late decades are based on production-oriented approaches not based on classification and coding. The production-oriented approaches can be further classified into: Descriptive Procedures, Cluster Analysis, Graph Theoretic, Artificial Intelligence, Mathematical Programming, and Meta-heuristic Approach, as presented in figure 2-2 (Ah kioon, 2007).

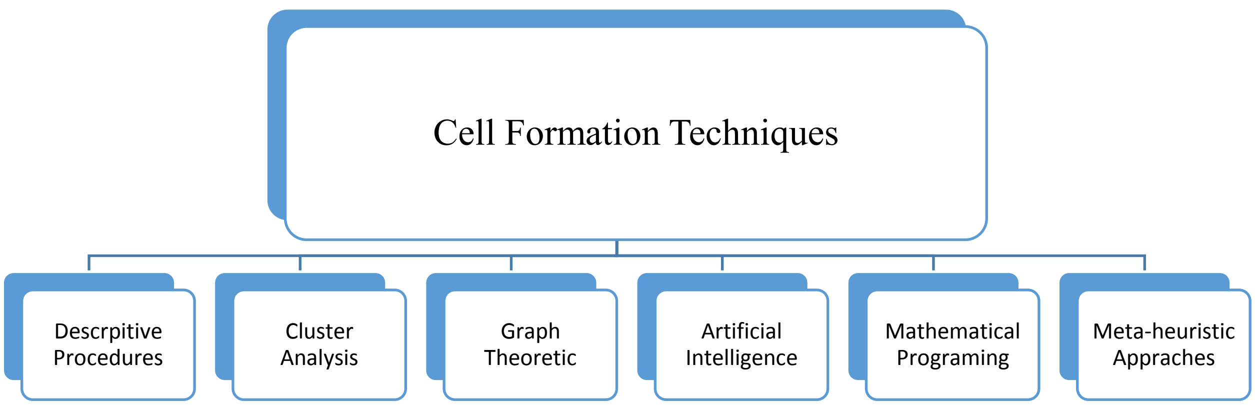

Figure 2-2 Classification of CF methods

2.2.1. Descriptive Procedures

In general, descriptive procedures can be classified into three major classes: 1) Part Families Identification (PFI), identifying the families of parts will be done first and then allocates machines to the families, 2) Machine Groups Identification (MGI), follows the reversal of the first class' steps, 3) Part Families/Machine Grouping (PF/MG), identifies the part families and machine groups simultaneously (Selim *et al.* 1998).

2.2.2. Cluster Analysis Procedures

Cluster analysis is composed of many diverse techniques for recognizing structure in a complex data set. The main objective of this statistical tool is to group either objects or entities or their attributes into clusters such that individual elements within a cluster have a high degree of "natural association" among themselves and that there is very little "natural association" between clusters. Clustering procedures can be classified as: 1) array-based clustering techniques, 2) hierarchical clustering techniques, and 3) non-hierarchical clustering techniques (Selim *et al.* 1998).

2.2.3. Graph Partitioning

Graph theoretic approaches can be used to structure the cell formation problem in a number of forms through a number of methods including Graph Partitioning Algorithms, Bipartite Graphs, Minimum Spanning Tree, and Network Flow (Ah kioon, 2007).

2.2.4. Artificial Intelligence-based Approaches

Researchers have increasingly applied Artificial Intelligence (AI) techniques to the cellular manufacturing system design problem. The techniques developed include syntactic pattern recognition, expert system/knowledge base, fuzzy mathematics, artificial neural networks (Ah kioon, 2007).

2.2.5. Meta-heuristic Approaches

A heuristic method is a procedure that is likely to discover a very good feasible solution, but not necessarily an optimal solution, for the specific problem being considered. The popularity of meta-heuristics is further explained by the fact that they have been successfully used to solve a wide range of optimization problems, especially combinatorial problems, whilst yielding an approximate solution in an acceptable computational time. The meta-heuristic that have been extensively adapted to solve the CM design problem are, namely, genetic algorithm, simulated annealing, and tabu search.

A large number of references on various applications of the methods described above can be found in Table 2-1.

Table 2-1 Review of various methods and techniques used in CM design

Descriptive Procedures		Barker (1970), El-Essawy and Torrance (1972), Beer and Witte (1987), Askin and Vakharia (1991).
Cluster Analysis	Array-based Clustering	McCormick et al. (1972), King (1980a, 1980b), King and Nakornchai (1982), Chan and Milner (1982), Chandrasekharan and Rajagopalan (1986a), Kusiak and Chow (1987), Khator and Irani (1987), Chandrasekharan and Rajagopalan (1989), Chu and Tsai (1990), Logendran (1990), Askin et al. (1991), Dagli (1994), Srinivasan (1994), Lokesh and Jain (2008), Lokesh and Jain (2009), Lokesh and Jain (2010a).
	Hierarchical Clustering	McAuley (1972), Stanfel (1985), Selvam and Balasubramanian (1985), Dutta et al. (1986), Choobineh (1988), Mosier (1989), Gunasingh and Lashkari (1989), Wei and Kern (1989). Seifoddini (1989), Gupta and Seifoddini (1990), Tam (1990), Kusiak and Cho (1992), Gupta (1993), Kamrani and Parsaie (1993), Vakharia and Wemmerlove (1995), Singh and Rajamani (1996), Jeon et al. (1998), Yasuda and Yin (2003).
	Non-Hierarchical Clustering	Lemoine and Mutel (1983), Chandrasekharan and Rajagopalan (1986b), Chandrasekharan and Rajagopalan (1987), Srinivasan and Narendran (1991), Nair and Narendran (1998), Ohta and Nakamura (2002).
Graph Partitioning	Graph Partitioning Approaches	Rajagopalan and Batra (1975), De Witte (1980), Faber and Carter (1986), Askin and Chiu (1990), Hertz et al. (1994), Mukhopadhyay et al. (2000).
	Bipartite Graphs	King and Nakornchai (1982), *Kumar et al. (1986).*
	Network Flow	Vohra et al. (1990), Song and Hitomi (1992), Wu and Salvendy (1993), Lee and Garcia Diaz (1996).

Artificial Intelligence	Syntactic Pattern Recognition	Wu et al. (1986).
	Expert Systems	Kusiak (1988), Elmaghraby and Gu (1989), Luong (1993), Luong et al. (2002).
	Fuzzy Logic	Xu and Wang (1989), Chu and Hayya (1991), Narayanaswamy et al. (1996), Gungor and Arikan (2000), Josien and Liao (2002), Lozano et al. (2002).
	Neural Networks	Moon (1990), Malave and Ramachandran (1991), Kusiak and Chung (1991), Kaparthi and Suresh (1992), Burke and Kamal (1992), Venugopal and Narendran (1992a), Kaparthi and Suresh (1992), Rao and Gu (1992), Liao and Chen (1993), Chu (1993), Liao and Lee (1994), Suresh and Kaparthi (1994), Chen and Cheng (1995), Zhang and Huang (1995).
Meta-heuristic Approaches	Genetic Algorithm	Venugopal and Narendran (1992b), Gupta et al. (1995), Gupta et al. (1996), Dimpoulos and Zalazala (1998), Moon and Kim (1999), Zhao and Wu (2000), Uddin and Shanker (2002), Wu et al. (2007), Mahdavi et al. (2009), Gharbi et al. (2012). Lokesh and Jain (2010b).
	Simulated Annealing	Chen and Srivastava (1994), Su and Hsu (1998), Sofianopoulou (1999), Chen et al. (1995), Boctor (1996), Su and Hsu (1998), Xambre and Vilarinho (2003), Arkat et al. (2007), Safaei et al. (2008), Kia et al. (2012).
	Tabu Search	Logendran et al. (1994), Sun et al. (1995), Dake et al. (1995), Aljaber et al. (1997), Lozano et al. (1999), Cao and Chen (2004), Cao and Chen (2005), Tavakkoli-Moghaddam et al. (2005), Ateme-Nguema and Dao(2009), Hamedi et al. (2012), Eguia et al. (2013).

2.2.6. Mathematical Programming

Mathematical programming approaches for the cell formation problem are widely employed by the researchers. These techniques can be classified as Linear Programming (LP), Linear and Quadratic Programming (LQP), Dynamic Programming (DP), and Goal Programming (GP) (Selim et al., 1998). Mathematical programming approaches have many noticeable advantages over other cell formation techniques such as the ability to incorporate a number of design logics in their objective function and constraints, for example, multiple and nonconsecutive part operations on the same machine, operation cost, workload balancing, production planning issues, and outsourcing of parts (Defersha, 2006). Although, mathematical programming formulation has the ability of producing an optimal solution, it suffers from critical limitation of being computationally interactable for realistically sized problems (Defersha, 2006).

Purchek (1974) was one of the first authors who introduced a LP model in order to formulate part/machine groups. Purchek's (1974) p-median model is the first model to cluster *n* parts (machines) into *p* part families (machine cells) using mathematical programming, in addition to the classical group technology concept as discussed by Kusiak (1987) in the presence of alternative routings. Successful applications of various modifications of the Kusiak's p-median model have been reported by many authors (Ribeiro and Pradin, 1993; Wang and Roze, 1995; Lee and Garcia-Diaz, 1996; Viswanathan, 1996; Deutsch et al., 1998).

Wei and Gaither (1990) proposed a multi-objective heuristic model considering machine capacity, product routings, relevant costs, and several objectives of production systems and a linear programming model to find the optimal solution for the cell formation problem.

Srinivasan et al. (1990) introduced PF/MG assignment problem by using a similarity coefficient matrix, where the objective of the model is to maximize the similarity. Boctor (1991) developed a mixed integer linear programming model for designing a CM model, which simultaneously assigns machines and parts to cells. The objective of the proposed model is to minimize the number of exceptional elements, where he defined an exceptional element as any operation included in the part route sheet that has to be performed outside the assigned cell. Rajamani et al. (1996) developed a mixed integer program for the design of CMS. They assumed multiple process plans for part production and that each operation in these plans can be performed on alternate machines. The objective of the model is to minimize the sum of investment, processing and material handling costs.

In order to accept a new part within an existing manufacturing cell, based on the processing requirements, a novel similarity coefficient was introduced by Garbie et al. (2005). Defersha and Chen (2006) proposed a non-linear mixed integer mathematical model for CMS design, dynamic cell reconfiguration, alternative routings, lot splitting, sequence of operations, multiple units of identical machines, machine capacity, workload balancing among cells, operation cost, cost of subcontracting part processing, tool consumption cost, setup cost, cell size limits, and machine adjacency constraints are incorporated into the proposed model. Ahkioon et al. (2009b) extended Defersha and Chen's (2006) model by addressing formation of compact cells by considering intra-cellular movement of parts, production planning (inventory holding), and internal production cost in their mixed integer non-linear programming model. Some linearization steps are followed to solve their mixed integer linear model. Ahkioon et al. (2009a) addressed routing flexibilities in a mathematical model for CMS design; alternate contingency process routings (i.e. serve as a backups when disruptions occur in the main routings) are formed in addition to alternate main process routings for all part types. Saxena and Jain (2011) made a literature review on the CMS design methods. They proposed a mixed integer nonlinear programming model for designing CMSs. Nonlinear terms have transformed into linear ones in order to get a mixed integer linear problem. They have also solved several scenario problems in order to validate the proposed model. The design of a robot cellular manufacturing system, where robots are used to carry out a large number of assembly operations, has been studied by Izui et al. (2013). They proposed a multi-objective layout optimization method for designing such a system. Change et al. (2013) proposed a two stage mathematical programming model in order to incorporate three critical issues; the cell formation problem, cell layout, and intracellular machine sequencing issues together. A tabu search approach is used to solve the proposed model. Askin (2013) presented an overview of manufacturing cell design concepts and introduce a mathematical formulation for designing a general cell formation problem which incorporates many design features such as: tool sharing and setup compatibility, assignment of workers to cells and specific tasks, allocating duplicate machines in single or multiple cells as economical.

Ignoring the "*human element*" in CMS design will reduce the reliability, and hence, the benefits of the proposed models expected from their implementation. Consequently, CMS models in which incorporate workforce management aspects in cellular manufacturing (e.g. worker assignments, hiring and firing costs) in addition to technical aspects (e.g. cell formation and design) have been developed. Nembhard (2001) presented a heuristic worker-task assignment based on individual worker learning rates, in which two tasks were examined, one with a long production run, the other with a short production run. Norman et al. (2002) developed a mixed integer programming model for worker assignment in manufacturing cells that incorporates both human and technical skills and their impact on system performance. Their model considers the case where there are different worker skill levels for each required skill. Bidanda et al. (2005) presented an overview and evaluation of a diverse range of human issues involved in cellular manufacturing based on an extensive literature review. Further, a survey to determine the importance of eight different human issues in cellular manufacturing was administered with a sample of academics, managers, and workers involved in cellular design and implementation. The results of the survey were presented and discussed. Wirojanagud et al. (2007) used General Cognitive Ability (GCA) as the measure for individual differences. They developed a mixed integer programming model to determine the amount of hiring, firing, and cross-training for each GCA level to minimize total costs, including training costs, salary costs, firing costs, and missed production costs over multiple time periods. Aryanezhad et al. (2009) developed a nonlinear integer programming model for a simultaneous dynamic cell formation and worker assignment problem. Part routing flexibility and machine flexibility and promotion of workers from one skill level to another are also considered. Mahdavi et al. (2010) proposed a nonlinear mixed integer programming model for designing a CMS while considering workforce management issues, two numerical examples are presented followed by a detailed discussion of the results. Aljuneidi and Bulgak (2015) proposed a nonlinear mixed integer programming model for designing a CMS considering workforce management, in the proposed model many manufacturing attributes have been considered such as parts intercellular movement, machine procurement, and machine capacity.

2.3. Reconfigurable Manufacturing Systems (RMSs)

Koren in 1996 (Koren et al. 1999) was the first who introduced the concept of "reconfigurablility" for a manufacturing system. Reviews of the literature on Reconfigurable Manufacturing Systems (RMSs) could be found in (Molina et al. 2005; Youssef and Elmaraghy 2007; Renzi et al. 2014). Reconfigurable Machine Tools (RMTs) paradigm was introduced and discussed by Landers et al. (2001). Lee (1997) discussed the reconfigurability issue in the design of products and manufacturing systems where the reconfigurability was analyzed based on many categories such as; the relationship of components routes, material handling costs, and the reconfiguration costs. Definition of various manufacturing paradigms and their economic goals have been illustrated by Mehrabi et al. (2000). Mehrabi et al. (2000) also presented a comparison among RMSs, dedicated transfer lines, and flexible manufacturing systems and outlined key characteristics of RMSs. The equipment layout assignment for the RMSs, in order to reduce the cycle time of core products, was discussed by Kuo (2001). Yamada et al. (2003) optimized the layout of a manufacturing cells and the allocation of transport robots for a RMS with the objective of minimizing the total transportation time. Abdi and Labib (2003) discussed strategic issues of selecting the system type among different manufacturing systems such as; RMS, and CMS using an Analytical Hierarchical Process (AHP) model. Further, AHP was used by Abdi and Labib (2004) in order to form products group based on operational similarities for RMSs. Detailed discussions and comparisons between flexible manufacturing systems and RMSs were presented by ElMaraghy (2005), where the latter was divided into two types: hard (physical) and soft (logical) reconfigurations. Youssef and ElMaraghy (2006) introduced the Reconfiguration Smoothness (RS) metric which provide a relative measure of the expected cost, time, and effort required to convert from one configuration to another. Bi et al. (2008) presented the needed strategies for any manufacturing system in order to meet their requirements, especially for the RMSs, since they considered the RMS as one of the most effective manufacturing systems. In this regard, they also outlined and discussed the key issues for RMSs followed by some suggestions and future research areas, where they emphasized that there is a need to combine RMSs with other production paradigms in order to face all of the relevant problems. Core characteristics, advantages, features, and a classification of RMSs were presented by Koren and Shpitalni (2010). They also proposed a mathematical method is for designing the RMSs. Introducing reconfigurability while designing a CMSs has been studied by Javadian et al. (2011). They developed a multi objective dynamic mathematical mode in order to minimize the total cell load variation and the sum of the miscellaneous costs. Pellicciari et al. (2012) discussed on how to enhance the changeability of a hybrid manufacturing reconfigurable system. Based on Pellicciari et al. (2012), a Hybrid Reconfigurable System (H-RS) is characterized by the coexistence and cooperation of industrial robots and skilled human workers to perform complex tasks within a common reconfigurable production environment where the changeability promises to achieve cost-effective and rapid system changes, as needed and when needed. Niroomand et al. (2012) studied the impact of reconfiguration characteristic for capacity investment strategies in manufacturing systems. Eguia et al. (2013) proposed a mixed integer linear programming model for designing a RCMS, in the proposed model, reconfigurable machine tools are considered as well, tabu search are used for solving large problem instances.

2.4. Remanufacturing System Design

Parkinson and Thompson (2003) presented a detailed discussion about remanufacturing; definitions of the various processes that take place in remanufacturing are given such as, refurbishing, recycling, and reconditioning along with a review of the literature in the field of remanufacturing. Relationships between the original equipment manufacturer and the third-party remanufacturer were discussed. They explained product EOL scenarios and the material flow of durable products. Since the products' design has a major impact on the remanufacturing efficiency, the concept of Design for Remanufacturing (DfRem) is becoming a popular area within the remanufacturing research. Hatcher et al. (2011) presented a review of the state of the art in DfRem. A literature review presenting the state of the art in tools and techniques; used to evaluate remanufacturing feasibility, was presented by Goodall et al. (2014).

Laan et al. (1999a) analyzed the influence of introducing the remanufacturing option in PUSH and PULL controlled production systems. Laan et al. (1999b) studied the impact of lead-time duration and variability on the estimated costs in a HMRSs with stochastic lead-times. Analysis of methods in stochastic inventory problems with substitutable products in HMRSs were proposed by Inderfurth (2004). Zanoni et al. (2006) presented a comparison among different inventory control policies; DUAL, PULL, separate PULL, and shift PULL in a HMRS where stochastic demand, return rate, and lead times are considered. Production planning and inventory control policies in a remanufacturing system have been studied by Li et al. (2009), where the demand and return amounts were considered to be stochastic. Bulmus et al. (2013) studied the influence of introducing remanufacturing option on the capacity and production decisions as well as whether the introducing of remanufacturing is profitable or not. Jiang et al. (2014) studied the process plan selection while introducing remanufacturing option. Baki et al. (2014) proposed a mixed integer model for solving the lot sizing problems for product returns and remanufacturing. They proposed a heuristic method in order to solve the proposed model. Chen and Abrishami (2014) presented a mixed integer programming model for production planning in a HMRS. While the demand for new and remanufactured products were considered separately, the production for both types take place in the same manufacturing facility by using the same resources. Demirel and Gokcen (2008) proposed a linear mixed integer mathematical model where forward and reverse flows are considered simultaneously. The objective of the model is to minimize the total costs; production, transportation, disassembly, disposal, collection, purchasing costs, and opening cost for disassembly, collection, and distribution centers. Hasanov et al. (2012) studied the inventory control policies in a manufacturing-remanufacturing system where the shortage in satisfying demands for remanufacturing and production items are either fully or partially backordered. Doh and Lee (2009) presented a mathematical model in order to maximize the total profit (i.e. the difference between the revenue obtained from selling remanufactured products and the relevant costs) in a remanufacturing system. LP relaxation approach was used to solve the proposed model. Wang et al. (2011) proposed a mathematical model for minimizing the total cost in a HMRS where demand and return rate are considered to be stochastic. The impact of the quantity of the manufactured products and the proportion of the remanufactured part to the returned products on the total cost of the system were analyzed. Based on the total inventory cost, and manufacturing-remanufacturing order variance Corum et al. (2014) proposed a comparison between a push-and pull-controlled HMRS and the traditional system. They found that HRMSs have lower order variances in comparison with the traditional system, where manufacturing and remanufacturing are performed separately. Guo and Ya (2015) considered the quality of recycled products, which would be used in remanufacturing in order to obtain the optimal recycling production strategy in HMRSs. HMRSs with the setup option to switch between manufacturing products using raw materials and remanufacturing products using returned products were studied by Polotski et al. (2015). Returned products are varied in their quality, because of that, there is a need to test these returned products to decide whether to accept or reject them. Acceptance options in a hybrid system have been considered by Veraene et al. (2014). Su and Xu (2014) considered the uncertainty of returned products quality with the objective of minimizing the remanufacturing cost. The effect of introducing the remanufacturing and disposing options in a hybrid system has been studied by Kim et al. (2013).

2.5. Sustainable Manufacturing Systems (SMSs) Design

There exist a vast amount of literature on sustainability as related to modeling, design, and analysis of Closed Loop Supply Chains (CLSCs) but not much literature on sustainability as related to modeling, design, and analysis of manufacturing systems. The large number of articles on sustainability existing in the literature do not directly focus on sustainability from a manufacturing system design and analysis perspective. Regarding the sustainability issues in manufacturing systems, the literature is very limited. Certain international journals have recently published survey papers; which present definitions, research trends, performance measurement, and challenges addressed by the research community in the sustainable manufacturing area [Garetti and Taisch, 2012; Garetti et al. 2012; Dubey et al. 2015a]. A review paper for research on both the process and systems level for designing a sustainable manufacturing was presented by (Haapala et al. 2013). Another literature review on Sustainable Business Development (SBD) was proposed by Gunasekaran and Spalanzani (2012), where they reviewed the tools, techniques, and performance measures and metrics for SBD used in the literature and indicated future research directions. In their work, they also developed a framework for SBD as shown in figure 2 – 3.

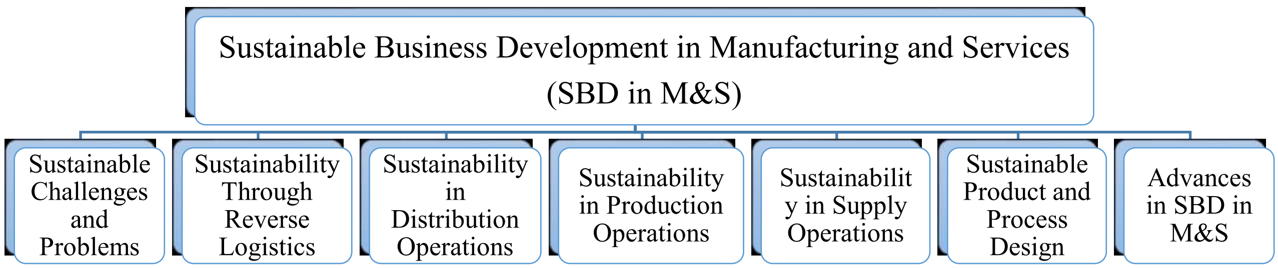

Figure 2-3 Sustainable Business Development in Manufacturing and Services [Gunasekaran and Spalanzani, 2012]

Many research papers have focused on the development of guidelines, indicators, metrics, methods, tools, and systems for sustainability performance assessment [Krajnc and Glavic, 2005; Larimiana et al., 2013; Dey and Cheffi, 2013; Bhattacharya et al., 2014; Garbie, 2014]. A comparison of these approaches was presented by Harik et al. (2015). As a result of those large number of papers, Yeon Lee and Tina Lee (2014) proposed a framework for a research inventory that focuses on papers related to sustainability assessment in manufacturing in such a way to make them easy to retrieve from the manufacturing companies. Harik et al. (2015) also developed a sustainability index for the food manufacturing industries. The index was built using the analytical hierarchy process and based on the four pillars of sustainability; environmental, economical, social, and manufacturing sustainability.

