Effect of Reconfiguration Characteristics on Manufacturing System Capacity Selection

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Abstract

Effect of reconfiguration characteristics on manufacturing system capacity selection

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The increasing frequency of new product introductions force today's companies to continuously upgrade their production capacities. The frequent revision of production capacities and the capacity loss during this period increase the importance of ramp up duration in evaluating capacity investments. This thesis aims to explore how a firm should optimally allocate its capacity investments among different manufacturing systems considering the capacity evolution in ramp up period. The proposed models in this thesis address a production facility making products that has a specific life cycle pattern.

In this study, the duration of reconfiguration period for reconfigurable manufacturing system (RMS) is modeled as a function of the amount of capacity change. Through a sensitivity analysis, the impact of reconfiguration on the selection of manufacturing systems has been analyzed with respect to different product life cycle patterns.

Through a mixed integer programming model, a various ramp up time patterns are taken into account and a more suitable reconfiguration type for a manufacturer in terms of system layout and response range is analyzed.

Finally, the response time of a system is considered in the context of a supply chain network to improve the supply chain responsiveness. The appropriate response speed is selected through a decision tree analysis and based on the expected cost of the supply chain. The results show a faster response speed is a better choice as the failure probability of main supply node increases and/or the recovery of the main supply node decreases.

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Indices:

T	Time Horizon
$i \in 1,..,T$	Current Time
$t \in 1,..,T$	Capacity Purchase Time
$p \in 1,..,P$	Number of products
d	Dedicated Capacity
f	Flexible Capacity
r	Reconfigurable Capacity

Common Parameters:

β_i	Discount Factor
$D_{i,p}$	Demand of Product p at time i
$PP_{i,p}$	Price of product p at time i
$\gamma_{i,p}$	Shortage cost of product p at time i
ε	Removing capacity time takes (0-100%) of adding capacity time
α^p	Production rate of Product p by one unit Dedicated Capacity
ϑ^p	Production rate of Product p by one unit Flexible Capacity
μ^p	Production rate of Product p by one unit Reconfigurable Capacity

General Variables:

$SA_{i,p}$	Product p Shortage at time i

DMS Parameters:

$CC^d_{i,p}$	Capacity Purchase Cost for Product p at time i

$SCF^{d}_{i,t,p}$	Salvage value for Capacity purchased at time t for product p that is sold at time i
$EPC^{d}_{i,p}$	Excess capacity Cost at time i for product p

FMS Parameters:

CC^{f}_{i}	Purchase Cost for at time i
$SCF^{f}_{i,t}$	Salvage value for capacity purchased at time t that is sold at time i
EPC^{f}_{i}	Excess capacity Cost at time i

RMS Parameters:

$RT_1, .., RT_5$	Time Required for each Reconfiguration Level
$RTC_1, .., RTC_5$	Reconfiguration Cost at each Reconfiguration Level
RBC_t	Base Cost at purchase time t
$RMC_{t,p}$	Module Cost at purchase time t for product p
$RMSCF_{i,t,p}$	Salvage Value for module purchased at time t for product p that is sold at time i
$RBSCF_{i,t}$	Salvage Value for base purchased at time t that is sold at time i
$EPC^{r}_{i,p}$	Excess capacity Cost at time i for product p

DMS variables

$PC^{d}_{i,p}$	Purchased Dedicated Capacity at time i for product p
$SU^{d}_{i,p}$	$\begin{cases}1 \text{ Dedicated Capacity is Scaled Up at time } i \text{ for product } p\\ 0 \ otherwise\end{cases}$
$SD^{d}_{i,t,p}$	$\begin{cases}1 \text{ Purchased Dedicated Capacity at time } t \text{ for product } p \text{ is Scaled Down at time } i\\ 0 \ otherwise\end{cases}$
$RC^{d}_{i,t,p}$	Removed Dedicated Capacity which is purchased at time t for product p at time i
$EC^{d}_{i,p}$	Dedicated Excess Capacity at time i for product p

$X_{i,p}$	The amount of product p which is produced by Dedicated Capacity at time i

FMS variables

PC_i^f	Purchased Flexible Capacity at time i
SU_i^f	$\begin{cases}1 \text{ Flexible Capacity is Scaled Up at time } i\\ 0\ otherwise\end{cases}$
$SD_{i,t}^f$	$\begin{cases}1 \text{ Purchased Flexible Capacity at time } t \text{ is Scaled Down at time } i\\ 0\ otherwise\end{cases}$
$RC_{i,t}^f$	Removed Flexible Capacity which is purchased at time t at time i
EC_i^f	Flexible Excess Capacity at time i
$Z_{i,p}$	The amount of product p which is produced by Flexible Capacity at time i

RMS Variables

$Q_{i,p}$	The amount of product p that is produced by Reconfigurable Capacity at time i
$EC_{i,p}^r$	Reconfigurable Excess Capacity at time i for product p
$ARMC_{i,t,p}$	Actual module capacity for product p at time i for base purchased at time t
$IRMC_{i,t,p}$	Nominal module capacity for product p at time i for purchased base at time t
$ADDMLE_{i,t,p}$	Added module capacity for product p module at time i for purchased base at time t
$RMDMLE_{i,t,p}$	Removed module capacity for product p module at time i for purchased base at time t
MRC_i	Maximum Reconfigurable Capacity is purchased at time i

$RC_{i,t}^{r}$	Removed Reconfigurable Capacity purchased at time t at time i
$SU_{i,p}^{r}$	$\begin{cases} 1 & \text{Module Capacity is Scaled Up at time } i \text{ for product } p \\ 0 & otherwise \end{cases}$
$SD_{i,p}^{r}$	$\begin{cases} 1 & \text{Module Capacity is Scaled Down at time } i \text{ for product } p \\ 0 & otherwise \end{cases}$
SUB_{i}^{r}	$\begin{cases} 1 & \text{Reconfigurable Base is Scaled Up at time } i \\ 0 & otherwise \end{cases}$
$SDB_{i,t}^{r}$	$\begin{cases} 1 & \text{purchased Reconfigurable Base at time } t \ is \text{ Scaled Down at time } i \\ 0 & otherwise \end{cases}$
$RC_{i,p}$	$\begin{cases} 1 & \text{Reconfiguration occursat time } i \text{ for product } p \\ 0 & otherwise \end{cases}$
$RL1_{i,p}, \ldots, RL5_{i,p}$	$\begin{cases} 1 & \text{if Reconfiguration occurs at Level } (1..5) \text{ at time } i \text{ for product } p \\ 0 & otherwise \end{cases}$

Chapter 4: The effect of system configuration and ramp up time on manufacturing system acquisition under uncertain demand

Parameters:	***Description***
T	Time horizon
P	Products
ς_t	Discount factor at time t
$\mu_{t,p}$	Product p demand mean at time t
$\sigma_{t,p}$	Product p variance at time t
C_p^d	Dedicated System unit capacity purchase cost for product p
C^r	Reconfigurable System unit capacity purchase cost
CP_p^d	Dedicated system production cost for product p
CP_p^r	Reconfigurable system production cost for product p
SC	Demand lost opportunity cost
EC	Excess capacity cost per unit
C_2^k, C_3^k	Capacity cost increase per unit capacity purchase for types II and III Reconfigurable System
$C_1^T..C_3^T$	Reconfiguration cost parameter base on reconfiguration time
M	Sufficiently large number
Z	Z value based on Serviceability

Variables:

$D\xi_{t,p}$	Dedicated system capacity at time t for product p
$D\lambda_{t,p}$	Dedicated system production at time t for product p
$D\Delta\xi_{t,p}^{+}$	Added capacity for Dedicated system at time t for product p

$D\Delta\xi_{t,p}^{-}$	Removed capacity for Dedicated system at time t for product p
$E\xi_{t,p}^{d}$	Excess Capacity of Dedicated system at time t for product p
$R\xi_{t}$	Actual capacity of Reconfigurable system at time t
$R\lambda_{t,p}$	Reconfigurable system production at time t for product p
$IR\xi_{t}$	Nominal capacity of Reconfigurable system at time t
$R\Delta\xi_{t}^{+}$	Added capacity for Reconfigurable system at time t
$R\Delta\xi_{t}^{-}$	Removed capacity for Reconfigurable system at time t
$U\xi_{t}^{r}$	Upper limit capacity during reconfiguration at time t for reconfigurable system
$L\xi_{t}^{r}$	Lower limit capacity during reconfiguration at time t for reconfigurable system
$E\xi_{t}^{r}$	Excess capacity of Reconfigurable system at time t
$\vartheta_{R}^{r},\vartheta_{R}^{d}$	Maximum Capacity that could be added to a system in each period
$D_{t,p}^{l}$	Product p demand lost at time t
$Y_{t}^{1}..Y_{t}^{3}$	Number of sub intervals are used for reconfiguration as binary variable for Type (I) Reconfiguration
$Y_{t}^{4}..Y_{t}^{6}$	Number of sub intervals are used for reconfiguration as binary variable for Type (II) Reconfiguration
$Y_{t}^{7}..Y_{t}^{9}$	Number of sub intervals are used for reconfiguration as binary variable for Type (III) Reconfiguration
$Y_{t,p}^{d}$	Series Reconfiguration as binary variable
$Y_{t}^{10},Y_{t,p}^{11}$	Auxiliary binary variables
$K^{1}..K^{4}$	Ramp up pattern binary variables

Chapter 5: Effect of response time on service level in supply chain network

Indices

T	Time horizon
$t \in 1,...,T$	Current time
t_D	Time of Disruption
M	A big number
d	DMS supplier
r	RMS supplier
$i \in \{1,2,3\}$	Number of added modules
$j \in \{100,200,300,400\}$	Nominal capacity

Input parameters

CP^d	Production cost of DMS
CP^r	Production cost of RMS
RC	Reconfiguration cost
SC	Shortage cost
EC^d	Excess capacity cost of DMS
EC^r	Excess capacity cost of RMS
HC^d	Finished goods holding cost of DMS
HC^r	Finished goods holding cost of RMS
$C\omega^d$	Work in process holding cost of DMS
$C\omega^r$	Work in process holding cost of RMS
Crm^d	Release material cost of DMS
Crm^r	Release material cost of RMS

C_{Max}^{d}	Maximum DMS capacity
C_{Max}^{r}	Maximum RMS capacity
C_{ml}^{r}	RMS Module capacity
θ_i^U	The coefficient of the upper limit for RMS capacity changes
θ_i^L	The coefficient of the lower limit for RMS capacity changes
Y_t^{DMS}	DMS status at time t (0 disrupted, 1 active)
$I_t^{d,ini}$	The DMS inventory value before disruption at time t (from initial plan)
$I_t^{r,ini}$	The RMS inventory value before disruption at time t (from initial plan)
$Y_t^{i,ini}$	The RMS capacity plan before disruption at time t (from initial plan)

Decision variables

$D\lambda_t$	DMS production at time t
$R\lambda_t$	RMS production at time t
$R\Delta\xi_t^+$	RMS added capacity at time t
$R\Delta\xi_t^-$	RMS removed capacity at t
D_t^l	Lost demand at time t
D_t^s	Satisfied demand at time t
D_t^d	DMS satisfied demand at time t
D_t^r	RMS satisfied demand at time t
$E\xi_t^d$	DMS capacity at time t
$E\xi_t^r$	RMS capacity at time t

I_t^d	DMS finished goods inventory at time t
I_t^r	RMS finished goods inventory at time t
ω_t^d	DMS Work in process at time t
ω_t^r	RMS Work in process at time t
rm_t^d	DMS release material at time t
rm_t^r	RMS release material at time t
$R\xi_t$	RMS actual capacity at time t
$IR\xi_t$	RMS nominal capacity at time t
$U\xi_t^r$	Upper limit for changes in RMS capacity at time t
$L\xi_t^r$	Lower limit for changes in RMS capacity at time t
$Y_t^i, Y_t^j, Y_t^5, Y_t^{10}$	Binary variables

Chapter 1: Introduction

Capacity Management is one of the most critical aspects of decision making that various organizations are dealing with daily. Some decisions are major decisions such as the construction of a major dam; others are small such as purchasing an additional stamping machine. Depending on the decision; the time frame varies in range of days, weeks, months and even years. Capacity decisions, large and small, add up to a massive commitment of capital (Freidenfelds, 1981).