Recently, sustainability in the operational level has becoming an attractive research area from both academic researchers and practitioners (Trentesaux and Prabhu, 2014; Gunasekaran and Irani, 2014). Giret et al. (2015) presented a literature review on sustainability in manufacturing operations scheduling; considering the two pillars of sustainability; namely, environmental and economic.

Jayal et al. (2010) presented an overview of recent trends and new concepts that are emerging for evaluating the sustainability contents at the product, process, and system levels for sustainable manufacturing. Achieving sustainability in a manufacturing enterprise is a big task and needs to consider many aspects from different perspectives, a tool to asses and to measure the current manufacturing enterprise position toward sustainability is needed as well, Garbie (2013) have studied and provided a holistic framework to the Design for Sustainable Manufacturing Enterprises (DFSME). In addition, he presented seven crucial aspects that should be taken into consideration while DFSME. These aspects are shown in Figure 2 – 4. Garbie (2013) also stressed the suitability of reconfigurable manufacturing technologies (hence; RMSs) for designing SMSs. Garbie (2015) proposed a cost and time minimization sustainability index based on the three pillars of sustainability; namely, the economic, social, and environmental. Saad (2003) suggested CMSs as a reconfiguration design issue. By considering a real case study from the carbon steel production and metal recycling sector, Bi et al. (2014) proposed a new perspective of system reconfiguration based on redesign, reduce, reuse, and recycle in order to achieve system adaptability and sustainability.

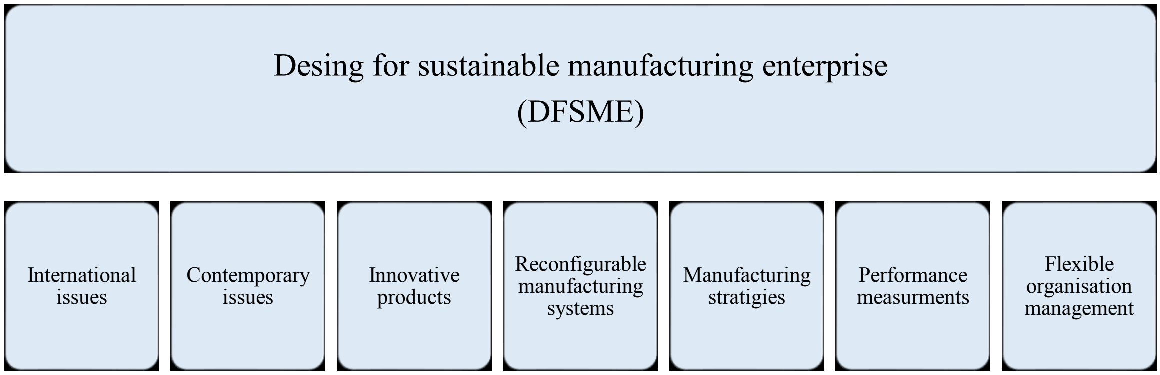

Figure 2-4 Aspects for design sustainable manufacturing enterprise

2.6. Closed Loop Supply Chains (CLSCs) *and* Reverse Logistics (RL)

While there exists a limited number of research articles related to the design and analysis of SMSs, there is a vast amount of research articles related to design and analysis of CLSCs reported in the literature. Figure 2-5 shows the number of articles on RL and CLSC from 2000 until September 2016 according to SCOPUS. Excellent reviews of the literature on RL and CLSC can be found in [Fleischmann et al., 1997; Rubio et al., 2008; Pokharel and Mutha, 2009; Guide and Van Wassenhove, 2009; Chanintrakul et al., 2009; Atasu and Van Wassenhove, 2010; Aras et al., 2010; Akcali and Cetinkaya, 2011]. Recently, Dubey et al. (2015b) proposed a detailed literature review on supply chain network design from the sustainability perspective and responsiveness. A review article of the recent literature focusing on RL and CLSCs can be found in (Govindan et al. 2015). Agrawal et al. (2015) proposed another review article, in which many articles on reverse logistics were presented, gaps in existing literature were identified, a detailed analysis of the literature were proposed, and future directions for researchers were outlined. Brandenburg et al. (2014) presented a literature review on sustainable supply chain management research area and discussed mathematical models used in the reviewed papers. In addition, literature for articles on how to manage CLSC networks with remanufacturing can be found in [Atasu et al. 2008 and Souza 2013].

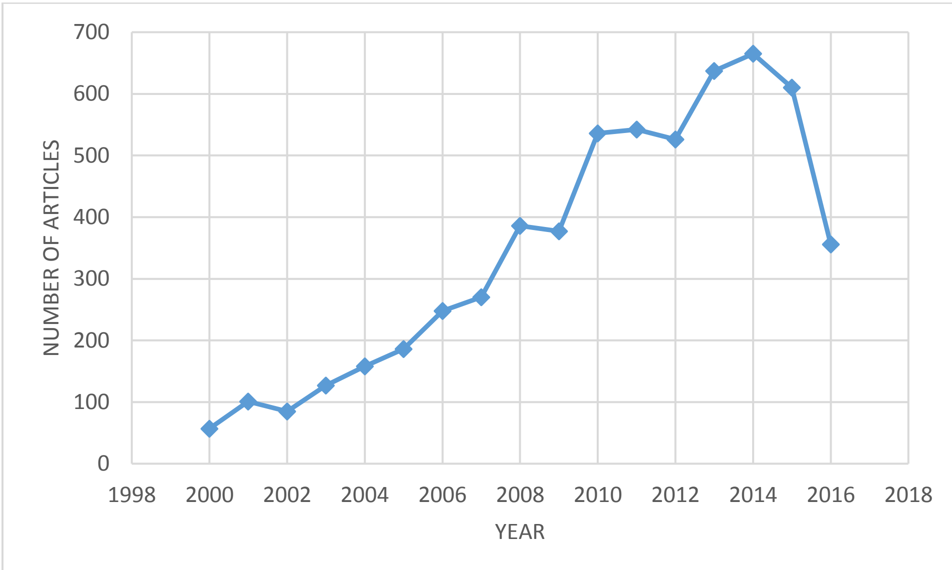

Figure 2-5 The number of scientific articles are identified by a search of "reverse logistics" or closed loop supply chain" from 2000 to September 2016

Salema et al. (2007) proposed a multi-product mixed integer model for designing a reverse logistics network, where demand and products returns were considered to be uncertain, and they assumed for each facility to have a limited production capacity and storage capacity. By using the simulated annealing algorithm, Pishvaee et al. (2010) solved their proposed mathematical model. Their model aims to design a RL network by minimizing the total transportation and fixed opening costs. Renting, inventory carrying, material handling, setup, and shipping costs were considered in the mixed integer non-linear programming model proposed by Diabat et al. (2013). The model was solved using genetic algorithms and artificial immune systems. Alshamsi and Diabat (2015) proposed a mixed integer linear programming model for designing a RL network design, the model incorporated the options of using in-house fleet and outsourcing. The model was tested on a real-life case study on large household appliances in the UAE.

Due to various environmental and governmental legislations, manufacturing firms are enforced to include all aspects and dimensions of sustainability in their manufacturing facility location models in order to design a green supply chain. Facility location models were used by a massive number of authors in order to formulate and design CLSC networks Literature review on sustainability aspects related to manufacturing facility location presented by [Chen et al. 2014; Melo et al. 2009].

Jayaraman et al. (1999) proposed a mixed-integer programming model in order to determine the location of remanufacturing/distribution facilities, the transhipment, production, and stocking of the optimal quantities of remanufactured products and used parts. Fleischmann et al. (2001) proposed a facility location model for CLSC network design. In addition, they studied the impact of product return flows on logistics networks. The model is designed based on forward facility location model. A single period mathematical model for configuring a CLSC was proposed by Amin and Zhang (2012). The network consists of manufacturing, collection, repairing, disassembly, recycling, and disposal centers. Generalized Algebraic Modeling System (GAMS) have used in order to solve the proposed model. The also presented a sensitivity analysis for some important parameters. Özceylan and Paksoy (2013) developed a mixed integer linear programming model for designing a CLSC network, within which the options of both refurbishing and purchasing of new raw material are considered. Additionally, they outlined a sensitivity analysis for various important parameters. John and Sridharan (2015) proposed a mathematical model for designing a RL network, the proposed model aims to minimize the total costs incorporated in all stages of the designed network, the model determines the products flow between each stage of the designed network and the number and location of different facilities to be opened. Chen et al. (2015) developed an integer programming model for designing a CLSC chain based on a cartridge recycling situation in Hong Kong. In the model, both delivery activity for different kinds of material extracted from used cartridges, and the classification of returned cartridges based on the quality are considered. A fuzzy mixed integer linear programming model for designing a capacitated CLSC under uncertainty was proposed by Jindal et al. (2015), the proposed model aims to maximize the total profit within the designed network

Dekker et al. (2012) presented a literature review of green logistic articles, in which the contributions of operations research to green logistics were outlined. Dernir et al. (2014) presented a review of recent research on green road freight transportation, where they presented the factors affecting fuel consumption and a review of the available vehicle emission models. Based on profitability and environmental impacts as well as by using a multi-objective programming. Forta et al. (2008) presented a framework for optimizing the design and evaluation of sustainable logistics network. Kannan et al. (2012) proposed a single product and a single period mixed integer linear programming model in RL. The model aims to minimize carbon emission, fixed opening cost for collection/ inspection center, transportation between the existing centers; customer, disposal, recovery, and collection/ inspection centers. Four types of carbon emission constraints; namely, the periodic, cumulative, global, and rolling carbon emission constraints, were considered in the lot sizing model presented by Absi et al. (2013). Zhao et al. (2013) developed a mathematical model for allocating the distribution centres based on minimizing CO2 emission. Zhang et al. (2014) considered the product lifetime and carbon emissions while designing a CLSC network. Sensitivity analyses for different parameters were presented as well. Soysal et al. (2014) developed a multi objective linear programming model for designing a logistics network, the model has been validated based on a real-life international beef supply chain, minimizing the total cost and the total amount of gas emissions as the objectives achieved by the proposed model. Tao et al. (2015) studied the design of multi-period CLSC, in their study they considered two types of carbon emission constraints; namely, periodic carbon emissions and global carbon emissions. Bazan et al. (2015) studied the design of RL logistics network through a model design and the consideration of energy used for manufacturing and remanufacturing, and greenhouse gas emissions from manufacturing, remanufacturing, and transportation operations. Marti et al. (2015) proposed a mathematical model for supply chain design considering three different carbon policies under demand uncertainty. In order to measure and analyse the carbon foot print in supply chains, Montoya-Torres et al. (2015) proposed a conceptual framework. Chen and Wang (2016) studied different carbon emission reduction policies and the effect of these policies on ordering and transportation mode selection while considering a stochastic demand. Nouira et al. (2016) presented a mixed integer programming model to develop supply chain design models where the demand for the final product depends on its per unit emissions. In their model, Peng et al. (2016) considered the greenhouse gas emissions while designing supply chain network. The objective of the model is to minimize the total costs of the supply chain as well as the carbon emissions. Zhalechain et al. (2016) presented a multi-objective mathematical model for designing a sustainable CLSC, the model considers many sustainability aspects such as carbon emissions, location-allocation decisions, and fuel consumption.

2.7. Findings in the literature review

In this chapter, we presented a literature review from the design perspective for sustainable manufacturing systems. Based on the review of recent literature on sustainability, CMSs, reconfigurabiltiy, remanufacturing, and CLSCs, our findings can be summarized as follows:

- While there exist a substantial literature on sustainability as it relates to CLSCs, there is a singular absence of articles that deal with designing SMSs.
- In view of the huge attention on sustainability in today's world, we believe that it is important to focus research on SMSs designs taking into account the production operations and the process design.
- There are many research articles on reverse logistics, but little on integration with the upstream side of supply chain operations such as product and process design, supply management, and production operations" (Gunasekaran and Spalanzani, 2012).
- For globalization issues as well as for the sustainability issues, cellular production systems and product oriented manufacturing systems are highly recommended to achieve and/or enhance mass customization and are variety restricted with system size. Thus, it is urgent to transfer and/or convert all of the traditional job shop

production systems to cellular systems while keeping at least one functional workshop (Garbie, 2013).

- Reconfigurable manufacturing systems (RMSs) own numerous advantages representing in reconfigurable components and machines, material handling systems and easily physical changing layouts to secure sustainability (Garbie, 2013).
- It has been emphasized that, in order to achieve the maximum benefits or to minimize the level of performance deterioration for a CM system, reconfiguration possibilities should be considered (Saad 2003).
- Frameworks for "*Designing for Sustainable Manufacturing Enterprises*" developed by Gabrie (2013) and for "*Sustainable Business Development in Manufacturing and Services*" developed by Gunasekaran and Spalanzani (2012) indicate a research framework as well as future research directions in design of sustainable manufacturing systems for our research work.
- Cellular Manufacturing System (CMS) and Reconfigurable Manufacturing System (RMS) designs are highly recommended for sustainable manufacturing system designs. (Gabrie, 2013).
- Sustainable business development decisions require a suitable mathematical and simulation models for making optimal decisions by quantifying various costs and benefits. At present, the literature on sustainable business development has a limited number of mathematical and simulation models (Gunasekaran and Spalanzani, 2012).

- While previous research in designing a manufacturing systems was focusing on minimizing the cost or maximizing the profit, the emphasis is gradually shifting to include optimization of additional system parameters such as minimizing the cost, minimizing the environmental impact, increasing the flexibility, and reducing the raw material used.

- It is critical that a sustainable supply chain be integrated with sustainable manufacturing processes, design, and systems in order to fulfill the sustainable manufacturing philosophy (Haapala et al. 2013).

- Achieving sustainability in manufacturing requires a holistic view spanning not just of the product and the manufacturing processes involved in its fabrication, but also the entire supply chain including the manufacturing systems across multiple product life-cycles (Jayal et al. 2010).

Chapter 3

3. Dynamic Cellular Remanufacturing System (DCRS) Design

3.1. Introduction

Remanufacturing may be defined as the process of bringing used products to "like-new" functional state with warranty to match, and it is one of the most popular product end-of-life scenarios. An efficient remanufacturing network lead to an efficient design of sustainable manufacturing enterprise. In remanufacturing network, products are collected from the customer zone, disassembled and remanufactured at a suitable remanufacturing facility. In this respect, another issue to consider is how the returned product to be remanufactured, in other words, what is the best layout for such facility. In order to achieve a sustainable manufacturing system, Cellular Manufacturing System (CMS) designs are highly recommended. Introducing the CMS while designing a remanufacturing network will benefit the utilization of such a network. In this chapter, we present and analyze a mathematical model for the design of Dynamic Cellular Remanufacturing Systems (DCRSs). The proposed DCRS model considers several manufacturing attributes such as multi period production planning, dynamic system reconfiguration, duplicate machines, machine capacity, available time for workers, worker assignments, and machine procurement, where the demand is totally satisfied from a returned product. A numerical example is presented to illustrate the proposed model. Figure 3 – 1, represents the material flow of the proposed system.

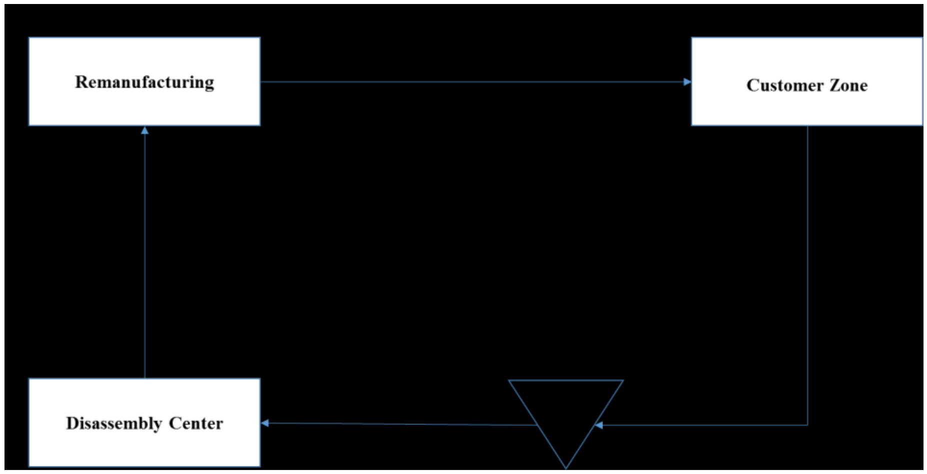

Figure 3-1 Material flow diagram for the proposed cellular remanufacturing system

3.2. The Proposed Mathematical Model

In this section, operation sequences for production of the returned products are not considered and the intercellular movements will depend on the movements of the returned products between cells. The cellular remanufacturing system deals only with remanufacturing option and the total demand will be satisfied by using returned products. Returned products are collected from the customer zone and stored at collected inventory point. After inspecting and testing them, the collected products are sorted into those to be disposed and those to be remanufactured. The notations used for the model are presented followed by the objective function and constraints:

Sets

$p = \{1, 2, 3... P\}$ Index set of part types.

$m = \{1, 2, 3... M\}$ Index set of machine types.

$c = \{1, 2, 3... C\}$ Index set of cells.

$t = \{1, 2, 3... T\}$ Index set of time periods.

$w = \{1, 2, 3... W\}$ Index set of worker types.

j = {1, 2, 3… J} Index of product types.

Parameters

D_{pt}	Demand for part type p in time period t
V_p^{inter}	Intercell movement cost of part type p
μ_{pmw}	= 1, if machine type *m* is able to process part type *p* with worker *w*,
	= 0, otherwise.
λ_{pm}	= 1, if part type *p* needs machine type *m,*
	= 0, otherwise.
t_{pmw}	Processing time part type p on machine type m with worker type w
T_{mt}	Time capacity of one machine of type m for one time period t
LL_c	Minimum number of machines limit in cell c
UL_c	Maximum number of machines limit in cell c
LW_c	Minimum size of cell c in terms of the number of workers
R_m^+	Relocation cost of installing one machine of type m
R_m^-	Relocation cost of removing one machine of type m
L^p	a large positive number
H_{pt}	Part holding cost per part type p per time period t
A_m	Quantity of machine type m available at time period $t=1$
A_w	Number of worker type w available
RW_{wt}	Available time for worker type w at time period t
S_{wt}	Salary cost of worker type w within period t
HI_{wt}	Hiring cost of worker type w within period t
F_{wt}	Firing cost of worker type w within period t
OV_m	Machine maintenance overhead cost of machine type m per unit time in time period t

OP_m Procurement cost per machine type *m*

γ_m Operating cost per unit time per machine type *m*

$£_p$ Internal production cost per part type *p*

$AQ_{j,t}$ Unit cost to acquire returned product *j* in time period *t*

$SD_{j,t}$ Setup cost to disassembling returned product *j* in time period *t*

$RD_{j,t}$ Unit cost to disassemble returned product *j* in time period *t*

$IN_{j,t}$ Unit inventory cost for storing returned product *j* in time period *t*

UR_p Average recovering rate of part *p* from all returned products

$B_{p,j}$ Number of part *p* contained in product *j*

DC_p Disposal cost per unit cost of part *p*

Decisions Variables

N_{mct} Number of type *m* machines to present at cell *c* at beginning of time period *t*

Y^+_{mct} Number of type *m* machines added in cell *c* at beginning of time period *t*

Y^-_{mct} Number of type *m* machines removed from cell *c* at beginning of time period *t*

BN_{mt} Number of machines of type m procured at time t

A^*_{mt} Quantity of machine type m available at time period t after accounting for machines that have been procured

Q_{pt} Number of part inventory of type *p* kept in time period *t* and carried over to period *(t+1)*

β_{pt} Production volume of part type p to be produced in time period t

L^+_{wct} Number of workers of type *w* added to cell *c* during period *t*

L^-_{wct} Number of workers of type *w* removed from cell *c* during period *t*

N_{wct} Number of workers of type *w* allotted to cell c in period *t*

v_{pct} = 1, if part type p is processed in cell c in period t.

= 0, otherwise.

z_{pmwct} = 1, if part type p is to be processed on machine type m with worker w in cell c in period t.

= 0, otherwise.

d_{jt} Number of returned product *j* to disassemble in time period *t*

r_{jt} Number of returned product *j* to acquire in time period *t*

$f_{j,t}$ Number of returned product *j* in inventory at the end of time period *t*

δ_{jt} = 1, if returned product *j* will be disassembled in time period *t*

= 0, otherwise.