Capacity management is used in myriad of applications such as communication network, gas and oil pipelines, electrical power generation, and manufacturing facilities (Luss, 1982). In all these applications, the level of decision making regarding capacity management could be viewed from three distinguished levels. These levels are strategic, tactical, and operational levels. For example, a company might decide to open a call centre in particular location. From the strategic level, the location of facility or building is a criterion of decision making. This kind of decision could not be made in a short term. Staffing patterns belong to tactical decision set and needs a time frame of a few months. Then, on a daily basis routine, operational decisions are made to determine the exact requirements.

Capacity decision making typically involves many concerns such as market, size, time, type, location, and utilization. In order to show the importance of a capacity decisions, an application from automotive industry is reviewed to illustrate how market trend could impact the evolution of capacity in auto industry.

1.1 An example of capacity management in practice

For many years the automotive industries endeavour to supply customers with high quality and low cost products. As emerging markets have developed into high quality producers in addition to being low cost centers, automotive manufacturers have moved production into these areas in search of more customers and greater cost savings; suppliers have naturally followed these trends.

While manufacturers have regularly increased sales volumes for vehicles worldwide, global production capacity growth has continued to outpace the customer demand. In recent years, the utilization of that global capacity has become the focus of attention. In 2005, there were 6 major plant closings around the world, but 18 new plants came on line during the same period (Figure 1-1). This trend is expected to continue over the coming years. Production Capacity Management (PCM) is clearly required to ensure that the costs of production enhance the affordability of products. PCM should be reviewed whenever a new plant (capacity) opens, or an existing plant (capacity) expands, contracts, or closes.

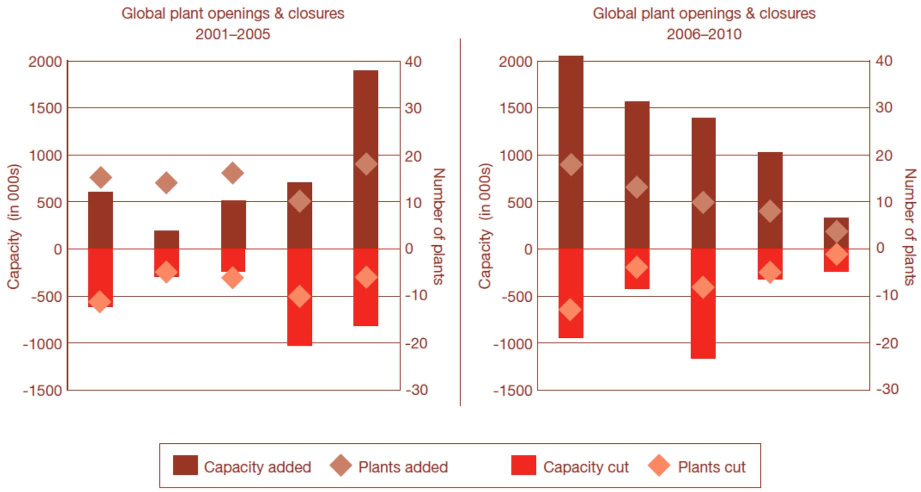


Figure 1-1 Automotive manufacturing capacity (source: PwC Automotive institute, AUTOFACTS 2006 Q3 forecast release)

One of the applications of PCM is manufacturing system design and selection (Lalic et al., 2005) which could be investigated from different aspect of decision process such as time for designing a product, level of work in process, equipment and tools, and production and delivery. Focusing on the manufacturing system selection decision analysis, manufacturing systems alternatives have evolved in parallel with the customer requirements. In order to select a manufacturing system, it is important to identify their characteristics. The following section describes the evolution of manufacturing system paradigms and their characteristics.

1.2 Evolution of manufacturing system paradigms

Manufacturing paradigms have changed by the aggressive competition on the global scale and rapid changes during the past decades. Starting with the industrial revolution, manufacturing system paradigms have evolved from mass production (dedicated lines) which focused on the reduction of product cost, to lean manufacturing (Noaker, 1994) to improve product quality while decreasing product costs, and then lead to the introduction of Flexible Manufacturing Systems (FMS) which address changes in work orders, production schedules, part programs, and tooling for production of a part family.

Dedicated Manufacturing Systems (DMS) are based on fixed automation and produce a company's core products. DMS is typically implemented for large scale capacity just for one product family at a time and able to produce products with lower unit cost. The first implementation of this philosophy is seen on Ford’s production line (Graham, 1988).

The limitation to one or two product variants causes DMS not to be considered as a favorable technology where large scale production is not justified (Black, 1991). DMS could be a desired system as long as market demand continuously matches the supply resulting in a continuous decrease in production cost (Pine, 1993). But with pressure of global competition to offer customized products, DMS is not fully utilized and unused capacity of DMS creates losses for manufacturer. The survey results reported by Tolio and Matta (1998) shows that the average utilization of DMS transfer lines is only 53%. The reason is that some products are at their introduction phase and some other at the end of their product life cycle.

FMS consist of computer numerically controlled (CNC) machines and other programmable automation. These systems are designed to address the production of a part family with similar processing characteristics. This part similarity is exploited to build in capability in order to address a variety of markets/products such that the total production volume is high enough to justify the investment. Although FMS is able to make low volume for a variety of products on the same system, the disadvantage of FMS lies in its high initial investment (Graham, 1988), fixed hardware, and fixed software (but programmable) making it difficult to adapt new technologies.

Another drawback to FMS is lack of responsiveness to market changes. From the design perspective, FMS is not designed for a quick change in its capacity. In addition to higher cost of FMS, there is another disadvantage to FMS. The designer of a Flexible manufacturing facility can not anticipate which processing capabilities may be needed during the lifecycle of the system. Thus, at the design phase, all possible capabilities are built in an FMS configuration. This full capability is often underutilized and constitutes a capital waste. Moreover, FMS does not allow changes to be made as a result of advances and innovation in technology and has limited capabilities in terms of upgrading add-ons, customization and changes in production capacity. According to Mehrabi et al. (2002), around 73% of manufacturers are looking for a system that could accommodate incremental increase in capacity of their existing production system while they do not need the extra functionality delivered by FMS.

A solution to cope with this limitation is a new manufacturing system technology that provides minimum lead time for launching and integrating new process technology while having the capability to upgrade quickly to new functionality (Pine, 1993). The Agile Manufacturing (AM) was introduced in 1991. AM is a new concept in manufacturing intended to improve easy access to integrated data, modular production and requires to manage change and uncertainty (Gunasekaran,1999). AM is a general concept that include all the enterprise level rather than just the manufacturing system. A manufacturing system that enables the premise of AM is introduced by Koren in 1996 (Koren, 1999) and is called Reconfigurable Manufacturing System (RMS).

Bi et al. (2008) define the RMS as a comprehensive system which is able to meet the changes and uncertainties of manufacturing environment. RMS has a modular structure (software and hardware) that allows ease of reconfiguration as a strategy to adapt to market demands. The key enabling technologies for RMS are modular machines and open-architecture controllers which enable the system to integrate/remove new software/hardware modules without affecting the rest of the system. In comparison with FMS, reduction of lead time for launching new systems (reconfiguring current system) plus rapid modification and integration of new technology (functionality) into existing system provides customized flexibility for a particular part family compared to FMS.

Moreover, the open ended architecture of RMS provides means to improve, upgrade, and reconfigure rather than to replace. In short, RMS is able to have exactly the required functionality and capacity, which in many cases occupies a middle ground between dedicated transfer lines and FMS in terms of production quantity and product variety. RMS could be a solution to industry which is looking for a system with more adaptable to changes in terms of capacity and gradual changes in functionality.

Therefore, in contrast to flexible capacity where the whole capacity and capability must be purchased at the same time, the Reconfigurable Capacity requires minimum initial capacity investment. RMS includes highly scalable capacity which is able to adjust capacity in small increments. Also, RMS possesses adaptable functionality to the new products. The composition of RMS consists of a base structure which machine modules could be added or removed in later time in order to adapt to product design/volume variations. For that reason, RMS can be either returned to its original state, or further modified to provide new functionality or production capacity as needed. Figure 1-2 shows the relation of capacity and functionality of different systems. Although that DMS and FMS stands in extreme ends of capacity and functionality, RMS occupy the middle ground between DMS and FMS.

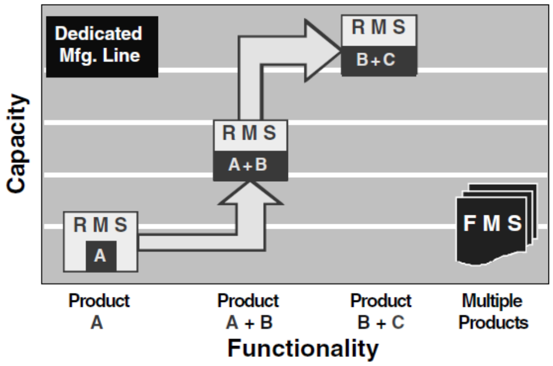


Figure 1-2 Manufacturing system functionality and capacity relation (Koren and Shpitalni, 2010)

The manufacturing system paradigms explained in this section are designed to address specific needs of a company. While each paradigm meets a set of requirements, the selection among these paradigms can depend on several internal and external factors such as, demand uncertainty, price, responsiveness, and cost. The consideration of such factors depends on the level the decision is made, varying from strategic to operational. In the next section, the classification of these levels is presented.

1.3 Manufacturing systems selection at different decision levels

Manufacturing system selection depends on many parameters that should be considered at different level of decisions. For example, at macro level parameters such as time to market (Boyaci and Ray,2003), price (Mieghem and Dada, 1999), and competition in the market (Goyal and Netessine, 2007) have impact on manufacturing system selection, and at micro level, hardware and software requirement (Mehrabi et al, 2002), and maintenance are examples of decision parameters that will identify the specifications. A manufacturer could select between different manufacturing systems based on the following considerations:

- Capacity type investment and evolution of capacity during the product life cycle
- Reconfiguration Time during product life cycle
- Minimum amount of capacity to meet pre-set service level
- Effect of product profit margin or capacity investment cost
- Diversification of capacity types versus single type capacity.

All these factors can be used to analyse the capacity selection decision from strategic, tactical, and operational levels. The decisions regarding capacity investment at the strategic level focus on the supply chain perspective (Beamon, 1998) and strategic interactions between different echelons of supply chain network (Chauhan et al., 2004). Each supply node in the network has great impact on the performance level of upstream and downstream nodes. Therefore, research in this area utilizes the models whose focus is on the demand evolution, product life cycle and lead time (Huh et al. (2005)). Strategic planning covers a time horizon between three to five years,

The operational level decisions focus on product and firm-specific operational environment and covers a few months of production planning. Dedicated, flexible, or reconfigurable systems represent different characteristics in terms of scalability and functionality, especially from the perspective of lead time during capacity changes.

At the tactical level, the capacity planning focuses on capacity evolution related to the operational aspects of the firm. At this level the focus is on the time, size and type of capacity investment for timeframe of one to three years. Therefore, the differentiating factor of a system at the tactical level decision making is its agility toward the market changes. For this reason, the scalability of a system is vital in terms of capacity expansion decisions and production allocation to each capacity type.