Objective function

Minimize

$$\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m=1}^{M} N_{mct}.OV_m \quad 1.1$$

$$+\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m=1}^{M} R_m^+.Y_{mk}^+(t) \quad 1.2$$

$$+\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m=1}^{M} R_m^-.Y_{mk}^-(t) \quad 1.3$$

$$+\sum_{t=1}^{T}\sum_{p=1}^{P} Q_{pt}.H_{pt} \quad 1.4$$

$$+\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{w=1}^{W} S_{wt}.N_{wct} \quad 1.5$$

$$+\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{w=1}^{W} HI_{wt}.L_{wct}^{+} \quad 1.6$$

$$+\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{w=1}^{W} F_{wt}.L_{wct}^{-} \quad 1.7$$

$$+\sum_{t=1}^{T}\sum_{p=1}^{P}\left[\left(\sum_{c=1}^{C} v_{pct}\right)-1\right].V_{p}^{inter}.\beta_{pt} \quad 1.8$$

$$+\sum_{t=1}^{T}\sum_{m=1}^{M} BN_{mt}.OP_{m} \quad 1.9$$

$$+\sum_{t=1}^{T}\sum_{p=1}^{P} \beta_{pt}.£_{p} \quad 1.10$$

$$+\sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{m=1}^{M}\sum_{w=1}^{W}\sum_{c=1}^{C} z_{pmwct} * \beta_{pt} * t_{pmw} * \gamma_{m} \quad 1.11$$

$$+\sum_{t=1}^{T}\sum_{j=1}^{J} AQ_{jt}.r_{jt} \quad 1.12$$

$$+\sum_{t=1}^{T}\sum_{j=1}^{J} SD_{jt}.\delta_{jt} \quad 1.13$$

$$+\sum_{t=1}^{T}\sum_{j=1}^{J} RD_{jt}.d_{jt} \quad 1.14$$

$$+\sum_{t=1}^{T}\sum_{j=1}^{J} IN_{jt}.f_{jt} \quad 1.15$$

$$+\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\left(1-UR_p\right)*DC_p*B_{p,j}*d_{j,t} \quad 1.16$$

Subject to:

$$\beta_{pt}+Q_{p(t-1)}-Q_{pt}=D_{pt};\forall(p,t) \quad (2)$$

$$v_{pct}=\min(1,\sum_{m=1}^{M}\sum_{w=1}^{W} z_{pmwct})\ ;\ \forall(p,c,t) \quad (3)$$

$$\sum_{c=1}^{C} z_{pmwct}\leq\mu_{mpw}\ ;\ \forall(p,m,w,t) \quad (4)$$

$$\sum_{c=1}^{C}\sum_{w=1}^{W} z_{pmwct}=\lambda_{pm};\forall(p,m,t) \quad (5)$$

$$N_{mct}=N_{mc(t-1)}+Y^{+}_{mct}-Y^{-}_{mct};\ \forall(m,c,t) \quad (6)$$

$$LB_c\leq\sum_{m=1}^{M} N_{mct}\leq UB_c;\ \forall(c,t) \quad (7)$$

$$\sum_{w=1}^{W} N_{wct}\geq L_{wc},\ \forall(c,t) \quad (8)$$

$$\sum_{m=1}^{M}\sum_{p=1}^{P} z_{pmwct}.t_{pmw}.\beta_{pt}\leq N_{wct}RW_{wt}\ \ ,\forall(w,c,t) \quad (9)$$

$$\sum_{w=1}^{W}\sum_{p=1}^{P} z_{pmwct}.\, t_{pmw}.\, \beta_{pt} \leq N_{mct}.\, T_{mt} \ , \forall(m, c, t) \tag{10}$$

$$N_{wc(t-1)} + L^{+}_{wct} - L^{-}_{wct} = NW_{wct} \ , \forall(w, c, t) \tag{11}$$

$$\sum_{c=1}^{C} N_{wct} \leq AW_{w} \ , \forall(w, t) \tag{12}$$

$$\sum_{c=1}^{C}\sum_{m=1}^{M}\sum_{w=1}^{W} z_{pmwct} \leq \beta_{pt}.\, L^{p}; \forall(p, t) \tag{13}$$

$$A^{*}_{m(t=1)} = A_{m(t=1)} + BN_{m(t=1)}, \forall(m) \tag{14}$$

$$A^{*}_{m(t+1)} = A^{*}_{mt} + BN_{m(t+1)}, \forall(m) \tag{15}$$

$$\sum_{c=1}^{C} N_{mct} \leq A^{*}_{mt}; \forall(m, t) \tag{16}$$

$$f_{j,t} + d_{j,t} - f_{j,t-1} = r_{j,t} \tag{17}$$

$$d_{j,t} \leq M\delta_{j,t} \tag{18}$$

$$\beta_{pt} \leq UR_{p} \sum_{j=1}^{J} B_{p,j} d_{j,t} \tag{19}$$

$$\sum_{p=1}^{P}\sum_{w=1}^{W} z_{pmwct} \leq L^{p} * N_{mct}, \forall(m, c, t) \tag{20}$$

$$\sum_{p=1}^{P}\sum_{m=1}^{M} z_{pmwct} \leq L^{p} * N_{wct}, \forall(w, c, t) \tag{21}$$

$$N_{mct}; Y^{+}_{mct}; Y^{-}_{mct} \geq 0 \text{ and integer } \ \forall(m, c, t)$$

$$L^{+}_{wct}; L^{-}_{wct}; N_{wct} \geq 0 \text{ and integer } \ \forall(w, c, t) \tag{22}$$

$$Q_{pt}; \beta_{pt}; O_{pt} \geq 0 \text{ and integer } \ \forall(p, t)$$

$$BN_{mt}; A^{*}_{mt} \geq 0 \text{ and integer } \forall(m,t)$$

$$v_{pct} \in \{0,1\} \ \forall(p,c,t) \quad (22)$$

$$z_{pmwct} \in \{0,1\} \ \forall(p,m,w,c,t)$$

The objective function has several terms. The first term represents machines maintenance overhead cost. The second term represents relocation cost of machines installation. The third term represents relocation cost of machines removal. The fourth term represents part holding cost. The fifth term represents the salary worker cost. The sixth term represents the hiring worker cost. The seventh term represents the firing worker cost. The eighth term represents part intercellular movement cost. The ninth term represents machine procurement cost. Tenth term represents the internal production cost. Term number eleven represents machine operating cost. Term number twelve represents the cost of acquiring the returned products. Term number thirteen represents the setup cost for disassembly operations. Term fourteen represents disassembly cost. Term number fifteen represents the inventory cost of the returned products. Term number sixteen represents parts disposal cost.

The objective function is subjected to constraints as follows: Constraint (2) shows that demand of part type p, in each time period t is satisfied through internal part production, and/or part inventory carried over from previous period. Equation (3) is to determine whether part type p is processed within cell c in period t. Constraints (4) and (5) is to make sure that only one worker is assigned for each part on each machine type. Constraint (6) is to ensure that the number of machines type m in current period is equal to the number of machines in the previous period, adding the number of machines moved in and subtracting the number of machines moved out of the cell c. By constraint (7), lower and upper bounds on sizes of cell in terms of the number of machines are enforced. Constraint (8) ensures that the minimum number of workers to be assigned to cell k in each period. Constraints (9) and (10) ensure that the available time for workers and capacity of machines are not exceeded, respectively. Equation (11) balances the number of workers between consecutive time periods. Constraint (12) guarantees that the total number of workers of each type assigned to different cells in each period will not exceed total available number of workers of that type. Constraint (13) ensures that If $\beta_{pt} = 0$, no machines, worker and cell should be considered. Constraint (14) relates to the machine availability constraint for period 1, taking into consideration the extra machines introduced through the machine procurement option. In period 1, the total number of machine of each type available is equal to the machine availability (before procurement) plus the number of machines procured in the same period 1. Constraint (15) relates to the machine availability constraint for the subsequent time periods. It takes into consideration the extra machines introduced through the machine procurement option in the period under consideration as well as those procured in all of the previous periods. Constraint (16) ensures that the total number of machines in each cell will not exceed the number of available machines. Constraint (17) shows that the number of returned product to disassemble in period t and the number of returned product to be kept in inventory to the next period is equal to the number in inventory from the previous period and the number to be acquired in period t .Constraints (18) is a logical constraint for disassemble. Constraint (19) gives the limit of the parts obtained from the returned products based on the quality level and bill of material. Constraints (20) and (21) are to ensure that the production route (in terms of machine and worker) in a specific cell will not be assigned for a product unless this type of machine and worker are already assigned to that specific cell. Constraint (22) is the logical binary and non-negativity integer requirements on the decision variable.

3.3. Linearization of the objective function

Objective function is a nonlinear integer equation due to nonlinear terms (1.8) and (1.11) in the objective function and also constraints (3), (9) and (10). To transform these terms to linear terms, the following new variables are defined:

$$\boldsymbol{F_{pct} = v_{pct} * \beta_{pt}} \qquad \mathbf{J_{pmwct} = z_{pmwct} * \beta_{pt}}$$

By considering these equations, following constraints must be added to the model:

$$F_{pct} \geq \beta_{pt} - L^p\left(1 - v_{pct}\right) \quad \forall(p, c, t) \quad (23)$$

$$F_{pct} \leq L^p * v_{pct} \quad \forall(p, c, t) \quad (24)$$

$$F_{pct} \leq \beta_{pt} \quad \forall(p, c, t) \quad (25)$$

$$J_{pmwct} \geq \beta_{pt} + L^p\left(1 - z_{pmwct}\right) \quad \forall(p, m, w, c, t) \quad (26)$$

$$J_{pmwct} \leq L^p * z_{pmwct} \quad \forall(p, m, w, c, t) \quad (27)$$

$$J_{pmwct} \leq \beta_{pt} \quad \forall(p, m, w, c, t) \quad (28)$$

$$F_{pct} \geq 0 \textit{ and is integer} \quad \forall(p, c, t) \quad (29i)$$

$$J_{pmwct} \geq 0 \textit{ and is integer} \quad \forall(p, m, w, c, t) \quad (30)$$

Also to linearize the proposed model, constraint (3) should be replaced by these two constraints:

$$\sum_{m=1}^{M}\sum_{w=1}^{W} z_{pmwct} \leq L^{p} * v_{pct}\, , \forall (p,c,t) \qquad (31)$$

$$\sum_{m=1}^{M}\sum_{w=1}^{W} z_{pmwct} \geq v_{pct}\, , \forall (p,c,t) \qquad (32)$$

Therefore, the proposed linear mathematical programming model is as follows:

Minimize:

$$Eq.(1.1)\ \ to\ \ Eq.(1.7)\ + \sum_{t=1}^{T}\sum_{p=1}^{P}\left[\left(\sum_{c=1}^{C} F_{pct}\right) - \beta_{pt}\right].V_{p}^{inter} +\ Eq.(1.9) +\ Eq.(1.10)$$

$$+\sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{m=1}^{M}\sum_{w=1}^{W}\sum_{c=1}^{C} J_{pmwct} * t_{pmw} * \gamma_{m} + Eq.(1.12)\ \ to\ \ Eq.(1.16)$$

St.: Constraints (2), (4) - (8), (11) - (32) and the new version of constraints (9) and (10) are:

$$\sum_{m=1}^{M}\sum_{p=1}^{P} J_{pmwct} * t_{pmw} \leq N_{wct} * RW_{wt}, \forall (w,c,t) \qquad (29)$$

$$\sum_{w=1}^{W}\sum_{p=1}^{P} J_{pmwct} * t_{pmw} \leq N_{mct} * T_{mt}, \forall (m,c,t) \qquad (30)$$

3.4. Numerical Example

After solving many examples in order to demonstrate the proposed model, in this section, a detailed solution for one example are presented. The model was solved using IBM ILOG CPLEX Optimization Studio 12.2/OPL. Tables 3 – 1 to 3 – 6 represent input data information; table 3 – 1 shows all the costs related to workers, while table 3 – 2 represents the costs related to machines and the machine’s capacity as well, in table 3 – 3 costs for returned products are shown, table 3 – 4 represents part's demand, recovering rate, and part's costs, parts-machines matrix are shown in table 3 – 5, and table 3 – 6 shows number of part p contained in returned product j.

Table 3-1 Worker's cost

Worker	**Period**	**Hiring**	**Salary**	**Firing**
1	1	270	470	0
1	2	285	490	145
2	1	260	460	0
2	2	290	485	145
3	1	200	455	0
3	2	250	475	155
4	1	265	450	0
4	2	280	480	140

Table 3-2Machine's information

Machine	**Cost**					**Capacity**	
	Operating	Overhead	Procurement	Removing	Installing	T 1	T2
1	18	400	4000	140	550	30	30
2	16	410	2000	130	530	30	30
3	14	430	2000	150	560	30	40

Table 3-3 Costs related to returned products

Returned Product	**Cost**			
	Period	Disassembly	Acquire	Inventory
1	1	30	25	40
1	2	35	15	40
2	1	25	35	50
2	2	30	20	50
3	1	20	25	30
3	2	18	28	30

Table 3-4 Part's information

Part	Cost					Demand	
	Disposing	Inventory	Production	Intercell	Recovering rate	T1	T2
1	200	4	20	11	0.5	0	1550
2	250	6	21	9	0.5	900	600
3	220	8	23	8	0.6	1700	500
4	300	10	20	10	0.2	1700	300

Table 3-5 Parts - Machines Matrix

Part	Machine	Value
1	1	1
1	2	1
1	3	1
2	1	1
2	2	1
2	3	0
3	1	1
3	2	0
3	3	1
4	1	0
4	2	1
4	3	1

Table 3-6 Number of part p contained in returned product j

Part	Product	Value
1	1	10
1	2	10
1	3	8
1	4	13
2	1	12
2	2	12
2	3	10
2	4	12
3	1	15
3	2	11
3	3	3
3	4	8

The example's results obtained with the proposed model are elaborated in the rest of this section, as seen in tables 3 – 7 to 3 – 11. Machine-Cell assignments are shown in table 3 – 7, for example, there is a need to assign two machines of type 1 in cell 1 for the first period, but for the second period, one machine of type 1 is needed for cell 1. Table 3 – 8 shows the Worker-Cell assignments, for example, two workers of type 1 should be hired for cell 1 in the first period, and for the second period there is a need to fire one of the two workers in order to have one worker in cell 1 for the second period. Production volume and production routes for each part and for each time period are illustrated in table 3 – 9 while table 3 – 10 shows the inventory planning for each part at the beginning of each time period. For example, for part type 1 the production volume in the first period should be 1193 units in cell 2 by using: worker type 2 on machine type 1, and two workers of type 4; one for machine type 2 and one for machine type 3. While the demand of part type 1 is zero for the first period, all 1193 units should be kept in inventory for the second period as shown in table 3 – 10, by this, there is a need to produce just 357 units in the second period with a total of 1550 units, which are the demand of part type 1 in the second period. The 357 units should be produce in cell 1 by using workers type 2 and 1 and machines 1, 2, and 3 as shown in table 3 – 9. In table 3 – 11, number of returned products to be acquired are shown; only type 3 is needed, 619 units for the first period and 65 for the second one.

Table 3-7 Machine – cell Assignments

Machine	Cells	Period	Value
1	1	1	**2**
1	1	2	**1**
1	2	1	**1**
1	2	2	**1**
2	1	1	**2**
2	1	2	**1**
2	2	1	**2**
2	2	2	**1**
3	1	1	**1**
3	1	2	**1**
3	2	1	**1**
3	2	2	**0**

Table 3-8 Worker - Cell Assignments

Worker	Cell	Period	Value
1	1	1	**2**
1	1	2	**1**
1	2	1	**0**
1	2	2	**0**
2	1	1	**1**
2	1	2	**1**
2	2	1	**1**
2	2	2	**1**
3	1	1	**2**
3	1	2	**1**
3	2	1	**0**
3	2	2	**0**
4	1	1	**0**
4	1	2	**0**
4	2	1	**2**
4	2	2	**2**

Table 3-9 Production Route and Production Planning

Product	Machine	Worker	Cell	Period	Value
1	1	2	2	1	**1193**
	2	4			
	3	4			
	1	2	1	2	**357**
	2	2			
	3	1			
2	1	3	1	1	**1143**
	2	1			
	1	3	1	2	**357**
	2	3			
3	1	3	1	1	**1771**
	3	2			
	1	3	1	2	**429**
	3	2			
4	2	2	2	1	**1857**
	3	2			
	2	1	1	2	**143**
	3	2			

Table 3-10 Inventory Planning

Inventory	Products	Periods	Value
	1	1	**1193**
		2	**0**
	2	1	**243**
		2	**0**
	3	1	**71**
		2	**0**
	4	1	**157**
		2	**0**

Table 3-11 Number of returned product to acquire

Acquire	Component	Period	Value
	1	1	**0**
		2	**0**
	2	1	**0**
		2	**0**
	3	1	**619**
		2	**65**

3.5. Sensitivity Analysis

In the proposed model, the cell size in terms of workers and machines numbers are user-defined through constraints 7 and 8, to see how the solution of the example in section 3.4 could be changed when the cell size is a system-defined instead of user-defined; the example are resolved by making the lower limit of the cells in terms of machines and workers are equal to zero and the upper limit of cells in terms of machines are equal to infinity, and the following tables 3 – 12 to 3 – 15 are showing the results. From these tables, one can see that the solution has built only on cell and assigned all the production tasks, workers, and machines to it by total saving of 0.46% comparing to the previous solution in section 3.4, which can be considered as a valuable saving but on the other hand the system lost its workload balance which can lead to a crowded cell (cell 1) while the other cell (cell 2) is idle.

Table 3-12 Machine – cell Assignments

Machines	Cells	Periods	Value
1	1	1	3
1	1	2	1
2	1	1	3
2	1	2	1
3	1	1	1
3	1	2	1

Table 3-13 Worker - Cell Assignments

Worker	Cell	Period	Value
1	1	1	2
2	1	1	1
2	1	2	1
3	1	1	2
4	1	1	2
4	1	2	1

Table 3-14 Production Route and Production Planning

<table>
<tr><th>Product</th><th>Machine</th><th>Worker</th><th>Cell</th><th>Period</th><th>Value</th></tr>
<tr><td rowspan="6">1</td><td>1</td><td>2</td><td rowspan="20">1</td><td rowspan="3">1</td><td rowspan="3">1238</td></tr>
<tr><td>2</td><td>4</td></tr>
<tr><td>3</td><td>1</td></tr>
<tr><td>1</td><td>2</td><td rowspan="3">2</td><td rowspan="3">312</td></tr>
<tr><td>2</td><td>2</td></tr>
<tr><td>3</td><td>4</td></tr>
<tr><td rowspan="4">2</td><td>1</td><td>1</td><td rowspan="2">1</td><td rowspan="2">1188</td></tr>
<tr><td>2</td><td>3</td></tr>
<tr><td>1</td><td>4</td><td rowspan="2">2</td><td rowspan="2">312</td></tr>
<tr><td>2</td><td>4</td></tr>
<tr><td rowspan="4">3</td><td>1</td><td>3</td><td rowspan="2">1</td><td rowspan="2">1824</td></tr>
<tr><td>3</td><td>2</td></tr>
<tr><td>1</td><td>2</td><td rowspan="2">2</td><td rowspan="2">376</td></tr>
<tr><td>3</td><td>2</td></tr>
<tr><td rowspan="4">4</td><td>2</td><td>1</td><td rowspan="2">1</td><td rowspan="2">1875</td></tr>
<tr><td>3</td><td>2</td></tr>
<tr><td>2</td><td>2</td><td rowspan="2">2</td><td rowspan="2">125</td></tr>
<tr><td>3</td><td>2</td></tr>
</table>

Table 3-15 Inventory Planning

Product	Period	Value
1	1	**1238**
1	2	**0**
2	1	**288**
2	2	**0**
3	1	**124**
3	2	**0**
4	1	**175**
4	2	**0**

Quality of returned product is an important factor in remanufacturing, UR_p which is the average recovering rate of part p from all returned products gives an indication of returned product's quality. Figure 3 – 2 shows how the objective function value could be considerably decreased by increasing the recovering rate value, this is due to the decreasing in the amounts of returned products to be acquired as shown in figure 3 – 3. In figure 3 – 2 the value of the recovering rate has been changed between 0.1 – 1.0, hence, the objective function value decreased from 12511606 at a value of 0.1 of the recovering rate to 193649 at a value of 1.0 of the recovering rate.

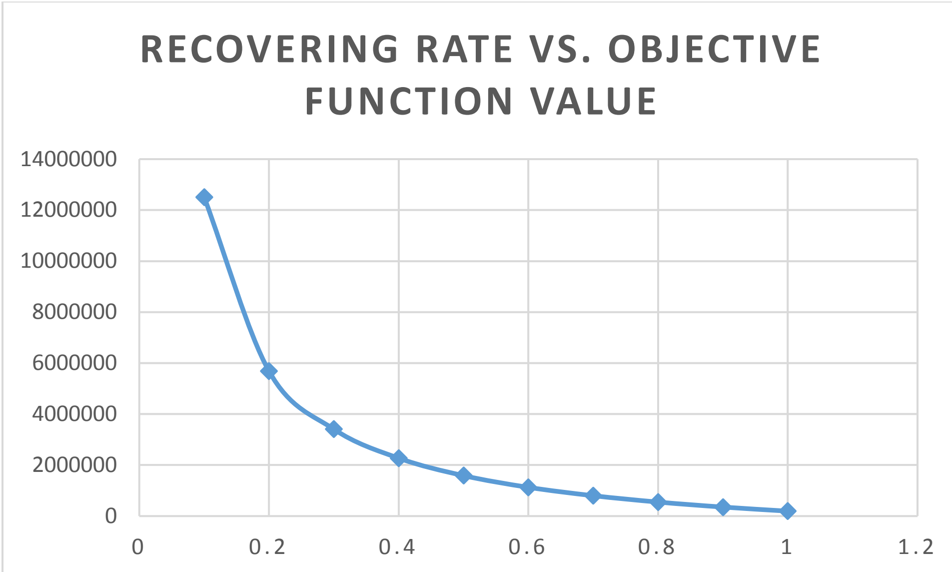

Figure 3-2 the effect of the recovering rate (UR_p) on the objective function value

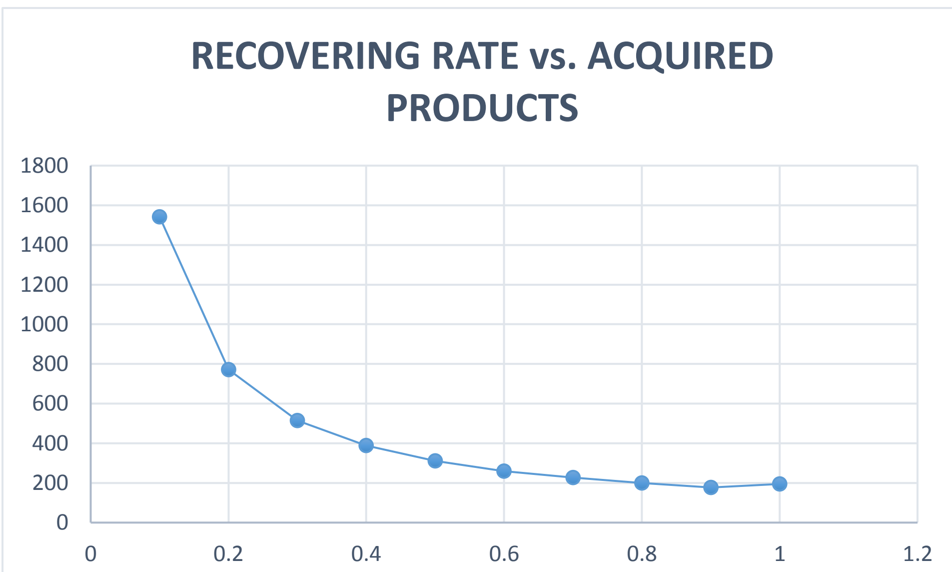

Figure 3-3 the effect of the recovering rate (UR_p) on the amount of returned products to be acquired

3.6. Chapter Summary

In this chapter, a mixed integer nonlinear programming for designing a dynamic third part remanufacturing cellular system, which is responsible to collect the returned products from the customer zone, disassemble, and use the disabled components in producing a remanufactured parts. By using some auxiliary variables the nonlinear formulation of the proposed model was linearized. The proposed model incorporates several design features with addition to workforce management, such as cell reconfiguration, production and inventory planning, disposal option, returned products' quality, and user-defined cell size in terms of the number of machines and workers. Several numerical examples have been solved in order to validate the proposed model, one detailed numerical example was presented with a discussion for the results. Sensitivity analysis for some important factors were reported; the difference between the user-defined and the system-defined cell size as well as the effect of the recovering rate on the objective function value and on the number of returned products to be acquired.

Chapter 4

4. A mathematical model for designing Reconfigurable Cellular Hybrid Manufacturing-Remanufacturing Systems

4.1. Introduction

In this chapter, we consider a classical cell formation problem in CMSs, bridged with a production planning problem, in hybrid manufacturing-remanufacturing systems, while addressing to “reconfiguration” issues for the CMSs for different production periods. We will name such a system as *Reconfigurable Cellular Hybrid Manufacturing-Remanufacturing System* (RCHMRS). Material flow in such a system is presented in Figure 4 – 1, where there are two types of components, namely new and remanufactured components, are to be produced. The new components are produced using the raw material. The other type of component, the remanufactured components, are produced using the core component after disassembling the returned products. In the classical cell formation problem machines are to be grouped into cells, parts into part families, and then assigned the part families to the machine groups in order to form relatively independent cells. The overall objective of the model is to minimize the total cost of the three main categories of costs; 1) Machine cost: maintenance and overhead costs, relocation costs of installation and removal of machines, machine procurement costs, and machine operating costs, 2) Costs associated with manufacturing and remanufacturing: production costs for both new and remanufactured components, holding cost for new components, holding cost for remanufactured components, setup cost for new components, setup cost for remanufactured components, 3) Costs associated with returned products for remanufacturing: cost of acquiring the returned products, setup cost for disassembly operations, disassembly cost, and inventory cost of the returned products.

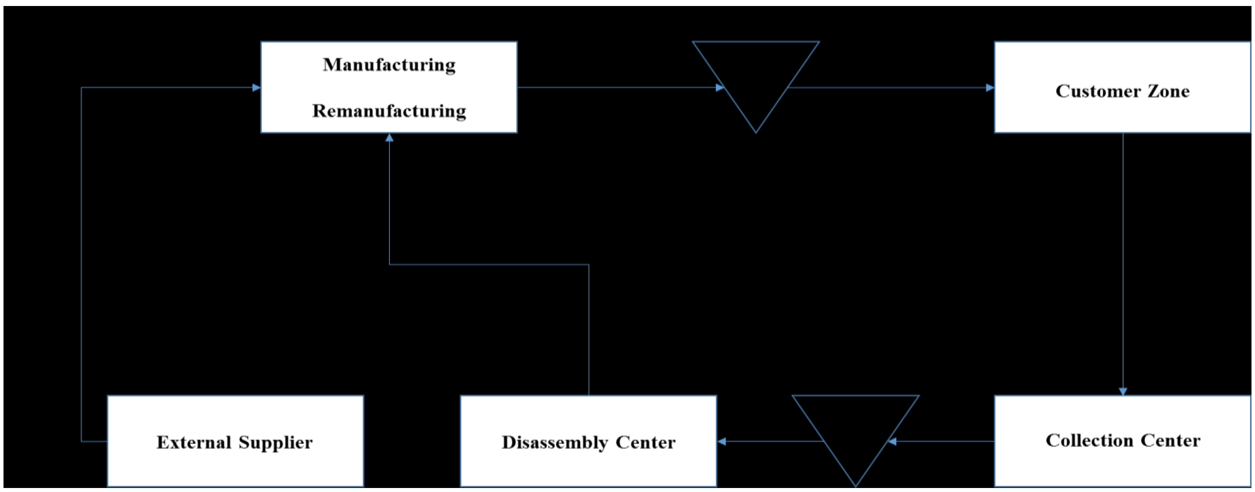

Figure 4-1 Material flow in the proposed CHMRS

4.2. The Proposed Mathematical Model

In this section a mixed integer linear programming (MILP) model for solving the above-described problem is formulated. Assumptions, parameters, decision variables, formulation, and a detailed description of the MILP model are proposed as well.

4.2.1. Model Assumptions

When formulating the proposed mathematical model, certain assumptions have been taken into consideration as follows:

- Predefined number of cells and the number is constant during all periods.
- The demand in each period is deterministic.

- The demand for each component type from new material and from remanufactured products are separate from each other.
- Each machine type has a limited capacity expressed in hours during each time period.
- Reconfiguration involves the addition and removal of machines to any cell and relocation from one cell to another between periods.
- Maintenance and overhead costs of each machine type are known. These costs are considered for each machine in each cell and period regardless that the machine is active or idle.
- The demand for each component in each period can be satisfied by production, inventory from the last periods.
- Unlimited source of the returned product.

4.2.2. Model Parameters and Decision Variables

The notations used for the model are presented followed by the objective function and constraints:

Sets

$i = \{1, 2, 3 \ldots I\}$ Index set of component types.

$m = \{1, 2, 3 \ldots M\}$ Index set of machine types.

$c = \{1, 2, 3 \ldots C\}$ Index set of cells.

t = {1, 2, 3… T} Index set of time periods.

j = {1, 2, 3… J} Index of product types.

Parameters

P_i	Unit manufacturing cost of new component *i*
S_i	Setup cost for manufacturing new component *i*
V_i	Unit inventory cost for new component *i*
$D_{i,t}$	Demand for new component *i* in time period *t*
$\overline{P}_i$	Unit remanufacturing cost of recovered component *i*
$\overline{S}_i$	Setup cost for remanufacturing recovered component *i*
$\overline{V}_i$	Unit inventory cost for remanufactured component *i*
$\overline{D}_{i,t}$	Demand for remanufactured component *i* in time period *t*
$B_{i,j}$	Number of component *i* contained in product *j*
UR_i	Average recovering rate of component *i* from all returned products
$AQ_{j,t}$	Unit cost to acquire returned product *j* in time period *t*
$RD_{j,t}$	Unit cost to disassemble returned product *j* in time period *t*
$SD_{j,t}$	Setup cost to disassembling returned product *j* in time period *t*

$IN_{j,t}$	Unit inventory cost for storing returned product *j* in time period *t*
M	A large positive number
$t_{i,m}$	Processing time of the new component *i* on machine type *m*
$\bar{t}_{i,m}$	Processing time of the remanufactured returned component *i* on machine type *m*
$st_{i,m}$	Setup time for manufacturing new component *i*
$\overline{st}_{i,m}$	Setup time for remanufacturing returned component *i*
T_m	Time capacity of one machine of type *m* during one period
LL	Lower size limit
UL	Upper size limit
$R_m^{\mp}$	Relocation cost per machine of type *m* per period
$\in_m$	Procurement cost per machine type m
A_{mt}	Quantity of machine type m available at time period *t*
OV_m	Machine maintenance overhead cost of machine type *m*
γ_m	Operating cost per unit time per machine type *m*

Decision variables

N_{mct}	Number of type *m* machines to present at cell *c* at beginning of time period *t*
Y^{+}_{mct}	Number of type *m* machines added in cell *c* at beginning of time period *t*
Y^{-}_{mct}	Number of type *m* machines removed from cell *c* at beginning of time period *t*
BN_{mt}	Number of machines of type m procured at time t
$\hat{A}_{mt}$	Quantity of machine type *m* available at time period *t* after accounting for machines that have been procured
e_{it}	Number of new component *i* in inventory at the end of time period *t*
X_{imct}	Number of new component *i* processed on machine type *m* in cell *c* in time period *t*
$\overline{e}_{it}$	Number of remanufactured component *i* in inventory at the end of time period *t*
$\overline{X}_{imct}$	Number of remanufactured component *i* processed on machine type *m* in cell *c* in time period *t*
d_{jt}	Number of returned product *j* to disassemble in time period *t*
r_{jt}	Number of returned product *j* to acquire in time period *t*

$f_{j,t}$ Number of returned product *j* in inventory at the end of time period *t*

θ_{it} = 1, if the system is setup to make new component *i* in time period *t*

= 0, otherwise.

$\overline{\theta}_{it}$ = 1, if the system is setup to remanufacture returned component *i* in time period *t*

= 0, otherwise.

δ_{jt} = 1, if returned product *j* will be disassembled in time period *t*

= 0, otherwise.

z_{imct} = 1, if new component *i* is to be processed on machine type *m* in cell *c* in period *t*

= 0, otherwise.

$\overline{z}_{imct}$ = 1, if returned component *i* is to be processed on machine type *m* in cell *c* in period *t*

= 0, otherwise.

Objective function

Minimize

$$\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m=1}^{M} N_{mct}.\, OV_m \qquad 1.1$$

$$+\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m=1}^{M} R_m^{\mp}.\left(Y_{mct}^{+}+Y_{mct}^{-}\right) \quad 1.2$$

$$+\sum_{t=1}^{T}\sum_{m=1}^{M} \epsilon_m.BN_{mt} \quad 1.3$$

$$+\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{c=1}^{C}\sum_{m=1}^{M} P_i * X_{imct}+\overline{P}_i * \overline{X}_{imct} \quad 1.4$$

$$+\sum_{t=1}^{T}\sum_{i=1}^{I} V_i \,.\, e_{it} \quad 1.5$$

$$+\sum_{t=1}^{T}\sum_{i=1}^{I} \overline{V}_i \,.\, \overline{e}_{it} \quad 1.6$$

$$+\sum_{t=1}^{T}\sum_{i=1}^{I} S_{it} \,.\, \theta_{it} \quad 1.7$$

$$+\sum_{t=1}^{T}\sum_{i=1}^{I} \overline{S}_{it} \,.\, \overline{\theta}_{it} \quad 1.8$$

$$+\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{c=1}^{C}\sum_{m=1}^{M} \gamma_m.\left(t_{im}.X_{imct}+\bar{t}_{im}.\overline{X}_{imct}\right) \quad 1.9$$

$$+\sum_{t=1}^{T}\sum_{j=1}^{J}\left(AQ_{jt}.r_{jt}+SD_{jt}.\delta_{jt}+RD_{jt}.d_{jt}+IN_{jt}.f_{jt}\right) \quad 1.10$$

Subject to:

$$e_{i,t-1} + \sum_{m=1}^{M}\sum_{c=1}^{C} X_{imct} - e_{i,t} = D_{i,t};\ \forall(i,t) \quad 2$$

$$\sum_{m=1}^{M}\sum_{c=1}^{C} X_{imct} \leq M\theta_{i,t};\ \forall(i,t) \quad 3$$

$$\bar{e}_{i,t-1} + \sum_{m=1}^{M}\sum_{c=1}^{C} \bar{X}_{imct} - \bar{e}_{i,t} = \bar{D}_{i,t};\ \forall(i,t) \quad 4$$

$$\sum_{m=1}^{M}\sum_{c=1}^{C} \bar{X}_{imct} \leq M\bar{\theta}_{i,t};\ \forall(i,t) \quad 5$$

$$f_{j,t} + d_{j,t} - f_{j,t-1} = r_{j,t};\ \forall(j,t) \quad 6$$

$$d_{j,t} \leq M\delta_{j,t};\ \forall(j,t) \quad 7$$

$$\sum_{m=1}^{M}\sum_{c=1}^{C} \bar{X}_{imct} \leq UR_i \sum_{j=1}^{J} B_{i,j} d_{j,t};\ \forall(i,t) \quad 8$$

$$LL \leq \sum_{m=1}^{M} N_{mct} \leq UL;\ \forall(c,t) \quad 9$$

$$\widehat{A}_{m(t=1)} = A_{m(t=1)} + BN_{m(t=1)};\ \forall(m,t) \quad 10$$

$$\widehat{A}_{m(t+1)} = \widehat{A}_{mt} + BN_{m(t+1)};\ \forall(m,t) \quad 11$$

$$\sum_{c=1}^{C} N_{mct} \leq \widehat{A}_{mt};\ \forall(m,t) \quad 12$$

$$N_{mct} = N_{mc(t-1)} + Y_{mct}^{+} - Y_{mct}^{-};\ \forall(m,c,t) \quad 13$$

$$\sum_{i=1}^{I} \left(X_{imct}.\, t_{i,m} + \overline{X}_{imct}.\, \overline{t}_{i,m}\right) \leq T_m.\, N_{mct};\ \forall(m,c,t) \quad 14$$

$$X_{imct} \leq M.\, z_{imct};\ \forall(i,m,c,t) \quad 15$$

$$\overline{X}_{imct} \leq M.\, \overline{z}_{imct};\ \forall(i,m,c,t) \quad 16$$

$$N_{mct}, BN_{mt}, Y_{mct}^{-}, Y_{mct}^{+}, \widehat{A}_{mt}, e_{it}, X_{imct}, \overline{e}_{it}, \overline{X}_{imct}, d_{jt}, r_{jt}, f_{j,t} \geq 0$$
$$\theta_{it}, \overline{\theta}_{it}, \delta_{jt}, z_{imct}, \overline{z}_{imct} = \{0,1\} \quad 17$$

The objective function has several terms. The first term (1.1) represents machine maintenance overhead costs. The second term (1.2) represents relocation costs of machine installation and removal. The third term (1.3) represents machine procurement costs. The fourth term (1.4) represents production cost for both new and remanufactured components. The fifth term (1.5) represents holding cost for new components. The sixth term (1.6) represents holding cost for remanufactured components. Term (1.7) represents setup cost for new components. Term (1.8) represents setup cost for remanufactured components. The ninth term (1.9) is the machine operating cost. Tenth term (1.10) represents the cost of acquiring the returned products, setup cost for disassembly operations, disassembly cost, and inventory cost of the returned products.

The objective function is subjected to constraints as follows: equation (2) shows that demand of new component type i, in each time period t is satisfied through internal part production, and/or part inventory carried over from previous period. Equation (3) ensures that there will be no internal production for new component unless if the system is setup to make a new component. Equation (4) shows that demand of remanufactured component type i, in each time period t is satisfied through internal part production, and/or part inventory carried over from previous period. Constraint (5) ensures that there will be no internal production for remanufactured component unless if the system is setup to make a remanufactured component. Equation (6) shows that the number of returned product to disassemble in period t and the number of returned product to be kept in inventory to the next period is equal to the number in inventory from the previous period and the number to be acquired in period t. Constraint (7) is a logical constraint for disassembly. Constraint (8) gives the limit of the parts obtained from the returned products based on the quality level and the bill of material. By constraint (9), lower and upper bounds on sizes of cell in terms of the number of machines are enforced. Constraint (10) relates to the machine availability constraint for period 1, taking into consideration that the extra machines introduced through the machine procurement option. In period 1, the total number of machine of each type available is equal to the machine availability (before procurement) plus the number of machines procured in the same period 1. Therefore, if $A_{m(t=1)} = 0$, there are no machines present in the system initially, meaning that a CM system is being designed and implemented from no existing manufacturing layout. If $A_{m(t=1)} > 0$, there are machines already available in the system, meaning that the existing manufacturing layout is being reconfigured to form a CM layout. Constraint (11) relates to the machine availability constraint for the subsequent time periods. It takes into consideration the extra machines introduced through the machine procurement option in the period under consideration as well as those procured in all of the previous periods. Constraint (12) ensures that the total number of machines in each cell will not exceed the number of available machines. Constraint (13) is to ensure that the number of machines of type m in current period is equal to the number of machines in the previous period, adding the number of machines moved in and subtracting the number of machines moved out of the cell c. Constraint (14) shows the machine capacity constraint. It ensures that the required internal production capacities for both new and remanufactured components respect the available machine capacities. Constraint (15) shows that the number of new components produced internally can be positive only if $z_{imct} = 1$, that is, it has been decided that part i would be produced internally by machine m in cell c. Constraint (16) shows that the number of remanufactured components produced internally can be positive only if $\overline{z}_{imct} = 1$, that is, it has been decided that part i would be produced internally by machine m in cell c. Constraint (17) is the logical binary and non-negativity integer requirements on the decision variable. The number of variables and constraints in the proposed model are illustrated in Tables 4 – 1 and 4 – 2 respectively.

Table 4-1 Number of variables in the proposed model

Variables	Count	Variables	Count
$\boldsymbol{N_{mct}}$	M×C×T	d_{jt}	J×T
$\boldsymbol{Y^{+}_{mct}}$	M×C×T	r_{jt}	J×T
$\boldsymbol{Y^{-}_{mct}}$	M×C×T	$f_{j,t}$	J×T
$\boldsymbol{BN_{mt}}$	M×T	θ_{it}	I×T
$\boldsymbol{\widehat{A}_{mt}}$	M×T	$\overline{\theta}_{it}$	I×T
$\boldsymbol{e_{it}}$	I×T	δ_{jt}	J×T
$\boldsymbol{X_{imct}}$	I×M×C×T	z_{imct}	I×M×C×T
$\boldsymbol{\overline{e}_{it}}$	I×T	$\overline{z}_{imct}$	I×M×C×T
$\boldsymbol{\overline{X}_{imct}}$	I×M×C×T		
Total = 3×(M×C×T) + 2×(M×T) + 4×(I×M×C×T) + 4×(I×T) + 4×(J×T)			

Table 4-2 Number of constraints in the proposed model

Constraint	Count	Constraint	Count
2	I×T	10	M×T
3	I×T	11	M×T
4	I×T	12	M×T
5	I×T	13	M×C×T
6	J×T	14	M×C×T
7	J×T	15	I×M×C×T
8	I×T	16	I×M×C×T
9	C×T		
Total = 5×(I×T) + 2×(J×T) + (C×T) + 3×(M×T) + 2×(M×C×T) + 2×(I×M×C×T)			

4.3. Numerical examples

Several example problems were solved in order to validate the applicability of the model developed with full details. A detailed discussion of one example problem is also illustrated below. The models were solved using IBM ILOG CPLEX Optimization Studio 12.2/OPL. The main advantage of using CPLEX is that, it is a high performance solver for Linear programming (LP) and Mixed Integer Programming (MIP) problems that offers various algorithms for solving the optimization models. The data set used is based on the data used by Chen and Abrishami (2014), where applicable, with additions of certain realistic cost parameters based on our experience of such systems. Ahkioon et al. (2009b) presented a summary of design data collected from a real-world company running in a CMS environment, which shows a typical realistic data set for a real company; in terms of the number of components, the number of cells, and the number of machine types. By these reported data from Ahkioon et al. (2009b) as well as from our previous observations of real-life CMSs, we could have an aggregate idea for the real size problem for a real-world CMS. Accordingly, as can be found in Table 4 – 3, we attempted to model different CMSs. Table 4 – 3 shows different scenario problems with different sizes. In this table elapsed time and optimality gap (difference between current solution and best bound on optimal solution) are shown as the problem size increases (number of variables and constraints). It is obvious that while the problem size increases, the elapsed time also increases. Problems shown in the table could be classified into three different groups; namely small-scale (problems 1-6), medium-scale (problem 7), and large-scale (problems 8 and 9) problems. Small-scale problems were successfully solved within 3 seconds while the medium scale problem was solved within 2,839 seconds (47.3 minutes). Based on our previous observations of CMSs, the medium size problem (problem 7) can be considered as one real size problem amongst many other real-world CMSs. Therefore, we can conclude that, a real size problem could be solved within a reasonable computational time. There was a difficulty in solving the large size problems since no optimal solution was obtained after 10 hours. By this, we can conclude that the branch and cut algorithm of CPLEX is unable to produce good quality solutions within reasonable computational times for large-scale problems of the CHMRS model.

4.3.1. Example problem and input data

In this example we consider a three time period production planning horizon for a RCMHRS with two cells, three types of machines, 3 types of components, and 3 types of returned products. Tables 4 – 4 and 4 – 5 present the production cost, the setup cost, and the demands for new and remanufactured components respectively for each time period. Table 4 – 6 presents the disassembly cost, the setup cost, the inventory cost as well as the acquisition cost for returned products. The numbers of components contained in different products are shown in Table 4 – 7. Table 4 – 8 gives the time that each machine needs to process each type of the new component as well as the time required to set up each machine for each type of the new component during each time period. On the other hand, Table 4 – 9 represents the same data for the remanufactured components. In table 4 – 10, machine overhead and maintenance costs, operating cost, procurement cost, and the relocation cost can be found. Time capacity for each type of machine during each time period is found in Table 4 – 11.

Table 4-3 Different problem scenario of the proposed model

Problem scenario	Number of component types	Number of time periods	Number of machines types	Number of cells	Number of variables	Number of constraints	Time elapse (seconds)	Optimality gap (%)
1	2	2	3	2	177	133	0	0
2	3	3	3	2	361	267	0	0
3	2	5	3	2	461	362	0.88	0
4	3	5	3	3	826	597	1.16	0
5	4	3	4	2	941	670	1.68	0
6	5	6	5	4	3,013	1,909	2.38	0
7	11	6	10	3	8,917	5,152	2,839	0.01
8	15	6	10	5	19,453	10,716	59,022	0.03
9	25	10	20	10	207,521	108,340	95,963	0.03

Table 4-4 Cost and demand for new component

Period	Cost and demand	Component type		
		1	2	3
1	Production cost	100	90	80
	Setup cost	600	700	600
	Inventory cost	100	120	105
	Demand	50	40	50
2	Production cost	100	90	80
	Setup cost	600	700	600
	Inventory cost	100	120	105
	Demand	40	35	55
3	Production cost	100	90	80
	Setup cost	600	700	600
	Inventory cost	100	120	105
	Demand	50	20	45

Table 4-5 Cost and demand for remanufactured component

Period	Cost and demand	Component type		
		1	2	3
1	Production cost	30	40	20
	Setup cost	400	500	450
	Inventory cost	50	80	60
	Demand	10	15	10
2	Production cost	30	40	20
	Setup cost	400	500	450
	Inventory cost	50	80	60
	Demand	20	10	10
3	Production cost	30	40	20
	Setup cost	400	500	450
	Inventory cost	50	80	60
	Demand	12	9	10

Table 4-6 Data for returned products

Period	Cost											
	Product 1				Product 2				Product 3			
	Disass.	Setup.	Invent.	Acq.	Disass.	Setup.	Invent.	Acq.	Disass.	Setup.	Invent.	Acq.
1	30	22	40	25	35	35	50	35	20	30	30	25
2	35	30	40	15	30	25	50	20	18	28	30	28
3	20	33	40	20	15	35	50	30	30	30	30	30

4.3.2. Results and discussion

Table 4 – 12 shows the quantity for both new and remanufactured components that should be kept in inventory in each time period t, for example, 3 units from the remanufactured component type 1 should be kept in inventory from period number 1 to the next period. Table 4 – 13 represents the quantity of each type of returned product to be purchased and to be disassembled in each time period. For example, there is no need to purchase or disassemble any unit from returned product type 3 for the whole planning period. Table 4 – 14 shows the production quantity of new components in each time period *t* that should be produced by each machine *m* in each cell *c*. For example, for new component type 2 in period 2 the quantity that should be produced is 35 units, 30 of which should be produced by machine type 1 in cell 1, while 5 units should be produced by machine type 1 in cell 2. Table 4 – 15 shows the same data for remanufactured components. The *Reconfigurable Manufacturing-Remanufacturing System* under consideration is a CMS, which should

provide the exact required functionality and capacity. The modular structure of a *Reconfigurable Manufacturing System* (in this case; a reconfigurable CMS) enables the system to integrate/remove new software/hardware modules without affecting the rest of the system (Niroomand et al., 2012). In this example, in order to produce the required demand for both the new products and the remanufactured products, there is a need for 5 machines of type 1 (1 in cell 1 and 4 in cell 2) and 2 machines of type 3 (1 in cell1 and 1 in cell 2) for the first period. In period 2, there is a need to remove 3 machines of type 1 from cell 2. Hence, this illustrates that along with production planning issues, the proposed model additionally assists the production managers how to configure/reconfigure the *Hybrid Cellular Manufacturing-Remanufacturing System* for different production periods.