One of the differentiating factors of RMS from its predecessors is the speed of change to a new state. This can be explained by the fact that adding capacity at a later time causes existing reconfigurable capacity to go under reconfiguration and loss of some amount of capacity during this period. This allows responding to market changes in a short period of time instead of building in a capability at the beginning of the production system's lifecycle, which bears the risk of underutilization. In other words, whenever the demand changes, the system goes through reconfiguration (scaling up/down) in order to adapt to the new capacity. During the reconfiguration period, system may lose some capacity due to machine shut down, new setup times, and time to reach steady state situation (figure 1-3).

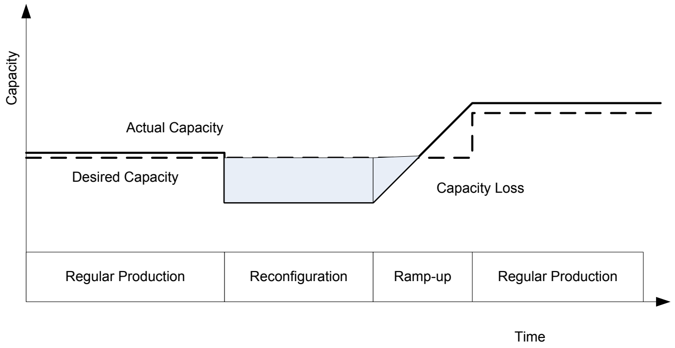


Figure 1-3 Ramp up during reconfiguration period

If RMS is designed correctly, many reconfiguration periods will occur during the lifetime of a reconfigurable system. Therefore, to make reconfiguration successful, short ramp up phases are critical to bring the system back on line quickly (Hu (1997)).

Another aspect of capacity evolution from the tactical perspective is the reconfiguration cost that the manufacturers must consider. The configuration of RMS and the way that RMS evolves from one configuration to another might affect manufacturers' future investment costs. This is mainly due to the differences in layout structure and convertibility characteristics of a configuration. Therefore, the composition of RMS itself or the compatibility of RMS with other types of systems like DMS will have a major effect on the duration of reconfiguration period.

While RMS allows building capacity and capability as required, the reconfiguration process may lead to some loss of sale. A capacity shortage or excess during RMS reconfiguration may affect service level since no production system has the capability to reach nominal capacity instantly. Thus, both RMS configuration cost and RMS reconfiguration speed have an impact on the evaluation of RMS investment decisions.

Table 1-1 Capacity planning decision levels

Planning level	**Decision factors**
Strategic	• Demand evolution • Production life cycle • Lead time
Tactical	• Capacity evolution • Time and Size • Type of Capacity investment
Operational	• Scalability • Functionality

In summary, Table 1.1 classifies the factors considered through different decision making levels. Ramp up time and reconfiguration period are important characteristics to assess the responsiveness of RMS. In other words, reconfiguration period is the major factor in assessing the agility of RMS and its capability to capture the market demand from tactical level. For that reason, while selecting the manufacturing system alternatives, companies should consider the impact of reconfiguration and the relevant RMS cost structure.

1.4 Research objective

As mentioned in section 1.3, manufacturing system selection depends on many parameters from system specification to market characteristics. For instance, due to monopoly and lack of competitors, some markets such as chemical industries might benefit more from DMS. In contrast, in markets, such as the electronic industry, where the frequency of new product introduction is high, FMS might be more advantageous. Furthermore, when either excess capacity or shortage of product is vital for a firm from the strategic point of view, ramp up and reconfiguration period should be evaluated in the selection of a system.

System reconfiguration and the way that a system evolves from one configuration to another might affect manufacturers' future investment costs. The variation comes from the differences in the layout structure and convertibility characteristics of a configuration. For this reason, the selection of a unique type of manufacturing system such as RMS or the combination of two different manufacturing systems such as RMS and DMS will have different effect on service level and capacity planning decisions. Therefore manufacturing system should not only be analyzed by its characteristics but also by their interaction with other systems.

Capacity shortage or excess during reconfiguration may affect service level since no system has the capability to reach nominal capacity instantly. Thus, system configuration and reconfiguration speed have impact on the evolution of capacity during ramp up. As a result of these factors, while selecting the manufacturing system alternatives, companies should consider the impact of reconfiguration and the relevant configuration cost structure.

The focus of this thesis is on the tactical level analysis of capacity planning from a firm's perspective by differentiating capacity types such as dedicated, flexible, and reconfigurable systems. The role of RMS during reconfiguration period is investigated since RMS has major effect on service level by adapting its capacity as needed.

1.5 Research methodology

In order to analyze these characteristics; first, a decision model is developed based on DMS, FMS, and RMS characteristics to explain how product life cycle and frequency of new product introductions could affect the selection of manufacturing systems. The ramp up time and reconfiguration period of RMS is incorporated in the model as a function of the amount of added or removed capacity. Thus, through an analysis of parameters such as excess capacity cost, shortage cost, reconfiguration speed, it is examined how the capacity mix of manufacturing systems is affected.

Second, a long term capacity planning model is developed by incorporating the impact of reconfiguration and layout characteristics in order to represent the responsiveness of RMS. The capacity alternatives are based on DMS and RMS characteristics to determine how different RMS reconfigurations affect responsiveness, and thus, customer service level. The ramp-up time and reconfiguration period of RMS are incorporated into the model as a function of added or removed capacity amount during the reconfiguration period. Finally, by subjecting the RMS and DMS configuration towards uncertain demand, the total cost of capacity plans are analyzed based on the capacity shortage cost and excess cost. Also the type of configuration that benefits the manufacturer during the planned time horizon is proposed in this chapter.

Third, the effect of reconfiguration period on system production capacity is considered. By modelling the congestion effect at production level, thus a better estimation of capacity utilization during the reconfiguration period is proposed. Congestion level is mainly considered at the operational level and the effect of congestion could have major impact on available capacity and ramp up period. Therefore, the congestion effect needs to be assessed in capacity analysis to give a better assessment of manufacturing system capacity. Congestion effect is formulated through clearing function and shows how production through put is affected by updating capacity.