Table 4-7 Number of parts contained in the returned products

Component type Product type	1	2	3
1	10	10	8
2	12	12	10
3	15	11	3

Table 4-8 Processing and setup time for new component

Machine type		Component type		
		1	2	3
1	Processing time	1	2	6
	Setup time	50	40	40
2	Processing time	2	4	4
	Setup time	40	20	50
3	Processing time	3	5	1
	Setup time	60	30	60

Table 4-9 Processing and setup time for remanufactured component

Machine type		Component type		
		1	2	3
1	Processing time	2	3	1
	Setup time	70	40	40
2	Processing time	1	4	2
	Setup time	80	60	20
3	Processing time	2	1	3
	Setup time	60	30	60

Table 4-10 Data for machines

Cost	Machine type		
	1	2	3
Operating cost	50	40	30
Overhead cost	200	250	225
Procurement cost	2000	3000	4000
Relocation cost	100	150	130

Table 4-11 Machines capacity

Period	Machine type		
	1	2	3
1	50	50	50
2	60	60	50
3	50	50	60

Table 4-12 Inventory levels of new and remanufactured products

Period		Component type		
		1	2	3
1	New component	0	0	0
	Remanufactured	3	0	0
2	New component	0	0	0
	Remanufactured	0	0	0
3	New component	0	0	0
	Remanufactured	0	0	0

Table 4-13 Returned product acquisition and disassembly

Period	Returned product type					
	1		2		3	
	Acquisition	Disassembly	Acquisition	Disassembly	Acquisition	Disassembly
1	3	3	0	0	0	0
2	0	0	3	3	0	0
3	0	0	2	2	0	0

Table 4-14 Production quantities of new components

		1			2			3		
Period		Mach.1	Mach.2	Mach.3	Mach.1	Mach.2	Mach.3	Mach.1	Mach.2	Mach.3
1	C 1	50	0	0	0	0	0	0	0	0
	C 2	0	0	0	80	0	0	0	0	40
2	C 1	0	0	0	30	0	0	0	0	6
	C 2	40	0	0	5	0	0	0	0	49
3	C 1	10	0	0	20	0	0	0	0	45
	C 2	40	0	0	0	0	0	0	0	0

Table 4-15 Production quantities of remanufactured components

		1			2			3		
Period		Mach.1	Mach.2	Mach.3	Mach.1	Mach.2	Mach.3	Mach.1	Mach.2	Mach.3
1	C 1	0	0	13	0	0	15	0	0	0
	C 2	0	0	0	0	0	0	10	0	0
2	C 1	0	0	0	0	0	10	0	0	0
	C 2	0	0	17	0	0	0	10	0	0
3	C 1	0	0	12	0	0	0	0	0	0
	C 2	0	0	0	0	0	9	10	0	0

4.4. Sensitivity analysis

Another aspect of the model to be discussed relates to the relationship between the recovering rate and the number of products needed in order to satisfy the demand, by explaining how the total cost as well as the total number of products needed vary while changing the recovering rate. In Figure 4 – 2, one can see how the total cost changes with respect to different values of the recovering rate starting from 0.1 and ending with 1.0 through gradual increments of 0.1 (assuming the same recovering rate for all types of returned products). It is clearly shown that the recovering rate has a significant impact on the total cost. The reduction in the total cost while changing the recovering rate between 0.1 and 0.5 will be relatively high in comparison with the case when the recovering rate is changed between 0.5 and 1.0. This is because of the considerable mitigation in the total number of returned products to be acquired. Figure 4 – 3 shows the relationship between the total numbers of products needed versus different values of the recovering rate. There is a large reduction in the number of returned products to be acquired epically when the recovering rate is changed between 0.1 and 0.5.

Table 4 – 16, shows the number of products to be acquired for each type due to each value of the recovering rate. For example, when the recovering rate is 0.1, we need to acquire 15 items in period 1 and 10 items in period 3 from product type 1 and 13 items in period 2 from product type 2, with a total of 38 items. Comparing with 20 items to be procured, in the case of having a recovering rate of 0.2, gradually increasing the recovering rate by 0.1 gives an advantage of lowering the number of returned products to be acquired by approximately half.

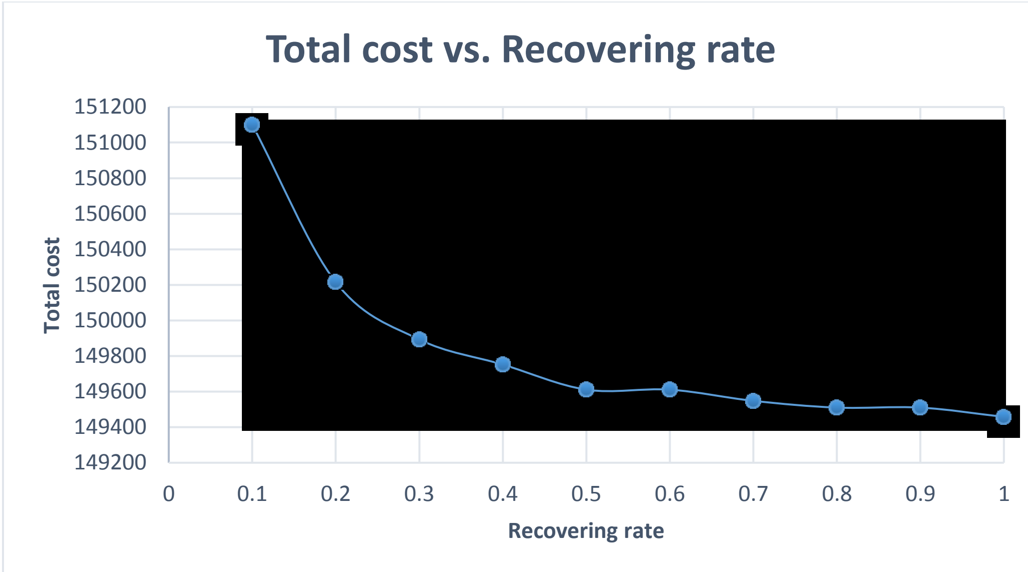

Figure 4-2 Total cost versus recovering rate

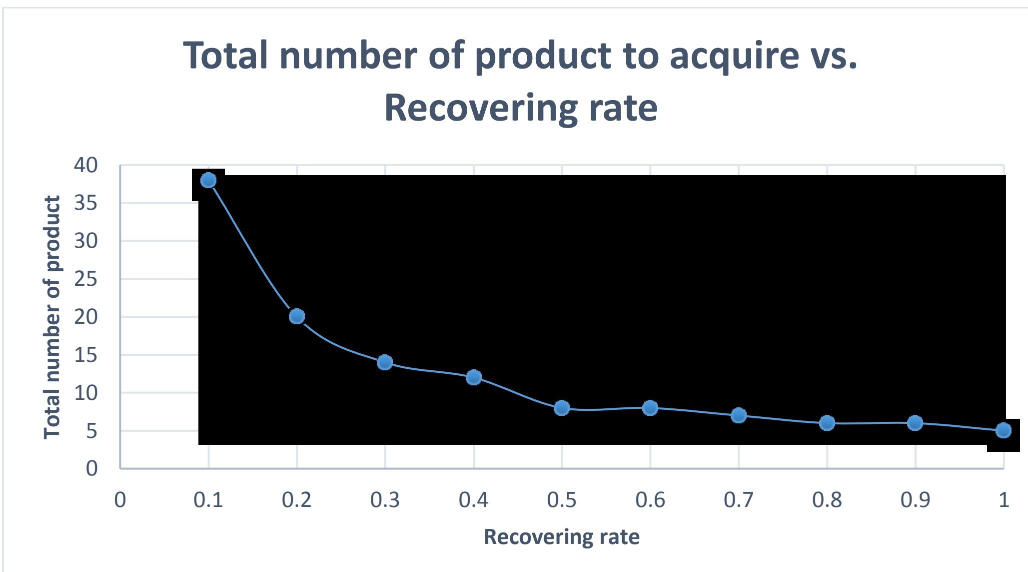

Figure 4-3 Acquired products versus recovering rate

Table 4-16 Number of acquired products for each recovering rate value

UR	*J1*			*J2*			*J3*			**Total**
	T1	*T2*	*T3*	*T1*	*T2*	*T3*	*T1*	*T2*	*T3*	
0.1	15		10		13					38
0.2	8		5		7					20
0.3	5		4					5		14
0.4	4		4					4		12
0.5	3		2					3		8
0.6	3		2					3		8
0.7			2		2			3		7
0.8	2		2					2		6
0.9	2		2					2		6
1			1				2	2		5

4.5. Chapter Summary

In this chapter, a mixed integer linear programming model for a *Reconfigurable Cellular Hybrid Manufacturing-Remanufacturing System* (RCHMRS) has been developed. To the best of the authors' knowledge this is the first integrated model, which considers CMSs and HMRSs simultaneously. This is, accordingly, one preliminary step towards the *Design for Sustainable Manufacturing Enterprise* (DFSME). The proposed model incorporates several design features including manufacturing new components and remanufacturing from returned products, machine capacites, relocation of machines (i.e. *reconfigurability*), machine procurement, operation time, and production planning. The overall objective of the model is to minimize the total cost of three main categories of costs; 1) Machine costs: Maintenance and overhead cost, relocation cost of machines installation and removal, machine procurement costs, machine operating costs, 2) Costs associated with manufacturing and remanufacturing: Production cost for both new and remanufactured components, holding cost for new components, holding cost for remanufactured components, setup cost for new components, setup cost for remanufactured components, 3) Costs associated with returned products for remanufacturing: Cost of acquiring the returned products, setup cost for disassembly operations, disassembly cost, and inventory cost of the returned products. The next step in research is to extend this model in order to incorporate recycling and disposing options.

Chapter 5

5. Designing a Cellular Manufacturing System Featuring Remanufacturing, Recycling, and Disposal Options: A Mathematical Modeling Approach

5.1. Introduction

In this chapter, we present a mathematical model, which attempts to integrate several Sustainable Manufacturing System (SMS) design aspects together; recycling, remanufacturing, disposing, reconfigurability, and cellular manufacturing in a Hybrid Manufacturing-Remanufacturing System. Fig. 5 – 1 represents the material flow network for such a model. Returned products are to be collected from the customer zone to a collection center, and then returned products are moved to a disassembly center with inventory options for those products to be held to the next period. In the disassembly center, returned products are disassembled and there are three types of output components: end-of-use components, end-of-life components, and disposed components. There is a need to facilitate a disposal center for disposed components, since a pure policy of no waste disposal technology is infeasible (Hasanov et al., 2012). The end-of-use components are to be remanufactured in order to satisfy the demand of the remanufactured components, while, the end-of-life components are to be recycled, recycled components will be used as a raw material for new components production. The manufacturing of new products and remanufacturing of returned components will take place in the same cellular manufacturing system, by using the same resources. Customers perceive recovered items to be of a lower quality, and thus following a different demand rate from produced (new) ones (Hasanov et al., 2012). Accordingly, demand rates for new components and for remanufactured components are modeled as two separate parameters in the model presented. Excess production quantity is to be held in inventory for the upcoming period.

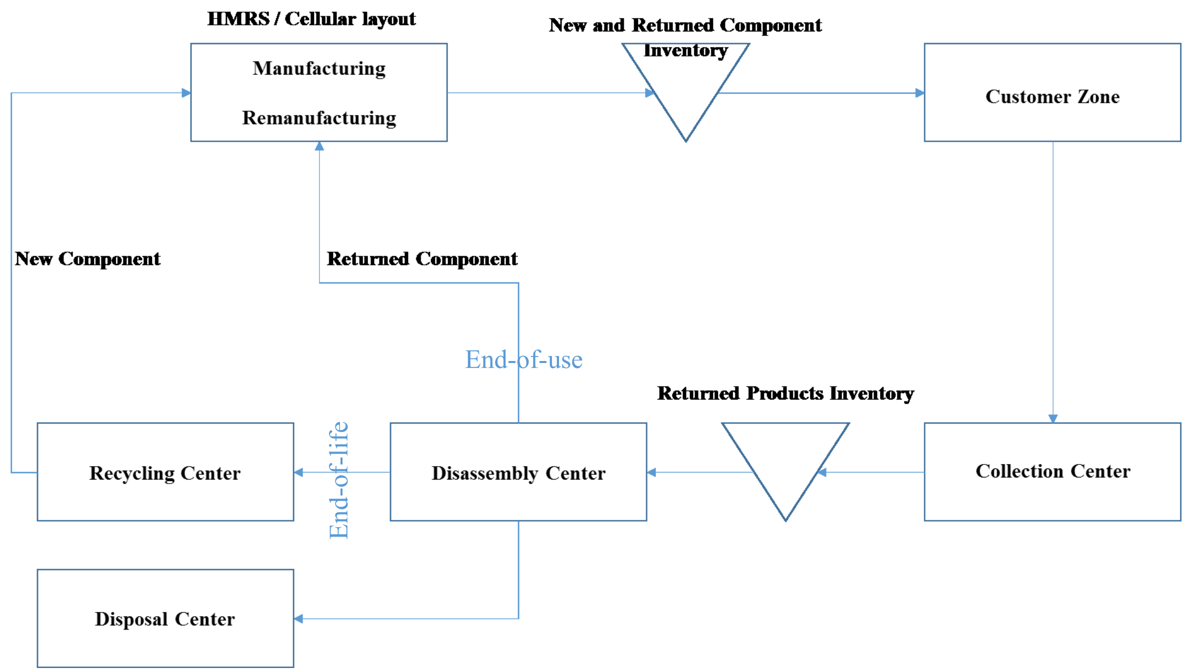

Figure 5-1 Material flow of the proposed model

5.2. The Proposed Mathematical Model

In this section a mixed linear integer programming (MILP) model for designing the system mentioned in the above section is proposed. Assumptions, parameters, decision variables, formulation, and a detailed description of the MILP model are presented as well.

5.2.1. Model Assumption

Certain assumptions, taken into consideration while designing the proposed model, are as follows:

- Unlimited source of returned products from the customer zone.
- Deterministic demand for new and remanufactured components and separate from each other.
- Predefined number of cells and the number is constant during all periods.
- Each machine type has a limited capacity expressed in hours during each time period.
- Recycled products used in manufacturing a new product have high quality level.

5.2.2. Model Parameters and Decision Variables

The notations used for the model are presented followed by the objective function, and constraints.

Sets

$i = \{1, 2, 3 \dots I\}$ Index set of component types.

$m = \{1, 2, 3 \dots M\}$ Index set of machine types.

$c = \{1, 2, 3 \dots C\}$ Index set of cells.

$t = \{1, 2, 3 \dots T\}$ Index set of time periods.

$j = \{1, 2, 3 \dots J\}$ Index of product types.

Parameters

P_i	Unit manufacturing cost of new component *i*
S_i	Setup cost for manufacturing new component *i*
V_i	Unit inventory cost for new component *i*
$D_{i,t}$	Demand for new component *i* in time period *t*
$\overline{P}_i$	Unit remanufacturing cost of recovered component *i*
$\overline{S}_i$	Setup cost for remanufacturing recovered component *i*
$\overline{V}_i$	Unit inventory cost for remanufactured component *i*
$\overline{D}_{i,t}$	Demand for remanufactured component *i* in time period *t*
$B_{i,j}$	Number of component *i* contained in product *j*
UR_i	Average recovering rate of component *i* from all returned products
$AQ_{j,t}$	Unit cost to acquire returned product *j* in time period *t*
$RD_{j,t}$	Unit cost to disassemble returned product *j* in time period *t*
$SD_{j,t}$	Setup cost to disassembling returned product *j* in time period *t*
$IN_{j,t}$	Unit inventory cost for storing returned product *j* in time period *t*
M	A large positive number
$t_{i,m}$	Processing time of the new component *i* on machine type *m*
$\overline{t}_{i,m}$	Processing time of the remanufactured returned component *i* on machine type *m*

$st_{i,m}$	Setup time for manufacturing new component *i*
$\overline{st}_{i,m}$	Setup time for remanufacturing returned component *i*
T_m	Time capacity of one machine of type *m* during one period
LL	Lower size limit
UL	Upper size limit
$R_m^{\mp}$	Relocation cost per machine of type *m*per period
$\in_m$	Procurement cost per machine type m
A_{mt}	Quantity of machine type m available at time period *t*
OV_m	Machine maintenance overhead cost of machine type *m*
Ɣ_m	Operating cost per unit time per machine type *m*
q_{ij}	Unit requirements for component *i* to produce one unit of product *j*
n_i	Unit recycling cost for component i
m_i	Unit disposing cost for component i
M_1	Max percent of end-of-use returns
M_2	Max percent of end-of-life returns

Decision variables

N_{mct}	Number of type *m* machines to present at cell *c* at beginning of time period *t*
Y_{mct}^{+}	Number of type *m* machines added in cell *c* at beginning of time period *t*
Y_{mct}^{-}	Number of type *m* machines removed from cell *c* at beginning of time period *t*

BN_{mt} Number of machines of type m procured at time t

$\hat{A}_{mt}$ Quantity of machine type *m* available at time period *t* after accounting for machines that have been procured

e_{it} Number of new component *i* in inventory at the end of time period *t*

X_{imct} Number of new component *i* processed on machine type *m* in cell *c* in time period *t*

$\overline{e}_{it}$ Number of remanufactured component *i* in inventory at the end of time period *t*

$\overline{X}_{imct}$ Number of remanufactured component *i* processed on machine type *m* in cell *c* in time period *t*

d_{jt} Number of returned product *j* to disassemble in time period *t*

r_{jt} Number of returned product *j* to acquire in time period *t*

$f_{j,t}$ Number of returned product *j* in inventory at the end of time period *t*

θ_{it} = 1, if the system is setup to make new component*i* in time period *t*

= 0, otherwise.

$\overline{\theta}_{it}$ = 1, if the system is setup to remanufacture returned component *i* in time period *t*

= 0, otherwise.

δ_{jt} = 1, if returned product *j* will be disassembled in time period *t*

= 0, otherwise.

z_{imct} = 1, if new component *i* is to be processed on machine type *m* in cell *c* in period *t*

= 0, otherwise.

$\overline{z}_{imct}$ = 1, if returned component *i* is to be processed on machine type *m* in cell *c* in period *t*

= 0, otherwise.

R_{it} Units of returned (end-of-use) component *i* to be remanufactured in time period t

F_{it} Units of end-of-life component *i* to be recycled in time period t

G_{it} Units of component *i* to be disposed in time period t

E_{it} Units of component *i* obtained in the disassembly center in time period t

Objective function

<u>*Minimize F1*</u>

$$\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m=1}^{M} N_{mct}.\,OV_m \tag{1.1}$$

$$+\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m=1}^{M} R_m^{\mp}.\,(Y_{mct}^{+} + Y_{mct}^{-}) \tag{1.2}$$

$$+\sum_{t=1}^{T}\sum_{m=1}^{M} \epsilon_m.\,BN_{mt} \tag{1.3}$$

$$+\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{c=1}^{C}\sum_{m=1}^{M} (P_i * X_{imct} + \overline{P}_i * \overline{X}_{imct}) \tag{1.4}$$

$$+\sum_{t=1}^{T}\sum_{i=1}^{I} (V_i\,.\,e_{it} + \overline{V}_i.\,\overline{e}_{it}) \tag{1.5}$$

$$+\sum_{t=1}^{T}\sum_{i=1}^{I} (S_{it}\,.\,\theta_{it} + \overline{S}_{it}.\,\overline{\theta}_{it}) \tag{1.6}$$

$$+\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{c=1}^{C}\sum_{m=1}^{M} \gamma_m.\,(\,t_{im}.\,X_{imct} + \overline{t}_{im}.\,\overline{X}_{imct}) \tag{1.7}$$

$$+\sum_{t=1}^{T}\sum_{j=1}^{J} AQ_{jt}.\,r_{jt} \tag{1.8}$$

$$+\sum_{t=1}^{T}\sum_{j=1}^{J} SD_{jt}.\delta_{jt}$$ 1.9

$$+\sum_{t=1}^{T}\sum_{j=1}^{J} RD_{jt}.d_{jt}$$ 1.10

$$+\sum_{t=1}^{T}\sum_{j=1}^{J} IN_{jt}.f_{jt}$$ 1.11

$$+\sum_{t=1}^{T}\sum_{i=1}^{J} m_{it}.G_{it}$$ 1.12

$$+\sum_{t=1}^{T}\sum_{i=1}^{J} n_{it}.F_{it}$$ 1.13

Subject to

$$e_{i,t-1}+\sum_{m=1}^{M}\sum_{c=1}^{C} X_{imct}-e_{i,t}=D_{i,t};\ \forall(i,t)$$ 2

$$\sum_{m=1}^{M}\sum_{c=1}^{C} X_{imct}\leq M\theta_{i,t};\ \forall(i,t)$$ 3

$$\bar{e}_{i,t-1}+\sum_{m=1}^{M}\sum_{c=1}^{C} \bar{X}_{imct}-\bar{e}_{i,t}=\bar{D}_{i,t};\ \forall(i,t)$$ 4

$$\sum_{m=1}^{M}\sum_{c=1}^{C} \bar{X}_{imct}\leq M\bar{\theta}_{i,t};\ \forall(i,t)$$ 5

$$f_{j,t}+d_{j,t}-f_{j,t-1}=r_{j,t};\ \forall(j,t)$$ 6

$$\sum_{m=1}^{M}\sum_{c=1}^{C} X_{imct}\leq F_{it};\ \forall(i,t)$$ 7

$$\sum_{m=1}^{M}\sum_{c=1}^{C}\overline{X}_{imct} \leq R_{it};\ \forall(i,t) \tag{8}$$

$$LL \leq \sum_{m=1}^{M} N_{mct} \leq UL;\ \forall(c,t) \tag{9}$$

$$\widehat{A}_{m(t=1)} = A_{m(t=1)} + BN_{m(t=1)};\ \forall(m,t) \tag{10}$$

$$\widehat{A}_{m(t+1)} = \widehat{A}_{mt} + BN_{m(t+1)};\ \forall(m,t) \tag{11}$$

$$\sum_{c=1}^{C} N_{mct} \leq \widehat{A}_{mt};\ \forall(m,t) \tag{12}$$

$$N_{mct} = N_{mc(t-1)} + Y^{+}_{mct} - Y^{-}_{mct};\ \forall(m,c,t) \tag{13}$$

$$\sum_{i=1}^{I}\left(X_{imct}.t_{i,m} + \overline{X}_{imct}.\overline{t}_{i,m}\right) \leq T_m.N_{mct};\ \forall(m,c,t) \tag{14}$$

$$X_{imct} \leq M.z_{imct};\ \forall(i,m,c,t) \tag{15}$$

$$\overline{X}_{imct} \leq M.\overline{z}_{imct};\ \forall(i,m,c,t) \tag{16}$$

$$R_{it} + F_{it} + G_{it} = E_{it}\ , \forall(i,t) \tag{17}$$

$$E_{it} = \sum_{j=1}^{J} B_{ij}\, d_{jt}\ , \forall(i,t) \tag{18}$$

$$R_{it} \leq M_1 E_{it}\ , \forall(i,t) \tag{19}$$

$$F_{it} \leq M_2 E_{it}\ , \forall(i,t) \tag{20}$$

$$G_{it} \leq (1 - M_1 - M_2)E_{it}\ , \forall(i,t) \tag{21}$$

$$d_{j,t} \leq M\delta_{j,t};\ \forall(j,t) \qquad 22$$

$$N_{mct}, BN_{mt}, Y^{-}_{mct}, Y^{+}_{mct}, \widehat{A}_{mt}, e_{it}, X_{imct}, \overline{e}_{it}, \overline{X}_{imct}, d_{jt}, r_{jt}, f_{j,t}, R_{it}, F_{it}, G_{it}, E_{it} \geq 0$$

$$\theta_{it}, \overline{\theta}_{it}, \delta_{jt}, z_{imct}, \overline{z}_{imct} = \{0,1\} \qquad 23$$

The objective function has several terms. The first term (1.1) represents machine maintenance overhead cost. The second term (1.2) represents relocation cost of machines installation and removal. The third term (1.3) represents machine procurement cost. The fourth term (1.4) represents production cost for both new and remanufactured components. The fifth term (1.5) represents holding cost for both new and remanufactured components. Term (1.6) represents setup cost for both new and remanufactured components. The seventh term (1.7) is the machine operating cost. Terms (1.8 to 1.11) represent the cost of acquiring the returned products, setup cost for disassembly operations, disassembly cost, and inventory cost of the returned products respectively. Term (1.12) represents the disposing cost. Term (1.13) represents the recycling cost.

The objective function is subjected to constraints as follows: equation (2) shows that demand of new component type *i*, in each time period *t* is satisfied through internal part production, and/or part inventory carried over from previous period. Equation (3) ensures that there will be no internal production for new component unless if the system is setup to make a new component. Constraint (4) shows that demand of remanufactured component type *i*, in each time period *t* is satisfied through internal part production, and/or part inventory carried over from previous period. Constraint (5) ensures that there will be no internal production for remanufactured component unless if the system is setup to make a remanufactured component. Equation (6) shows that the number of returned product to disassemble in period t and the number of returned product to be kept in inventory to the next period is equal to the number in inventory from the previous period and the number to be acquired in period t. Constraint (7) gives the limit of the new components obtained from the returned products. Constraint (8) gives the limit of the returned components obtained from the returned products. By constraint (9), lower and upper bounds on sizes of cell in terms of the number of machines are enforced. Constraint (10) relates to the machine availability constraint for period 1, taking into consideration the extra machines introduced through the machine procurement option. Constraint (11) relates to the machine availability constraint for the subsequent time periods. Constraint (12) ensures that the total number of machines in each cell will not exceed the number of available machines. Constraint (13) is to ensure that the number of machines type m in current period is equal to the number of machines in the previous period, adding the number of machines moved in and subtracting the number of machines moved out of the cell *c*. Constraint (14) shows the machine capacity constraint. Constraint (15) shows that the number of new components produced internally can be positive only if $z_{imct} = 1$. Constraint (16) shows that the number of remanufactured components produced internally can be positive only if $\overline{z}_{imct} = 1$.Constraint (17) shows that the number of components in disassembly center is equal to the summation of end-of-use, end-of-life and disposed components. Constraint (18) gives the limit of the components obtained from the returned products. Constraint (19) gives the limit of end-of-use components obtained from the returned products. Constraint (20) gives the limit of end-of-life components obtained from the returned products. Constraint (21) gives the limit of disposed components. Constraints (22) is a logical constraint for disassembly. Constraint (23) is the logical binary and non-negativity integer requirements on the decision variable.

5.3. Numerical example

In this section, we apply and test our model presented in the previous section through a numerical example. This example consists of 2 types of components, 2 types of machines, 2 types of products, 2 cells, and 2 time periods.

5.3.1. Input data

Tables 5 – 1 to 5 – 7 represent the input data for the numerical example. Table 5 – 1 and 5 – 2 represent the demand and the cost associated with the new and remanufactured components respectively. Table 5 – 3 shows the costs of the returned products. In Table 5 – 4 the number of components contained in the returned products is shown. Processing time and setup time for both new and remanufactured components are represented in Tables 5 – 5 and 5 – 6. Table 5 – 7 shows machine costs. In addition to below input data, M1=0.5, M2=0.3, disposing cost is 60 for the first component and 70 for the second one, and the recycling cost is 300 for the first component and 400 for the second one. The input data are based on the work by Chen and Abrishami (2014).

Table 5-1 Cost and demand for new component

Period	Cost and demand	Component type	
		1	2
1	Production cost	200	300
	Setup cost	400	500
	Inventory cost	10	8
	Demand	200	600
2	Production cost	200	300
	Setup cost	400	500
	Inventory cost	10	8
	Demand	300	600

Table 5-2 Cost and demand for remanufactured component

Period	Cost and demand	Component type	
		1	2
1	Production cost	100	150
	Setup cost	200	250
	Inventory cost	5	5
	Demand	100	250
2	Production cost	100	150
	Setup cost	200	250
	Inventory cost	5	5
	Demand	250	300

Table 5-3 Data for returned products

Period	Cost							
	Product 1				Product 2			
	Disass.	Setup.	Invent.	Acq.	Disass.	Setup.	Invent.	Acq.
1	60	200	5	50	80	250	5	60
2	80	150	6	40	50	150	6	30

Table 5-4 Number of components contained in the returned products

Component type Product type	1	2
1	10	15
2	13	9

Table 5-5 Processing and setup time for new component

Machine type		Component type	
		1	2
1	Processing time	6	4
	Setup time	40	40
2	Processing time	4	8
	Setup time	60	60

Table 5-6 Processing and setup time for remanufactured component

Machine type		Component type	
		1	2
1	Processing time	3	2
	Setup time	20	20
2	Processing time	2	4
	Setup time	30	30

Table 5-7 Data for machines

Cost	Machine type	
	1	2
Operating cost	50	50
Overhead cost	70	40
Procurement cost	400	300
Relocation cost	40	80
Capacity	500	100

5.3.2. Results and discussion

Table 5 – 8 shows the production routes, quantity and inventory for each component in each time period. For example, the new component type 2 has a demand of 600 units for the first period, but there is a need to produce 645 units, the excess quantity (45 units) will be kept in inventory to satisfy a portion of the demand in period 2; the demand in period 2 is 600, but the production quantity is 555 units, obviously there is a shortage of 45 units and this shortage will be satisfied from the inventory. There are two routes to be used to produce 645 units of the new component type 2 in the first period, the fist route is to produce 270 units by machine type 1 in cell 1, while the second route is to produce 375 units by machine type 1 in cell 2. On the other hand, the quantity of 555 units to be produce in the second period should be produced by only one rout which is by machine type 1 in cell 2.

Figure 5 – 2 shows the allocation and the number of each machine type for each cell. For example, there is a need to have 4 machines of type 1 in cell 2 for the first period, and for the second period this quantity should be increased by one, so, 5 machines of type 1 should be exist in cell 2 for the second period.

Table 5-8 Production routes, quantities and inventory for both components

Routes and Quantities	*Production*	*Demand*	*Inventory*
New Components			
i1 m1 c1 t1 209	209	200	9
i1 m1 c1 t2 284 i1 m1 c2 t2 7	291	300	0
i2 m1 c1 t1 270 i2 m1 c2 t1 375	645	600	45
i2 m1 c2 t2 555	555	600	0
Remanufactured Components			
i1 m1 c1 t1 54 i1 m2 c2 t1 50	104	100	4
i1 m1 c1 t2 68 i1 m1 c2 t2 78	146	150	0
i2 m1 c1 t1 2 i2 m1 c2 t1 250	252	250	2
i2 m1 c1 t2 296 i2 m1 c2 t2 2	298	300	0

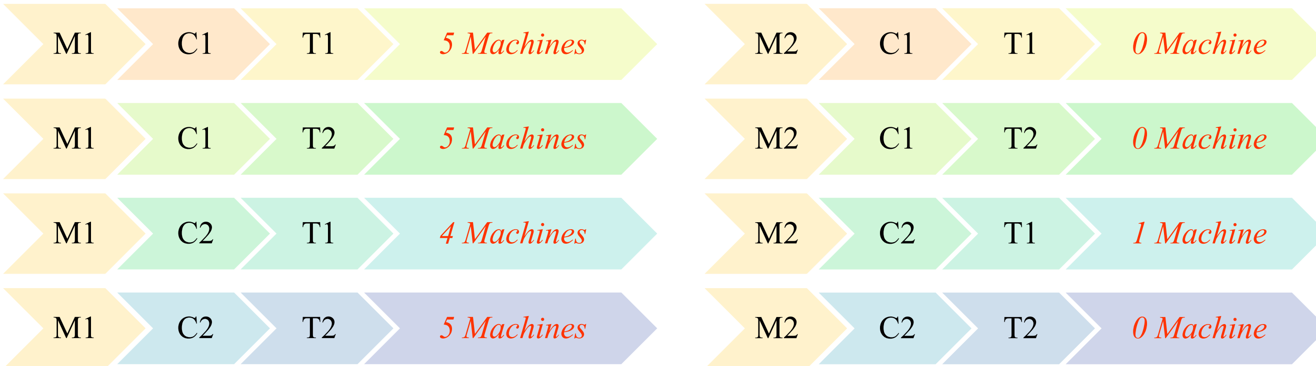

Figure 5-2 Allocation and quantity of machine types

All the information about the quantity of returned products, and the quantity of components that can be obtained from these returned products is found in Table 5 – 9. For example, 86 units of product type 1 should be acquired in the first period, and this quantity leads to have 740 units of component type 2 in the disassembly center for the first period, the 740 units could be divided based on the quality percentage into: 148 to be disposed, 370 to be recycled, and 222 could be used to produce a remanufactured components.

The *Reconfigurable Hybrid Manufacturing-Remanufacturing System* under consideration is a reconfigurable CMS, which should provide the exact required functionality and capacity. The modular structure of a Reconfigurable Manufacturing System (*i.e. a reconfigurable CMS; in this case*) enables the system to integrate/remove new software/hardware modules without affecting the rest of the system (Niroomand et al., 2012). In this example, in order to produce the required demand for both the new products and the remanufactured products, there is a need for 9 machines of type 1 (5 in cell 1 and 4 in cell 2) and 1 machine of type 2 (0 in cell1 and 1 in cell 2) for the first period. In period 2, there is a need to add 1 extra machine of type 1 for cell 2, also, there is a need to remove 1 machine of type 2 from cell 2. Hence, this illustrates that along with production planning issues, the proposed model additionally assists the production managers how to configure/reconfigure the *Hybrid Cellular Manufacturing-Remanufacturing System* for different production periods (e.g. how many machines from each type are needed for each period in each cell).

Table 5-9 Returned products quantities and obtained components

	Quantity in Diss. Ass. Center	Disposed	Recycled	Remanufactured
Comp 1 T1	860	172	430	258
T2	740	148	370	222
Comp 2 T1	1290	258	645	387
T2	1110	222	555	333
There is a need to acquire *86* units of Product type 1 in Period 1, and to acquire *74* units in Period 2, *zero* units of Product type 2 in Period 1&2.				

5.4. Independent cell formation Model (F2) and Discussion of the Results

One of the main characteristics of the cellular manufacturing system is to have independent cells. To enforce the model to build independent cells, two constraints should be added. These are as follows:

$$\sum_{c=1}^{C} z_{imct} = 1;\ \forall(i,m,t) \qquad (24)$$

$$\sum_{c=1}^{C} \overline{z}_{imct} = 1;\ \forall(i,m,t) \qquad (25)$$

F2 is the new model with constraints 24 and 25. Solving F2 with the same data of the above mentioned numerical example yields the following results: Table 5 – 10 shows the production routes, quantity and inventory for each component in each time period. One can see how independent cells could be realized by adding constraints 24 and 25. New component type 1 and remanufactured components type 1 and 2 are to be produced in cell 1 for the first two periods, while the new component type 2 is to be produced in cell 2 for the next two periods. Figure 5 – 3 shows the allocation and the number of each machine type for each cell. There is no need for machine type 2, and 10 machines from type 1 are needed; 5 in each cell for the two periods. Table 5 – 11 shows that there is a need to acquire 80 units of product type 1 in each period and there is no need to acquire any units of product type 2.

Table 5-10 Production routes, quantities and inventory for both components

Routes and Quantities	*Production*	*Demand*	*Inventory*
New Components			
i1 m1 c1 t1 200	200	200	0
i1 m1 c1 t2 300	300	300	0
i2 m1 c2 t1 600	600	600	0
i2 m1 c2 t2 600	600	600	0
Remanufactured Components			
i1 m1 c1 t1 217	217	100	117
i1 m1 c1 t2 33	33	150	0
i2 m1 c1 t1 250	250	250	0
i2 m1 c1 t2 300	300	300	0

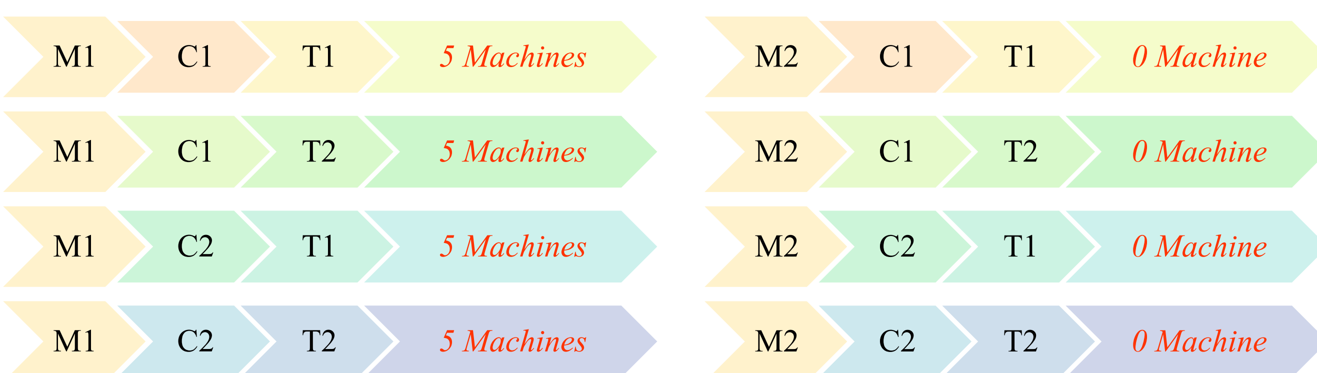

Figure 5-3 Allocation and quantity of machine types

Table 5-11 Returned products quantities and obtained components

	Quantity in Diss. Ass. Center	Disposed	Recycled	Remanufactured
Comp 1 T1	800	160	400	240
T2	800	160	400	240
Comp 2 T1	1200	240	600	360
T2	1200	240	600	360
There is a need to acquire *80* units of Product type 1 in Period 1, and to acquire *80*units in Period 2, *zero* units of Product type 2 in Period 1&2.				

5.5. Computational experiments

The models were solved using IBM ILOG CPLEX Optimization Studio 12.2/OPL. Table 12 shows 10 different scenario problems, for each scenario the number of component types, the number of time periods, the number of machine types, the number of returned products type, and the number of cells are reported. All of the computational experiments were performed on Intel® core ™ 3.30 GHz workstation, with the problems being solved using IBM ILOG CPLEX Optimization Studio 12.2/OPL. The number of constraints and the number of variables for each problem scenario are also presented in Table 5 – 12.

Table 5-12 Different problem scenarios

Problem scenario	Number of component types	Number of time periods	Number of machine types	Number of products	Number of cells	Number of variables		Number of constraints	
						F1	F2	F1	F2
1.	2	2	2	2	2	145	145	126	142
2.	3	2	3	2	3	347	347	260	396
3.	3	3	3	2	3	520	520	399	453
4.	4	3	3	3	3	664	664	496	568
5.	4	3	4	2	4	1057	1057	728	824
6.	4	3	4	2	5	1285	1285	862	958
7.	4	3	4	3	5	1297	1297	868	964
8.	5	4	5	3	5	2089	2089	1381	1581
9.	5	6	5	2	4	3109	3109	2077	2377
10.	5	6	5	4	4	3157	3157	2101	2401

The solving ability of CPLEX was tested by increasing problem size through the use of both models F1 and F2. Comparisons are made between the computational times taken and the total system costs. In Table 5 – 13, the computational results obtained by solving both models F1 and F2 are shown as well as the objective function values obtained. OBJF1 and OBJF2 are the objective functions obtained from F1 and F2 respectively. The additional percentage cost (OBJ_{F1-F2}) of forming independent cells can be calculated as: $OBJ_{F1-F2} = 100*(OBJ_{F2}/OBJ_{F1} - 1)$. The computational time obviously increases while increasing the problem size for both of the models. On the other hand, one can see that F1 needs less computational time than F2 in solving the same problem. Regarding F1, problems 1 – 5 solved within less than a minute, problems 6 – 8 solved within 10 minutes, while problems 9 and 10 could not be solved to optimality, we obtained a solution with 0.7% optimality gap for problem 9 after 1.5 hours; CPLEX stopped solving the problem due to insufficient memory. For the second model, F2, problems 1 – 3 solved within less than a minute, problems 4 and 5 solved within 15 minutes, problems 6 and 7 solved within 5 hours, while problems 9 and 10 could not be solved to optimality, we obtained a solution with 0.7% optimality gap for problem 8 after 1.4 hours. No optimal solution was obtained after 5 hours for problem 10 by using both models F1 and F2. By this, we can conclude that the branch and cut algorithm of CPLEX is unable to produce good quality solution in reasonable computational times for large-scale problems for the proposed models.

The additional costs, when implementing independent cells, are also shown in Table 5 – 13. Since no optimal solution was found for problems 9 and 10, the best integer solution found so far is used as a means of comparing the costs from models F1 and F2. A comparison of the optimal costs from models F1 and F2 shows that the cost impact of implementing independent cells is very low for all the problems solved. The highest additional percentage cost is 0.479% for problem 4, followed by 0.285% for problem 2 and the lowest additional percentage cost is 0.011 for problem 6.

Table 5-13 Summary of computational results

	Model F1		Model F2		
Problem scenario	OBJ_{F1}	Time elapsed (Seconds)	OBJ_{F2}	Time elapsed (Seconds)	OBJ_{F1-F2} (%)
1.	1849870	0.33	1852135	0.36	0.122
2.	2504515	1.84	2511660	2.95	0.285
3.	3569141	13.32	3573354	1.72	0.118
4.	4634253	6.58	4656449	925	0.479
5.	4362689	4.99	4363176	781	0.011
6.	4362318	163	4362988	9087	0.015
7.	4351566	403	4352226	17771	0.015
8.	7903885	161	7910770*	5000*	0.087
9.	10822527*	5485*	N.A.	N.A.	N.A.
10.	N.A.	N.A.	N.A.	N.A.	N.A.

5.6. Chapter Summary

In this chapter, a mixed integer linear programming model for designing a sustainable reconfigurable cellular sustainable hybrid manufacturing-remanufacturing enterprise has been presented. The most commonly used two recovery options, namely remanufacturing and recycling, have been introduced. The model proposed has potential applications to SMS designers; particularly for designing Reconfigurable Cellular Hybrid Manufacturing-Remanufacturing Systems. To the best of the authors' knowledge this is the first integrated model, which considers CMSs and HMRSs simultaneously while featuring remanufacturing, recycling, and disposal options. The overall objective of the model is to minimize the total cost of the three main categories of costs; 1) Machine cost: maintenance and overhead costs, relocation costs of installation and removal of machines, machine procurement costs, and machine operating costs, 2) Costs associated with manufacturing, remanufacturing, recycling, and disposing: production costs for both new and remanufactured components, holding cost for new components, holding cost for remanufactured components, setup cost for new components, setup cost for remanufactured components, recycling cost for end-of-life components, and disposing costs for components that couldn't be used for any further usage, 3) Costs associated with returned products for remanufacturing: cost of acquiring the returned products, setup cost for disassembly operations, disassembly cost, and inventory cost of the returned products.

Chapter 6

6. Carbon footprint and facility location for designing reverse logistics network introducing a hybrid manufacturing-remanufacturing systems

6.1. Introduction

In this chapter, a mathematical model is designed to minimize the carbon foot prints and the total cost which contains the opening costs for different centers and the transportation costs between these centers. Figure 6 – 1, shows the material flow and the required centers to build the hybrid manufacturing-remanufacturing system. Returned products are to be collected from the customer zones while each customer zone has its own demand from both types of new and remanufactured components, thus final components is to be transferred from the manufacturing facilities to the customer zones in order to satisfy each customer zone demand. After collecting returned products from the customer zones by collection centers, which every center needs to send them to the opened disassembly centers in order to disassemble, test, and sort to send the output components into three main groups. The first group, the end-of-life components, to be send to the opened recycled centers to recycle them and resend them as raw material to the opened manufacturing facilities, hence to be used to produce the new components, while the second group, end-of-use components, are to be send to the opened manufacturing facilities for remanufacturing, the third group is the components which are not valid for any further use, need to be disposed by any opened disposal centers.

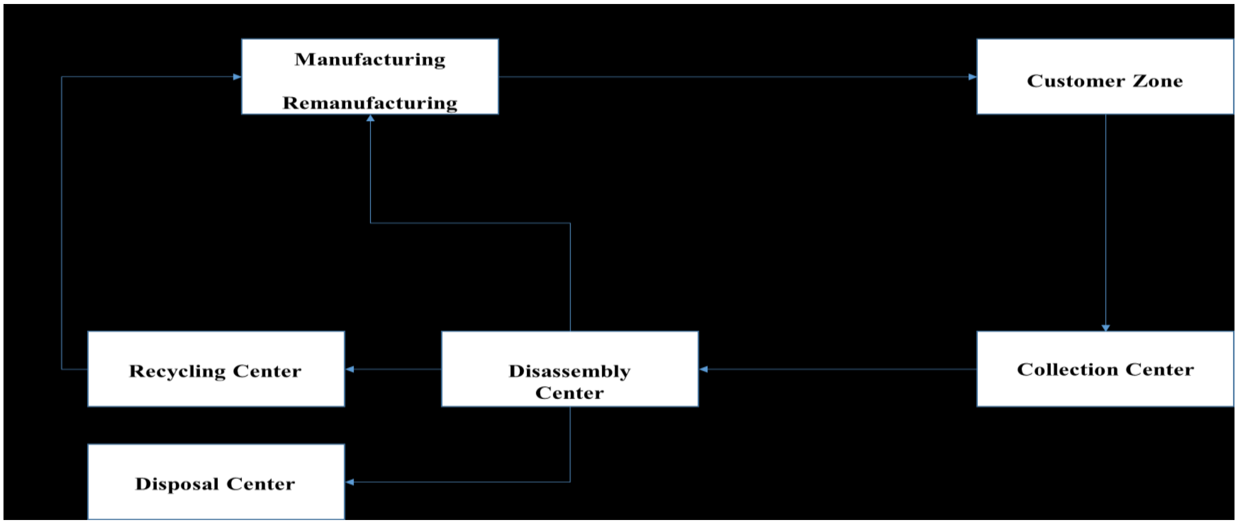

Figure 6-1 Material flow for the proposed hybrid manufacturing remanufacturing system

6.2. The Proposed Mathematical Model

In this section a mixed linear integer programming (MILP) model for designing the system mentioned in the above section is proposed. Assumptions, parameters, decision variables, formulation, and a detailed description of the MILP model are presented as well.

6.2.1. Model Assumptions

Certain assumptions have been taken into accounts while formulating the proposed MILP model as follows:

- Unlimited source of returned products.
- Single period, multi products, and multi components.
- The demand for each component type and for each customer zone is known and deterministic.

- The demand for each component type from new material and from remanufactured products are separate from each other.
- All distances between the candidate centres, all related costs, carbon emission, and capacities are predefined.
- Multi existing customer zones.

6.2.2. Model Parameters and Decision Variables

The notation used and the proposed MILP mathematical formulation is presented below:

Sets

c= {1, 2, 3…C}	Index set of collection centers.
b= {1, 2, 3…B}	Index set of disassembly centers.
r= {1, 2, 3…R}	Index set of recycling centers.
p= {1, 2, 3…P}	Index set of disposal centers.
m= {1, 2, 3…M}	Index set of manufacturing centers.
u= {1, 2, 3…U}	Index set of customer zones.
i= {1, 2, 3…I}	Index set of component types.
j= {1, 2, 3…J}	Index set of product types.