In assessing the impact of manufacturing system at the tactical level, some parameters are examined. These parameters are manufacturing system's scalability, manufacturing system layout, reconfiguration period, ramp up period, and the impact of work in process level on capacity utilization.

Each problem scenario is modeled by Mathematical programming. System characteristics are presented through mixed integer linear programming (MILP). By solving the model to optimality, the following aspects are observed: capacity allocation, amount of investment on different system type, impact of layout and configuration, and the effect of ramp up time on facilitating the production congestion during the disruption.

The objective functions are developed by expressing the firm cash flows or operational costs depending on the decision level. For example, in chapter 3, the model objective is maximizing present worth of cash flow for a predetermined time horizon in order to perform a strategic level analysis. In chapter 4 and 5, the objective function is minimizing the manufacturing system related lifecycle costs. Capacity evolution during planned time horizon is taken into account by each system constraint such as scalability difference, ability to produce multiple products, and percentage of available capacity during reconfiguration.

The drivers of all proposed MILP models to optimize the system configuration are the operational costs and associated opportunity costs. The operational costs include the costs associated with the production and reconfiguration period, and the opportunity costs include the lost sale costs associated with the ramp up period. Integration of these costs helps a decision maker to investigate the performance of manufacturing systems capacity in a multi period setting.

The MILP results are then verified in a simulation environment by incorporating the randomness in demand and ramp up behavior. For example, the output from the MILP model such as the amount of system capacity, reconfiguration period and capacity evolution is used in the simulation model with random demand and ramp up duration. Validating the results of the MIP model in simulation allows observing which reconfiguration type provides better service level under random demand. The schematic of this proposed methodology is shown in Figure 1-4.

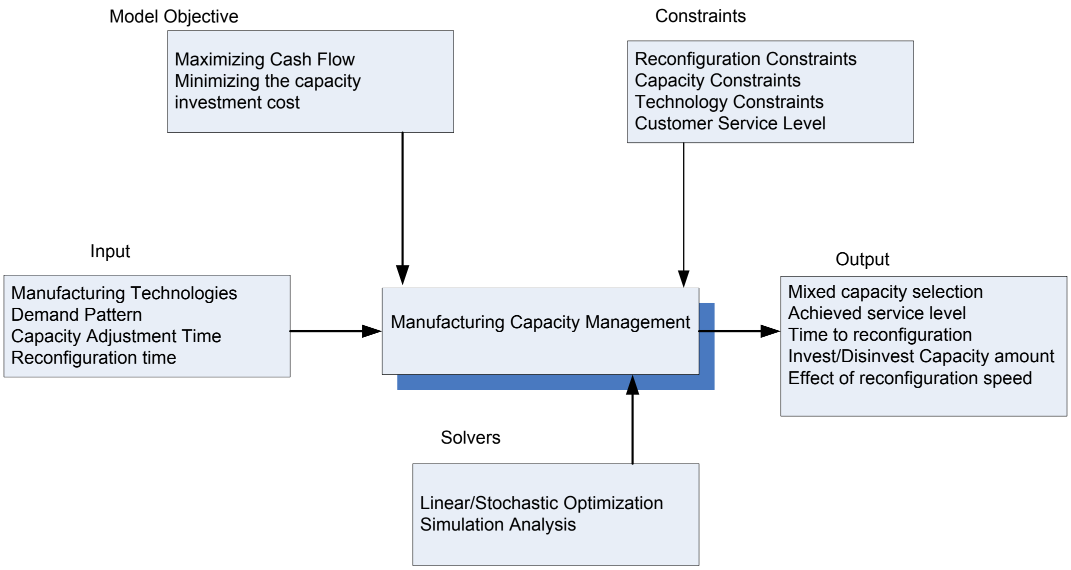


Figure 1-4 Schematic of proposal model

By performing sensitivity analysis on the MILP model and verifying the results through the simulation, ideal characteristics of ramp up behaviour are determined. Also, this decision making framework provides manufacturer a good approach for analysing a manufacturing system type or combination of different manufacturing systems in satisfying customer demand with appropriate amount of required capacity.

1.6 Contributions

Contributions of the thesis are threefold. First, by developing a mathematical model and implementing sensitivity analysis, it is shown how a firm should optimally allocate its capacity investment among DMS, FMS, and RMS considering the capacity evolution in ramp up period. The proposed model addresses a firm making multiple products for which demand is deterministic and has a specific life cycle. The duration of reconfiguration is modeled as function of the amount of capacity change. This improvement in modeling approach will lead to better manufacturing system selection by avoiding the underestimation or overestimation of the required capacity.

Second, at the tactical decision making level by incorporating the layout characteristics of selected system alternatives comprising of (DMS) and (RMS), it is intended to analyze what type of reconfiguration is more suitable for a manufacturer in terms of system layout and response range. Through a mixed integer programming model which incorporates various ramp up time patterns and takes into account RMS and DMS scalability lead time, it is seen how capacity is allocated to RMS and DMS based on system cost, system responsiveness, and reconfiguration speed.

Third, the impact of critical operational characteristics such as response time and congestion are added to MIP model along with a modified mathematical model where disruption scenarios are incorporated. The appropriate response speed is selected through a decision tree analysis by minimizing the expected costs of a two echelon supply chain. The selection is made with respect to three different attitudes of the decision maker towards risk. Through a sensitivity analysis, it is shown that a faster response speed is a better choice for manufacturer as the failure probability increases and/or recovery probability decreases.

1.7 Thesis Outline

The reminder of this thesis is organized as follows: Chapter 2 provides a comprehensive literature review on the capacity management in manufacturing system and reviews the major study around the capacity investment on manufacturing system. The relevant literature is divided to three separate sections: First, the internal factors of selecting, updating, and improving capacity through the product life cycle and industry behavior are reviewed. The goal of this section is to understand how these factors are affecting the optimal capacity selection regarding the investment cost, technology choice and market behavior. Second, the external factors on capacity management are reviewed. The goal of this section is how indirect factors such as new product development, time to market could impact the capacity management. Finally, reconfiguration period is reviewed precisely to understand how RMS can help decision makers to come up with improved capacity selection along with other systems such as DMS or FMS. At the end of literature review a condense summary of all literature sections is discussed from strategic, tactical and operational perspective. Also, the importance of each system from the strategic, tactical and operational level is reviewed.