Parameters

f_c	Fixed cost to set up collection center ***c***

f_m	Fixed cost to set up manufacturing center ***m***
f_b	Fixed cost to set up disassembly center ***d***
f_r	Fixed cost to set up recycling center ***r***
f_p	Fixed cost to set up disposal center ***p***
c_i	Transportation cost for a unit component per a unit distance
c_j	Transportation cost for a unit product per a unit distance
CAP_{im}	Manufacturing capacity of new component ***i*** in manufacturing center ***m***
$\overline{CAP_{im}}$	Manufacturing capacity of remanufactured component ***i*** in manufacturing center ***m***
CAP_{jc}	Collection capacity of product ***j*** in collection center ***c***
CAP_{jb}	Disassembly capacity of component ***j*** in disassembly center ***b***
CAP_{ir}	Recycling capacity of component ***i*** in recycling center ***r***
CAP_{ip}	Disposal capacity of component ***i*** in disposal center ***p***
D_{iu}	Demand for new component ***i*** from the customer zone ***u***
$\overline{D_{iu}}$	Demand for remanufactured component ***i*** from the customer zone ***u***
$B_{i,j}$	Number of component ***i*** contained in product ***j***
M_1	Max percent of end-of-use returns

M_2 Max percent of end-of-life returns

d_{mu} Distance between manufacturing center ***m*** and customer zone ***u***

d_{uc} Distance between customer zone ***u*** and collection center ***c***

d_{cb} Distance between collection center ***c*** and disassembly center ***b***

d_{bp} Distance between disassembly center ***b*** and disposal center ***p***

d_{br} Distance between disassembly center ***b*** and recycling center ***r***

d_{bm} Distance between disassembly center ***b*** and manufacturing center ***m***

d_{rm} Distance between recycling center ***r*** and manufacturing center ***m***

φ Cost of carbon credits in $ per ton CO_2

CO_2^{cap} legal limit of the CO_2 quantity can be emitted each year

E CO_2 transportation emissions factor per unit of returned product/ component in g/km

LE_m CO2 equivalent per manufacturing center location opened

LE_c CO2 equivalent per collection center location opened

LE_b CO2 equivalent per disassembly center location opened

LE_r CO2 equivalent per Recycling center location opened

LE_p CO2 equivalent per Disposal center location opened

Decision variables

y_m $= \begin{cases} 1 \text{ if a manufacturing center is open at location } \boldsymbol{m}; \\ 0 \text{ otherwise} \end{cases}$

y_c $= \begin{cases} 1 \text{ if a collection center is open at location } \boldsymbol{c}; \\ 0 \text{ otherwise} \end{cases}$

y_b $= \begin{cases} 1 \text{ if a disassembly center is open at location } \boldsymbol{b}; \\ 0 \text{ otherwise} \end{cases}$

y_r $= \begin{cases} 1 \text{ if a recycling center is open at location } \boldsymbol{r}; \\ 0 \text{ otherwise} \end{cases}$

y_p $= \begin{cases} 1 \text{ if a disposal center is open at location } \boldsymbol{p}; \\ 0 \text{ otherwise} \end{cases}$

x_{imu} Quantity of new components shipped from manufacturing center ***m*** to customer zone ***u***

$\overline{x_{\imath mu}}$ Quantity of remanufactured components shipped from manufacturing center ***m*** to customer zone ***u***

x_{juc} Quantity of product ***j*** shipped from customer zone ***u*** to collection center ***c***

x_{jcb} Quantity of product ***j*** shipped from collection center ***c*** to disassembly center ***b***

x_{ibp} Quantity of component ***i*** shipped from disassembly center ***b*** to disposal center ***p***

x_{ibr} Quantity of component ***i*** shipped from disassembly center ***b*** to recycling center ***r***

x_{ibm} Quantity of component ***i*** shipped from disassembly center ***b*** to manufacturing center ***m***

x_{irm} Quantity of components shipped from recycling center ***r*** to manufacturing center ***m***

CO_2 Amount of carbon dioxide (CO_2) emitted currently in tons

Objective function

Minimize

$$\sum_{c=1}^{C} f_c . y_c + \sum_{b=1}^{B} f_b . y_b + \sum_{r=1}^{R} f_r . y_r + \sum_{p=1}^{P} f_p . y_p + \sum_{m=1}^{M} f_m . y_m + \quad [1]$$

$$\sum_{i=1}^{I} \sum_{m=1}^{M} \sum_{u=1}^{U} c_i . d_{mu} . (x_{imu} + \overline{x_{\imath mu}}) + \sum_{j=1}^{J} \sum_{u=1}^{U} \sum_{c=1}^{C} c_j . d_{uc} . x_{juc}$$
$$+ \sum_{j=1}^{J} \sum_{c=1}^{C} \sum_{b=1}^{B} c_j . d_{cb} . x_{jcb} + \sum_{i=1}^{I} \sum_{b=1}^{B} \sum_{p=1}^{P} c_i . d_{bp} . x_{ibp}$$
$$+ \sum_{i=1}^{I} \sum_{b=1}^{B} \sum_{r=1}^{R} c_i . d_{br} . x_{ibr} + \sum_{i=1}^{I} \sum_{b=1}^{B} \sum_{m=1}^{M} c_i . d_{bm} . x_{ibm} \quad [2]$$
$$+ \sum_{i=1}^{I} \sum_{r=1}^{R} \sum_{m=1}^{M} c_i . d_{rm} . x_{irm}$$

$$+ \varphi\left(CO_2 - CO_2^{cap}\right) \quad [3]$$

Subject to

$$\sum_{m=1}^{M} x_{imu} = D_{iu} \quad \forall i, u \quad [4]$$

$$\sum_{m=1}^{M} \overline{x_{\imath mu}} = \overline{D_{\imath u}} \quad \forall i, u \quad [5]$$

$$\sum_{b=1}^{B} x_{jcb} = \sum_{u=1}^{U} x_{juc} \quad \forall j, c \quad [6]$$

$$\sum_{m=1}^{M} x_{irm} = \sum_{b=1}^{B} x_{ibr} \quad \forall i, r \tag{7}$$

$$\sum_{u=1}^{U} \overline{x_{\imath mu}} = \sum_{b=1}^{B} x_{ibm} \quad \forall i, m \tag{8}$$

$$\sum_{u=1}^{U} x_{imu} = \sum_{r=1}^{R} x_{irm} \quad \forall i, m \tag{9}$$

$$\sum_{m=1}^{M} x_{ibm} \leq M_1 . (\sum_{j=1}^{J} \sum_{c=1}^{C} B_{ij} . x_{jcb}) \quad \forall i, b \tag{10}$$

$$\sum_{r=1}^{R} x_{ibr} \leq M_2 . (\sum_{j=1}^{J} \sum_{c=1}^{C} B_{ij} . x_{jcb}) \quad \forall i, b \tag{11}$$

$$\sum_{p=1}^{P} x_{ibp} = (1 - M_1 - M_2) . (\sum_{j=1}^{J} \sum_{c=1}^{C} B_{ij} . x_{jcb}) \quad \forall i, b \tag{12}$$

$$\sum_{m=1}^{M} x_{irm} \leq CAP_{im} * y_m \tag{13}$$

$$\sum_{b=1}^{B} x_{ibm} \leq \overline{CAP_{\imath m}} * y_m \tag{14}$$

$$\sum_{u=1}^{U} x_{juc} \leq CAP_{jc} * y_c \tag{15}$$

$$\sum_{c=1}^{C} x_{jcb} \leq CAP_{jb} * y_b \tag{16}$$

$$\sum_{b=1}^{B} x_{ibr} \leq CAP_{ir} * y_r \tag{17}$$

$$\sum_{b=1}^{B} x_{ibp} \leq CAP_{ip} * y_p \tag{18}$$

$$\sum_{i=1}^{I} \sum_{m=1}^{M} \sum_{u=1}^{U} E . d_{mu} . x_{imu} + \sum_{i=1}^{I} \sum_{m=1}^{M} \sum_{u=1}^{U} E . d_{mu} . \overline{x_{\imath mu}} +$$
$$\sum_{j=1}^{J} \sum_{u=1}^{U} \sum_{c=1}^{C} E . d_{uc} . x_{juc} + \sum_{j=1}^{J} \sum_{c=1}^{C} \sum_{b=1}^{B} E . d_{cb} . x_{jcb} + \tag{19}$$
$$\sum_{i=1}^{I} \sum_{b=1}^{B} \sum_{p=1}^{P} E . d_{bp} . x_{ibp} + \sum_{i=1}^{I} \sum_{b=1}^{B} \sum_{r=1}^{R} E . d_{br} . x_{ibr} +$$

$$\sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{m=1}^{M} E\,.\,d_{bm}.\,x_{ibm} + \sum_{i=1}^{I}\sum_{r=1}^{R}\sum_{m=1}^{M} E\,.\,c_{rm}\,.\,x_{irm} + \sum_{m=1}^{M} LE_{m}.\,y_{m} + \sum_{c=1}^{C} LE_{c}\,.\,y_{c} + \sum_{b=1}^{B} LE_{b}\,.\,y_{b} + \sum_{r=1}^{R} LE_{r}\,.\,y_{r} + \sum_{p=1}^{P} LE_{p}\,.\,y_{p} = CO_2$$

$$y_m, y_c, y_b, y_r, y_p \in [0,1] \qquad [20]$$

$$x_{imu}, \overline{x_{imu}}, x_{juc}, x_{jcb}, x_{ibp}, x_{ibr}, x_{ibm}, x_{irm}, x_{imu}, \overline{x_{imu}}, x_{juc}, x_{jcb}, x_{ibp}, x_{ibr}, x_{ibm}, x_{irm}, CO_2 \geq 0 \qquad [21]$$

The objective function is to minimize the overall costs, divided into three main categories as follow: The first term represents the fixed opening cost of collection, disassembly, recycling, disposal, and manufacturing centers respectively, transportation cost of the components and products between all centers are shown in the second term, the third term is the cost of the carbon emissions, which is Cost of carbon credits in $ per ton CO_2 multiply by the difference between the amount of carbon dioxide (CO_2) emitted currently in tons and CO_2^{cap}; legal limit of the CO_2 quantity can be emitted each year. CO_2^{cap} is a constant number that would not change the values of the decision variables. However, this constant is still included in the objective function since it is needed to determine its value. An example to this legal limit; the Quebec cap and trade (C&T) system is intended for companies in the industrial and electricity sectors that emit 25,000 metric tons or more of CO_2 equivalent annually (ex: aluminum smelters, cement factories, electricity producers, etc.), as well as fossil fuel distributors that must cover GHG (Greenhouse Gas) emissions associated with all products they distribute in Québec (gasoline, diesel fuels, propane, natural gas and heating oil) (Gouvernement du Québec, 2016).

Constraint (4) and (5) ensure that the quantity of new and remanufactured components transferred from the manufacturing centers to customer zones would equal to the demand of each type respectively. Constraints 6-9 are the balance equations for the collection, disassembly, recycling, disposal, and manufacturing centers: the quantities that enter to these centers are equal to the amount of products/components that leave the centers. Constraints (10), (11), and (12) restricts the amount of components transferred from the disassembly center to the manufacturing, recycling, and disposal centers respectively based on the recovery rates. Quantities transferred from one center to another one should not exceed the recipient center's capacity and this satisfied through constraints 13-18. CO2 emissions from transportation and facilities are calculated by constraint 19. Constraint (20) and (21) is the logical binary and non-negativity integer requirements.

6.3. Illustrative Example

In this section the model will be illustrated through a detailed example. The considered network includes two customer zones (u1, u2), two potential collection centers (c1, c2), three potential disassembly centers (b1, b2, and b3), two potential recycling centers (r1, r2), two potential disposal centers (p1, p2), three potential manufacturing centers (m1, m2, and m3), three components types, and two types of returned products. The objective of this network design is to specify which candidate centers to be opened and to determine the quantity of components and products flow between the network facilities, also, the amount of carbon dioxide (CO_2) emitted currently in tons. Tables 1-16 present the example input data. Table 6 – 1 shows the setup cost for each potential center. Tables 6 – 2 to 6 – 6 give the capacity for each manufacturing, disposal, recycling, disassembly, and collection centers respectively. Distances between every two different centers are shown in tables 6

– 7 to 6 – 13. CO2 equivalent per center location opened are shown in table 6 – 14. Demand for each component type from each customer zone are shown in table 6 – 15. Table 6 – 16 shows the number of component i contained in product j. Percentage rates of returned products are as follows: M1= 0.3, M2= 0.5. CO_2 transportation emissions factor per unit of returned product/component in g/km = 0.01, and the Cost of carbon credits in $ per ton CO_2 = 10, while the legal limit of the CO_2 quantity can be emitted each year = 5000. Transportation cost per components 1, 2, and 3 are 2, 3, and 4 respectively, while transportation cost per Products 1 and 2 are 8and 9 respectively.

Table 6-1 Setup cost for each center

Collection centers	c1	8000
	c2	10000
Disassembly centers	b1	30000
	b2	20000
	b3	25000
Recycling centers	r1	20000
	r2	25000
Disposal centers	p1	10000
	p2	12000
Manufacturing centers	m1	60000
	m2	50000
	m3	55000

Table 6-2 Manufacturing facility capacity in terms of components

	Manuf. 1	Manuf. 2	Manuf. 3
New Comp. 1	1000	800	900
New Comp. 2	500	300	400
New Comp. 3	700	900	800
Rem. Comp.1	400	300	350
Rem. Comp.2	250	300	400
Rem. Comp.3	300	200	350

Table 6-3 Disposal centers capacity in terms of components

	Disposal 1	Disposal 2
Comp. 1	600	550
Comp. 2	600	700
Comp. 3	500	650

Table 6-4 Recycling centers capacity in terms of components

	Recycling 1	Recycling 3
Comp. 1	500	400
Comp. 2	250	200
Comp. 3	600	500

Table 6-5 Disassembly centers capacity in terms of products

	Disass. 1	Disass. 2	Disass. 3
Product 1	700	600	650
Product 2	800	600	700

Table 6-6 Collection centers capacity in terms of products

	Collection 1	Collection 2
Product 1	100	100
Product 2	600	400

Table 6-7 Distances between disassembly and manufacturing centers

	Manuf. 1	Manuf. 2	Manuf. 3
Disass. 1	200	180	190
Disass. 2	180	200	180
Disass. 3	200	150	170

Table 6-8 Distances between disassembly and disposal centers

	Disposal 1	Disposal 2
Disass. 1	200	150
Disass. 2	200	190
Disass. 3	250	180

Table 6-9 Distances between disassembly centers and recycling centers

	Recycling 1	Recycling 2
Disass. 1	150	150
Disass. 2	200	190
Disass. 3	200	250

Table 6-10 Distances between disassembly centers and collection centers

	Collection 1	Collection 2
Disass. 1	200	200
Disass. 2	250	120
Disass. 3	150	200

Table 6-11 Distances between manufacturing facilities and customer zones

	Custom. zone 1	Custom. zone 2
Manuf. 1	320	300
Manuf. 2	130	150
Manuf. 3	200	300

Table 6-12 Distances between manufacturing and recycling centers

	Recycling 1	Recycling 2
Manuf. 1	100	150
Manuf. 2	150	100
Manuf. 3	120	140

Table 6-13 Distances between collection centers and customer zones

	Collection 1	Collection 2
Custom. zone 1	200	200
Custom. zone 2	160	160

Table 6-14 CO2 equivalent per center location opened

	Center 1	Center 2	Center 3
Disassembly	10	10	10
Recycling	40	40	-
Disposal	50	50	-
Manufacturing	20	20	20
Collection	20	20	-

Table 6-15 Demand for each component type from each customer zone

	Custom. zone 1	Custom. zone 2
New Comp. 1	300	400
New Comp. 2	100	100
New Comp. 3	400	200
Rem. Comp.1	100	200
Rem. Comp.2	200	150
Rem. Comp.3	200	100

Table 6-16 Number of component i contained in product j

	Comp. 1	Comp. 2	Comp. 3
Product 1	10	15	15
Product 2	30	20	10

The proposed model is solved using IBM ILOG CPLEX Optimization Studio 12.2/OPL. Number of constraints and variables for the illustrative example are l108 and 151 respectively. The optimal total cost (objective function value) is obtained as $3540872. While, the amount of carbon dioxide (CO2) emitted currently in tons is equal to CO2=10868. The second candidate of the collection centers, the first candidate of the disassembly centers, both candidates of the recycling centers, the second candidate of the disposal centers and two of the potential manufacturing centers are opened as shown in table 6 – 17.

Table 6-17 Decisions on potential centers

	Center 1	Center 2	Center 3
Disassembly	Open		
Recycling	Open	Open	-
Disposal		Open	-
Manufacturing		Open	Open
Collection		Open	-

The optimal results; the opened centers and the quantities of products and components flow between the centers are shown in figure 6 – 2. Returned products; 63 units of product 1 and 26 units of product 2 are to be collected from the customer zone 2 by collection center 2 and then transferred these quantities to disassembly center 1, which disassemble these products into components and the three type of output components are to be transferred to disposal, recycling, and manufacturing centers as follow: 282 units of component 1, 293 units of component 2, and 241 units of component 3 are to be transferred to disposal center 2. While the quantities transferred to the recycling centers are as follows: 700 units of component 1 (300 to recycling center 1 and 400 to recycling center 2) 200 units of component 2 to recycling center 2, and 600 units of component 3 (100 to recycling center 1 and 500 to recycling center 2). The quantities received by the hybrid manufacturing-remanufacturing centers from the disassembly center in order to produce the remanufactured components are as follows: 300 units of component 1 to center 2, 350 units of component 2 (300 to center 2 and 50 units to center 3), and 300 units of components 3 (200 to center 2 and 100 units to center 3). The remanufactured components produced by the hybrid manufacturing-remanufacturing centers and transferred to the customer zones are as follows: 300 units of component 1 (100 from center 2 to customer zone 1, and 200 from center 2 to customer zone 2), 350 units of component 2 (150 from center 2 to customer zone 1, 50 from center 3 to customer zone 1, 150 from center 2 to customer zone 2) and 300 units of component 3 (100 from center 2 to customer zone 1, 100 from center 3 to customer zone 1, and 100 from center 2 to customer zone 2). In order from the hybrid manufacturing-remanufacturing centers to satisfy the demand for the new components, then they should receive (from the solution of this example only center 2 will be responsible to make the new components) the following units from the recycling centers: 700 units of component 1 (400 from recycling center 2 and 300 from recycling center 1), 200 units of component 2from recycling center 2, and 600 units of component 3 (500 from recycling center 2 and 100 from recycling center 1). Quantities of new components transferred from the hybrid manufacturing-remanufacturing center 2 to the customer zones are as follows: 700 units of component 1 (300 to customer zone 1 and 400 to customer zone 2), 200 units of component 2 (100 to customer zone 1 and 100 to customer zone2), and 600 units of component 3 (400 to customer zone 1 and 200 to customer zone 2).

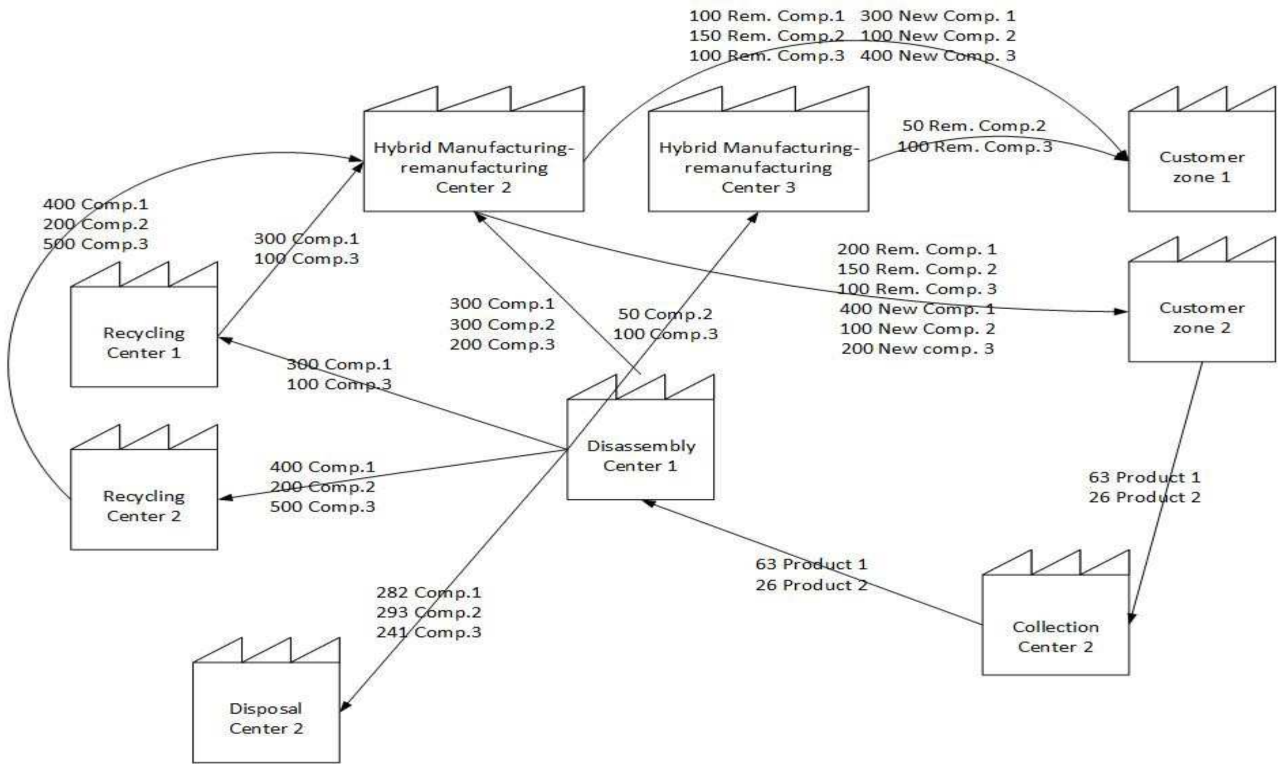

Figure 6-2 Optimal results for illustrative example

6.4. Sensitivity Analysis

Both M1 (maximum percent of end-of-use returns) and M2 (maximum percent of end-of-life returns) are crucial parameters in the reverse logistics network, since both reflects the quality of returned products. In order to observe the effect of these two parameters on the objective function value, sensitivity analysis is implemented. Changing in the objective function value is observed while changing the values of both parameters. First scenario, the value of M2 set to a fix value 0.3 and M1 has been changed from 0.3- 0.7, figure 6 – 3 shows the result. Second scenario, the value of M1set to a fix value 0.3 and M2 has been changed from 0.3- 0.7, figure 6 – 4 shows the result. It is obvious from both figures that both M1 and M2 has a strong impact on the objective function value, that is when we decrease the values of M1 and/or M2 the objective function value increase. In spite of, M2 has a bit higher impact than M1 on the objective function value. Now, the question is what is the optimal value for both parameters that gives the minimum objective function value? To answer this question, both parameters values have changed at the same time, the results shown in table 6 – 19 and plotted in figure 6 – 5. One can see that the recommended value of M1 and M2 to get a minimum objective function value is achieved when the value of M1=0.3 and M2=0.7, and this optimal value is the minimum even if we compared it with values achieved from the first and the second scenarios. While the maximum value of the objective function is achieved when M1=0.9 and M2=0.1.