Chapter 3 presents the mathematical model of how a firm should optimally allocate its capacity investments among DMS, FMS and RMS considering the capacity evolution in ramp up period. The proposed model addresses a firm making multiple products for which demand is deterministic and has a specific life cycle. Furthermore, the duration of reconfiguration period is modeled as a function of the amount of capacity change. Chapter 4 investigate the optimal allocation of a firm’s capacity investments at the tactical decision making level by incorporating the layout characteristics of selected system alternatives comprising of DMS and RMS. Particularly, sequencing of stages in a series or a parallel configuration impacts the responsiveness in addressing to capacity change requirements. Furthermore, the analysis is extended to suitable reconfiguration type for a manufacturer in terms of system layout and response range. In this chapter a MILP model is proposed which incorporates various ramp up patterns and takes into account RMS and DMS scalability lead time. By solving the MIP model to optimality, it is observed how capacity is allocated to RMS and DMS based on system cost, system responsiveness, and reconfiguration speed. A discrete event simulation model is used to validate the MIP results under uncertain demand scenarios. Chapter 5 combines the effect of work in process congestion on capacity management and considers how the speed of RMS could help to resolve the issue of congestion during the DMS disruption period. Chapter 6 contains summary, conclusion and future research. This chapter also highlights the major contributions of this thesis.

Chapter 2: Literature review

The relevant literature is divided to three separate sections: First, the internal factors of selecting, updating, and improving capacity through the product life cycle and industry behavior are reviewed. The goal of this section is to understand how these factors are affecting the optimal capacity selection regarding the investment cost, technology choice and market behavior. Second, the external factors on capacity management are reviewed. The goal of this section is how indirect factors such as new product development, time to market and risk of investment could impact the capacity management. Third, the studies that incorporate reconfiguration period are reviewed to understand how RMS can help decision makers to come up with improved capacity selection along with other systems such as DMS or FMS. As a conclusion, a critical summary that integrates the above areas within capacity planning at the strategic, tactical and operational levels is presented.

There are different definitions of capacity in literature in Slack et al. (1995) and Buffa (1983). However, a comprehensive definition is given by Van Mieghem (2003) which defines capacity as a measure of processing abilities and limitations that stem from the scarcity of various processing resources and is presented as vector of stocks of various processing resources. The author reviews the literature on strategic capacity management concerned with determining the sizes, types and timing of capacity adjustments under uncertainty and believes stochastic capacity portfolio optimization for capacity planning are essential.

Luss (1982) shows different applications of capacity expansion models in different industries and review the existing models and solution methodologies in the area of capacity expansion. As a conclusion the major factors regarding the capacity management are categorized as follows:

- Size: Finite/Continuous
- Time: Single period/Multiple Period
- Location: Single/Multiple
- Cost: Holding Cost/ Congestion Cost
- Demand: Stochastic/Deterministic
- Deferring expansion: Shortage/Inventory
- Decision maker constraints: Upper bound on expansion sizes
- Capacity modification: capacity conversion/Replacement
- Special issues with multi facility : multi types (product)/ multi locations

Julka et al. (2007) review a current state of research for capacity expansion in manufacturing plants of corporations. They classified factors as input and output in order to contrast previous models. Tables 2-1 to Table 2-3 show the frequency of consideration of these factors in previous models.

Table 2-1 Models input factors and frequency usage (Julka et al.(2007))

Inputs	**Examples**	**Cited**
Production Cost	Production Cost, Labor costs,	43
Investment Cost	Capacity Unit Cost, Capacity replacement cost	20
Product demand	Demand uncertainty, Unsatisfied demand	17
Initial Capacity	Initial Flexible Capacity, Initial Dedicated Capacity	10
Investment Budget	Regional expansion budget, Global expansion budget	6
Market Economic Factors	Shortage Penalty, Local Taxes	6
Accounting Policies	Expected net present values, Allocation of overhead	6
Lead Time and Learning	Capacity expansion lead time, Learning cost reduction	4
Other Costs	Capacity holding cost, Capacity relocation costs	3
Production Efficiency	Input-Output relation, Technical coefficient modeling	2

Table 2-2 Model output factors and the frequency of usage (Julka et al.(2007))

Output	Examples	Cited
Production volume	Dedicated Technology, Flexible Technology	9
Amount of capacity addition	Dedicated Technology, Flexible Technology	8
Production quantity		8
Timing of capacity expansion		6
Total capital invested	New Facility	5
Return on capital invested		4
Labor, production and transport costs		4
Price of product	Dedicated Technology, Flexible Technology	3
Inventory carrying costs	Input-Output relation, Technical coefficient modeling	3
capital invested in each plant		3
Total discounted costs	Capacity holding cost, Capacity relocation costs	2
Capacity shifted	from old facility to new	1

While the factors being considered are numerous, the assumptions made by the scholars in developing capacity management models are listed in Table 2-3.

Table 2-3 Model assumptions by frequency of usage

Assumption	Cited
Dedicated technology available	8
Single plant producing multiple products	6
Multiple plants Multiple products	5
Flexible technology available	3
Risk of capacity shortages	3
Limited global budget	3
Deferred capacity expansion	2
Limited regional budget	2
Capacity take certain lead time to come online	1
Input-output Relationship between plants	1
Limited transport capacity	1
Service level to customer	1
Limited intra-regional shipment	1
Machine replacement permitted	1
Quantity discount	1
Overhead absorption of products at plant	1
Capacity relocation permitted	1

Among the above factors, market demand (Rocklin et al. (1984), Ryan (2004), and Netessine et al. (2002)) and cost of capacity acquisition (Ryan and Marathe (2009), Bernstein and DeCroix (2004)) always have been considered as the main factors in considering the capacity selection problem. All other factors could be added to analysis based on the complexity of analyzed problem. This study shows that a realistic capacity planning model should at least have the factors stated in Table 2-4

Table 2-4 Important input and output factors a model must possesses

Input	Output
1) Product demand	1) Production volume
2) Investment Cost	2) Amount of capacity addition
3) Production Cost	3) Production quantity
4) Initial Capacity	4) Timing of capacity expansion

2.1 Capacity management in manufacturing systems

Investment in capacity has a major role in a firm’s cash flow. With ever shrinking product lifecycles in today's competitive markets, the machinery will become obsolete faster than before due to new technologies and unpredictable nature of market demand. Therefore, the selection of proper manufacturing system that can accommodate these requirements is a must.