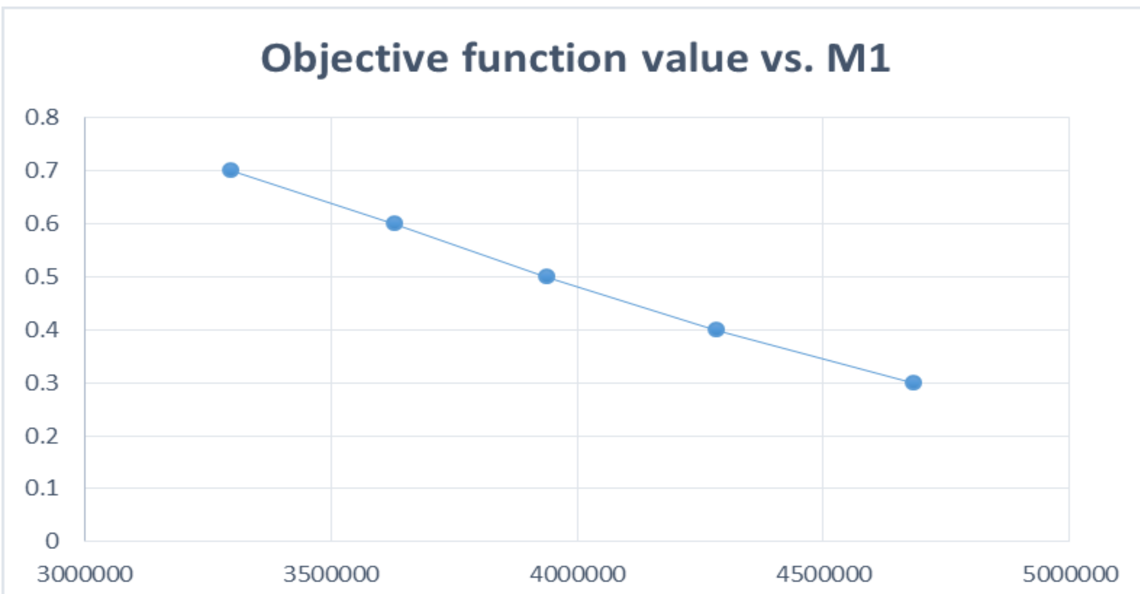

Figure 6-3 The effect of M1 on the objective function

Table 6-18 Objective function value vs. M1&M2

Objective function	*M1*	*M2*
3503354	0.1	0.9
3199602	0.2	0.8
3115714	0.3	0.7
3119942	0.4	0.6
3155082	0.5	0.5
3206658	0.6	0.4
3297376	0.7	0.3
3490536	0.8	0.2
4198265	0.9	0.1

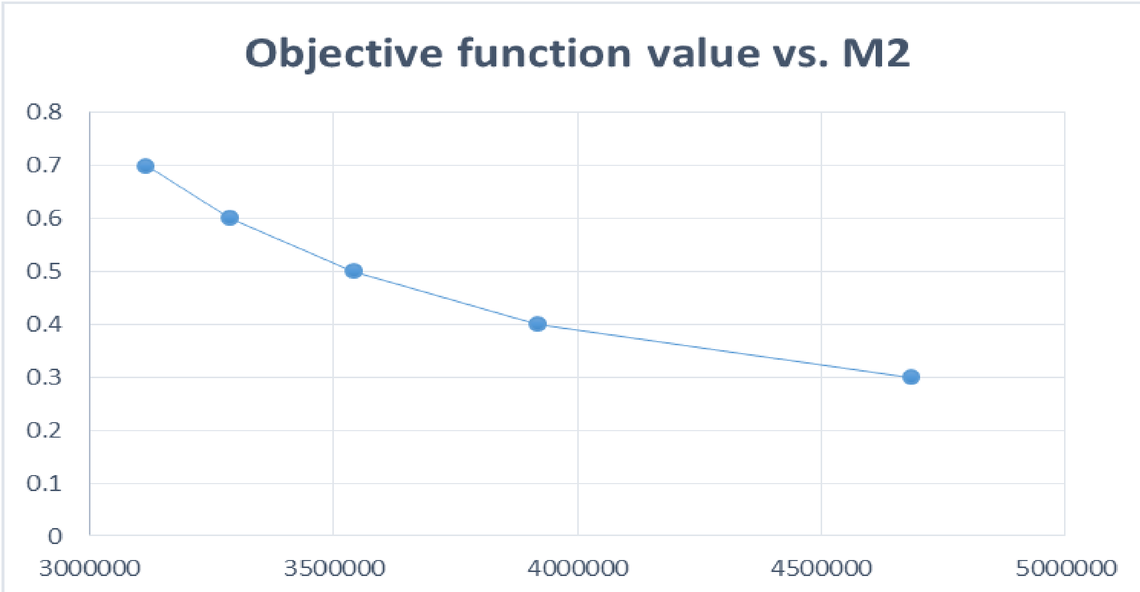

Figure 6-4 The effect of M2 on the objective function

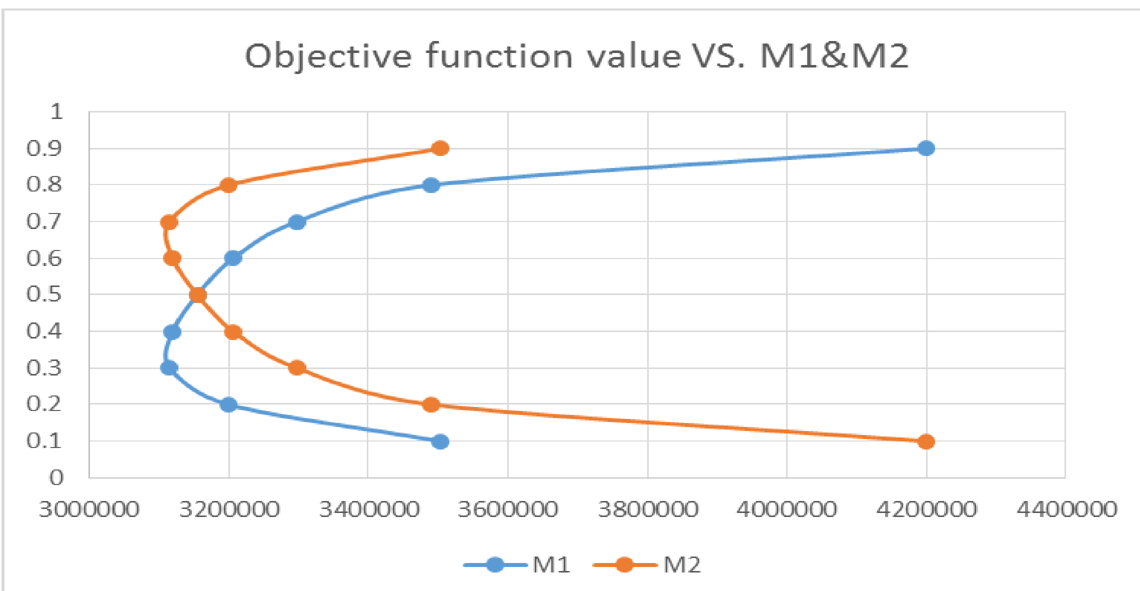

Figure 6-5 The effect of both M1&M2 on the objective function

Another critical factor in designing a reverse logistics network is *E;* the CO_2 transportation emissions factor per unit of returned product/ component in g/km, which has a main impact on the total cost and the carbon foot-print. In order to justify this impact, figure 6 – 6 represents how the value of the objective function varies over changing the value of *E* between 0.01 - 0.1, it is obvious that there is a linear relationship between the objective value and *E*, as when E increases the objective function value increases as well. Same relationship is found over a wider range of *E*, see figure 6 – 7. The increment of the total cost while increasing the *E* value is due to the considerable increment in the value of carbon dioxide (CO_2) emitted. Figure 6 – 8 shows the value of CO_2 vs. *E* (0.01- 0.1).

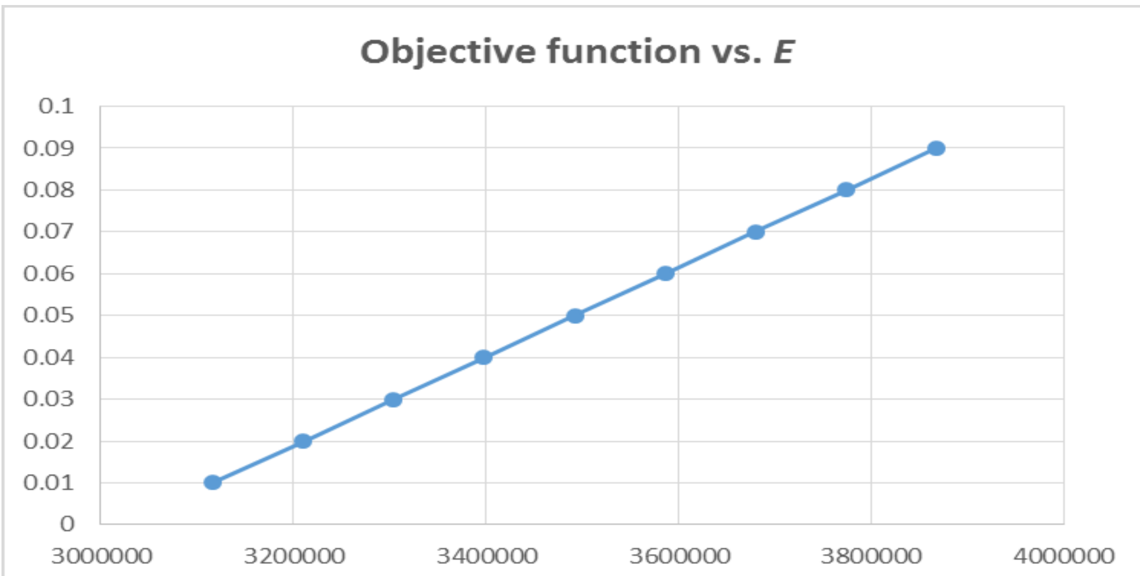

Figure 6-6 The effect of E on the objective function

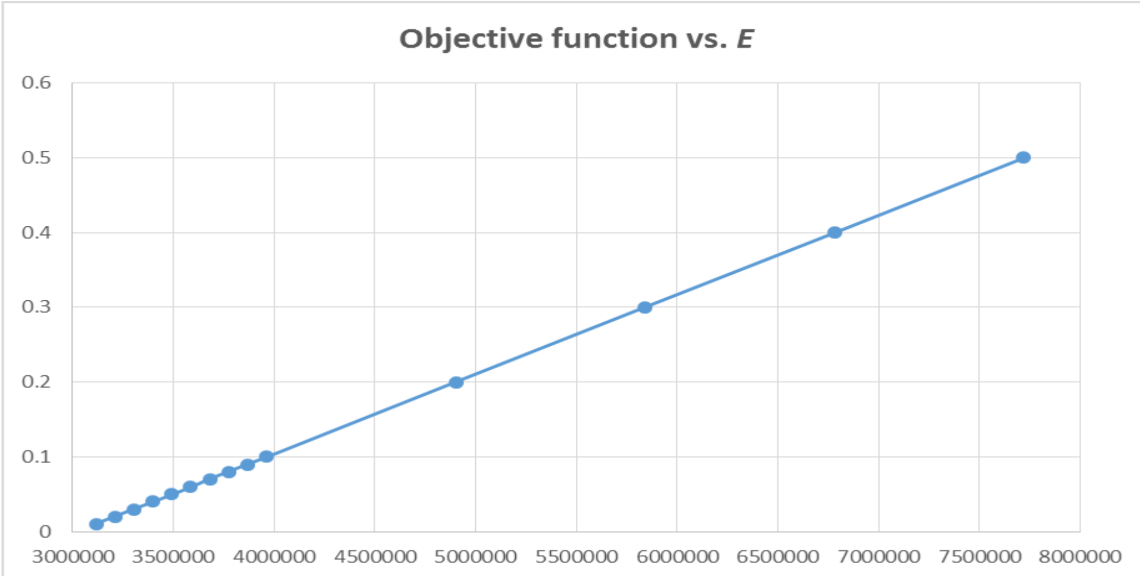

Figure 6-7 The effect of E on the objective function over a wide range

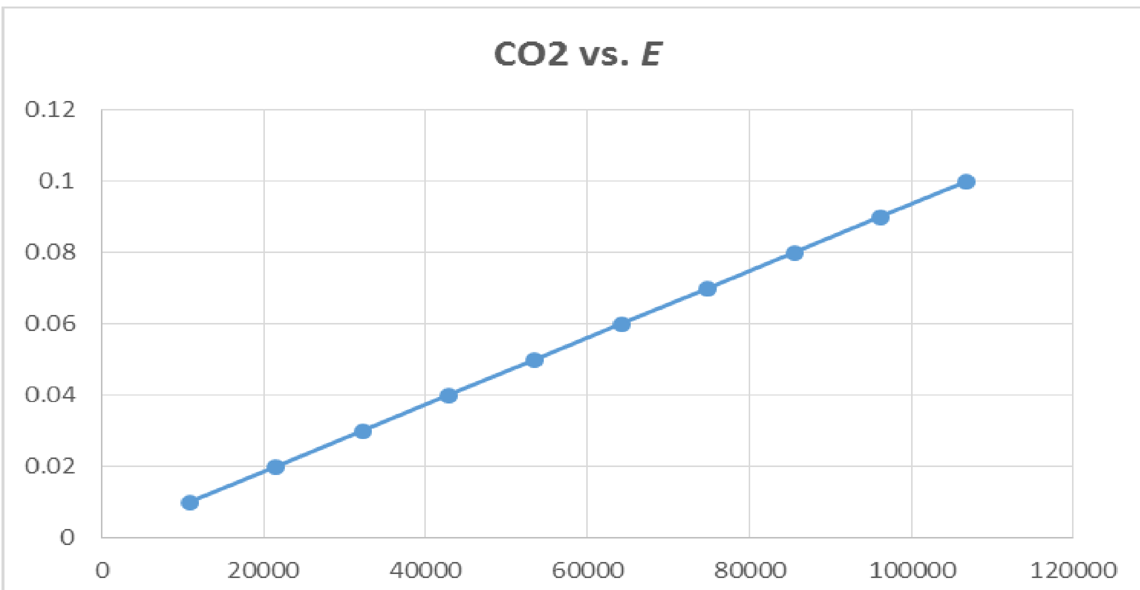

Figure 6-8 The effect of E on the CO2 value

6.5. Computational results and discussions

In this section, nine different test problems of various sizes were solved in order to validate the proposed model. The proposed model is solved using IBM ILOG CPLEX Optimization Studio 12.2/OPL on Intel® Core i5, 3.3 GHz processor with 16 GB RAM.

Each one of the numerical examples used is solved as an integrated model and the solving ability of CPLEX is being tested as the problem size increases (number of variables and constraints). Table 6 – 19 shows the results of the nine different scenario problems. In this table elapsed time and optimality gap (difference between current solution and best bound on optimal solution) are shown. It is obvious that while the problem size increases, the elapsed time also increases. Problems shown in the table could be classified into three different groups; namely small-scale (problems 1-7), and medium-scale (problem 8and 9) problems; CPLEX stopped solving problems after problem 9 due to insufficient memory. Small-scale problems were successfully solved within 7 seconds while the medium scale problem was solved within (2.5 hrs. approximately). By this, we can conclude that the branch and cut algorithm of CPLEX has a difficulty to produce good quality solutions within reasonable computational times for medium-scale problems of the proposed model.

Table 6-19 Summary of computational results

Problem scenario	Product	Comp.	Collection center	Disassembly center	recycling center	Manufacturing center	Disposal center	Custom. zone	CPU time	Gap %	Variable	**Const.**
1	2	3	2	3	2	3	2	2	0.52	0	151	108
2	2	3	4	3	4	3	4	4	1.26	0	283	146
3	4	6	4	3	4	3	4	4	0.89	0	288	215
4	2	3	4	6	4	6	4	4	1.78	0	574	215
5	2	3	8	6	8	6	8	8	1.4	0.05	1090	291
6	2	3	8	12	8	12	8	8	6.07	0	2242	429
7	2	3	8	24	8	24	8	8	1.19	0	5149	705
8	2	3	16	24	16	24	16	16	4597	0.10	8866	857
9	4	6	16	24	16	24	16	16	7986	0.05	17634	1713

6.6. Chapter Summary

In this chapter, a carbon footprint-based reverse logistics network design that consists of customer, collection, disassembly, recycling, disposal, and manufacturer (hybrid manufacturing-remanufacturing system) sites are introduced. The proposed mixed integer linear programming model aims to minimize the total cost involved in the reverse logistics network consisting of the fixed opening cost of collection, disassembly, recycling, disposal, and manufacturing centers , transportation cost of the components and products between all centers , and the cost of the carbon emissions resulting from the transportation and the facilities. The model proposed has potential applications to supply chain managers designing a reverse logistics network while considering a hybrid manufacturing-remanufacturing system. The model will help them to answer many relevant design questions for such a network (such as which candidate sites are to be opened). The proposed approach has also potential applications at the operations level to production managers running these different kind of centers. The model will offer solutions to the operational problems; such as production planning problems (e.g. the number of new and remanufactured components to be produced in each period).

Chapter 7

7. Summary, Conclusion and Future Research

7.1. Summary and Conclusion

Sustainability is increasingly becoming a decisive issue in many aspects of life. While sustainability appears to be a popular research area in general, one cannot observe much emphasis on research in design issues of sustainable manufacturing systems presently. In view of this, this dissertation addresses to design problems in Sustainable Manufacturing Systems; by considering a number of recommended aspects for designing a sustainable manufacturing system, as reported in the literature. These are the consideration of recovery options, CMSs, Reconfigurable Manufacturing Systems, Hybrid Manufacturing-Remanufacturing Systems, Closed Loop Supply Chains as well as considerations of sustainability in both the closed loop supply chain and the manufacturing system levels simultaneously [Haapala et al., 2013; Jayal et al., 2010; Gunasekaran and Spalanzani, 2012; Garbie, 2013; Difrancesco and Huchzermeier, 2016]. To this aim, different mathematical models have been proposed towards reaching the goal of designing a sustainable manufacturing enterprise.

Beginning with the recovery options consideration, especially the most widely used one "Remanufactuirng", and by looking through the recently published articles, it has been founded that remanufacturing process are used by the Third Part Remanufacturer (TPR) or by the Original Equipment Manufacturing (OEM) (Parkinson and Thompson, 2003). Aside from this, the best layout for a manufacturing facility that helps to achieve the sustainability goal is the cellular layout, thus, Cellular Manufacturing Systems (CMSs) are recommended for both types of manufacturing facilities, namely; TPR and OEM (Garbie, 2013). In addition, Saad (2003) emphasized that in order to achieve the maximum benefit or to minimize the level of performance deterioration for a CM system, the reconfiguration capabilities should be considered in CMSs. Subsequently, cellular reconfigurable systems are highly recommended for designing both TPR and OEM.

In chapter 3, a mixed integer nonlinear programming model has been proposed in order to design reconfigurable cellular system for a third part remanufacturer. The system totally depends on the remanufacturing process. In this model, CM system design, workforce management aspects, and remanufacturing process have been considered simultaneously. The proposed model have been linearized and solved for many numerical examples. The model will help the decision makers in the manufacturing system to answer many relevant design questions for such systems (such as the cell formation problem). The proposed approach has also potential applications at the operations level to production managers running third part manufacturing systems. The model will offer solutions to the operational problems; such as production planning problems (e.g. the number of new and remanufactured components to be produced in each period), reconfiguration of cells for each production period (e.g. the number and type of machines to be added/removed for each cell for each period).

Designing OEM systems are presented in both Chapters 4 and 5. In such OEM manufacturing and remanufacturing are to take place within the same facility. This type of manufacturing system is called a Hybrid Manufacturing-Remanufacturing System (Chen and Abrishami, 2014). Chapter 4 presents a simultaneous investigation of Reconfigurable Cellular Manufacturing Systems (CMSs) and Hybrid Manufacturing-Remanufacturing Systems (HMRSs) and proposes an integrated approach in design optimization, analysis, and process planning aspects as an attempt to address to a large number of design issues for "Sustainable Manufacturing Systems". A mixed integer linear programming (MILP) model, which considers a classical cell formation problem in CMSs, bridged with a production planning problem, in Hybrid Manufacturing-Remanufacturing Systems, while addressing to "reconfiguration" issues for the CMS for different production periods, has been developed. The model proposed has potential applications to *Sustainable Manufacturing System* designers designing Reconfigurable Cellular Hybrid Manufacturing-Remanufacturing Systems.

In Chapter 5, the proposed model is an extension of the proposed model in chapter 4, in order to consider the options of recycling (for the end-of-life parts), remanufacturing (for end-of-use parts), and disposing of the parts with no further use as a forward step for DFSME. Aside from this, the new parts production totally depends on the recycled parts coming from the recycling center, wherein chapter 4 it depends on the raw material purchased from outsourcing. Several numerical examples problems are solved and the computational results have been reported.

In chapter 6, a mathematical model approach has been proposed for designing an environmental friendly green supply chain which considered as one of the pillars for designing a sustainable manufacturing enterprise. Green supply chain has many aspects such as carbon foot prints, plants location, and the introduction of recovery options such as remanufacturing and recycling which are highly used. In addition, hybrid manufacturing–remanufacturing system is considered, this type of systems became one of the most popular manufacturing systems used in reverse logistics network design. To this aim, a mixed integer linear model for designing a reverse logistics network is developed, the model considers the carbon foot prints, facility location, and material flow while considering a hybrid manufacturing-remanufacturing system. A detailed discussion of a numerical example is presented to illustrate the proposed model. Sensitivity analysis for some important parameters are presented as well.

Along these lines, mathematical models for designing an environmentally friendly green supply chain, reconfigurable cellular hybrid manufacturing-remanufacturing system, and a third part reconfigurable remanufacturing system have been proposed, which can be considered as the first models that incorporate all the main essential aspects simultaneously, reported in the literature, towards designing sustainable manufacturing enterprises. The models have been formulated, solved, analyzed, along with this, sensitivity analysis for the crucial aspects have been presented.

7.2. Future Research

The future works for this dissertation can be summarized as follow:

7.2.1. Developing Efficient Solution Approaches

The proposed mathematical models in this dissertation have been solved by commercial software (CPLEX) which is in the most cases was not able to give an exact solution for large size problem. Thus, it is worthwhile to propose some solution approaches in order to find an exact solution within a reasonable computational time particularly for large size problems. To this aim, the use of metaheuristic methods is recommended.

7.2.2. Further Consideration of CM Design Attributes

The CM design attributes considered in the proposed models are one of the most important design attributes used in CM design. However, there are some other recommended design attributes that can enhance the proposed mathematical models, such as:

A. Intercellular material handling cost.
B. Intracellular material handling cost.
C. Considering of Stochastic demand.
D. Routing flexibility.
E. Workforce management in designing the HMRS.

7.2.3. Further Consideration of Recovery Options

Recycling, remanufacturing, and disposing are the three recovery options used in this dissertation. Although, these options are the most popular and the most used ones, there are another recovery options which can be considered while consider these three options, such as:

A. Refurbishment.
B. Reuse ‘as is’.
C. Repair.

7.2.4. Further Consideration of Sustainability Aspects

Actually, calling an enterprise as a “sustainable enterprise” needs a huge amounts of effort and needs to take into consideration so many aspects from different perspective. In this dissertation some major steps towards the design for sustainable manufacturing enterprise

(DFSME) have been considered. Taking into account remanufacturing and recycling is one step toward DFSME, additional major steps, reported in different published articles, in DFSME which considered in our paper are as follow:

A. Considering the sustainability in both the closed loop supply chain and the manufacturing system levels simultaneously.
B. Considering Cellular manufacturing system (CMS).
C. Considering reconfigurability for the production system:
D. Considering a hybrid manufacturing-remanufacturing system.
E. Considering the three most popular recovery options; recycling, remanufacturing, and disposing.

In this dissertation, unlimited source of returned products has been considered. The case of limited source of returned products will be considered in future research. In addition, there are other sustainability issues, reported by Garbie 2013, which should be taken into consideration in order to go a further steps toward the DFSME such as:

A. International issues.
B. Innovative products.
C. Contemporary issues.

7.2.5. A case study

Basically, there is a need to implement the proposed models on a real case study, in order to examine their abilities to solve real life problems as well as to identify their limitations and challenges.

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