Among the possible production systems, DMS could be a best option for producing the product quickly and cost efficiently. Nevertheless, DMS is cost effective as long as demand exceeds supply. In today's world DMS cannot be a reliable source of production because DMS’s single product functionality does not cover the scope of customized products requested by the customers.

In contrast to DMS, FMS focuses on customized production and is able to produce a small batch of several part families on the same system with shortened change over time (Li Tang et al, 2005). The reduced capacity of FMS, high initial investment caused manufacturers to adopt FMS only in markets with high product margins and high variety.

Fine and Freund (1990) study investment in product-flexible manufacturing capacity. Using a two stage stochastic programming model, the firm decides about the investment in manufacturing capacity before the resolution of uncertainty in product capacity. The second stage, i.e. when the demand for products is known, the firm implements its production decisions, constrained by the first stage investment. Analysis done by the authors show that at larger demand risk, a larger investment in dedicated capacity is needed and flexible capacity is only useful if it can produce cheaper than dedicated capacity at higher risk

Van Mieghem (1998) performs a similar analysis and investigates the optimal investment in flexible manufacturing capacity as a function of product prices. It is shown that it is not always advantageous to invest in flexible capacity when the product demands? are uncorrelated.

Another study regarding the cost of capacity investment in dedicated and flexible system under uncertain demand has been done by Ceryan and Koren (2009). In this study, the capacity selection is formulated to show how decisions are affected by the investment costs, product revenues, demand forecast scenarios and volatilities over the planning period. The analysis and numerical examples shows that optimal investment strategies include a larger share of flexible systems under low flexible investment cost, high product revenues, and high demand uncertainties within and across periods.

With the introduction of RMS paradigm, several studies focus on investment comparison with conventional manufacturing systems. Narongwanich et al. (2002) develop a model which optimally allocates capacity investments between dedicated systems (DMS) and reconfigurable systems (RMS) in different demand scenarios. The result of their model shows that firms should keep a portfolio of dedicated and reconfigurable machines tools, and the mix should be driven by relative costs of each, considering the frequency of new products to market and the stochastic nature of demand level They argue that ISD (Invest, Stay, and Disinvest) policy is valid when the capacity comes in discrete increments rather than continuous and is optimal when the DMS and RMS modules have identical module sizes. Equality of DMS and RMS modules is not a valid assumption since RMS aims to provide better scalability.

In addition to the capacity evolution and production capabilities that impact the manufacturing system selection, other external factors such as product demand also play an important role. Therefore, before focusing on the feature of RMS and response time of RMS during the market changes, the influence of external factors such as market dynamics are reviewed.

2.2 Negative impacts of external factors that can be reduced by response time

The market dynamics are influenced by two major factors: new product introductions, external disruptions. For example, in electronic and semiconductor industry, the frequency of new product introduction is high. Thus, in this market, manufacturers regularly require new investment in machinery. In such an environment, the risk of not satisfying market demand could cause major loss of market share (e.g. Research In Motion Company). On the other hand, the occurrence of capacity disruptions caused by natural disasters such as earthquake or fire may result in some capacity changes as a result of a contingency strategy. In such conditions, the responsiveness of the production facilities is critical. In the face of disruptions, usually the demand of product temporarily shifts to a backup supplier while the production capacity of main supply nodes is reduced remarkably.

The most important factors that trigger the response time in capacity management area are new product introductions and disruptions. Every stage of product life cycle requires the new capacity level selection whereas disruptions require a prompt adjustment of capacity in order to recover the affected service. In this section the importance of these factors towards capacity planning and selection are reviewed in detail.

2.2.1 Product lifecycle

Market demand and product lifecycle has a direct impact on capacity selection (Angelus and Porteus, 2002). Lifecycle of any product is divided to four stages, introduction to market, growth, maturity, and the decline stage. Each stage has a distinguished characteristic and differs from one product to another product. However, in terms of the capacity requirement, a similar strategy could be generalized without considering the product type specification. For example, in growth stage, excess capacity is more desirable than any other life cycle stage. Angelus and Porteus (2002) consider product life-cycle in capacity and production management. They assume that product demand increases stochastically at the beginning of the life cycle and decrease after a specific time period. The developed model is an extension of newsvendor model which grasps both perishable (left over inventory cannot be carried over to next period) and non-perishable products. The policy for managing capacity is followed by ISD (Invest, Stay put, Disinvest) policy which can be defined as a chase strategy: if initial capacity is below the lower target limit, then bring the capacity up to that limit, if initial capacity is above the upper target limit, then bring capacity down to that limit, otherwise, make no changes. The optimal capacity plan follows the trend of product lifecycle and it falls in expansion period, constant period and downsizing period. In a similar study, Chen, et al, (2002) grasp the uncertainty in product life cycles and analyze the effect of dynamic demands in a manufacturing plant with multiple products. A stochastic programming approach is used to determine technology choices and capacity plans.

In addition to the shape of product life cycle, the frequency of product introduction to market also has impact on capacity selection and responsiveness. Druehl et al. (2009) believe that a faster pace is generally associated with faster diffusion, a higher market growth rate and faster margin decay. So, minor differences in the product development cost function can significantly impact the pace. It means that subtle differences in the shape of the product development cost curve, can result in differences of more than fifty percent in the pace of new generations. Therefore, faster pace of new product to market needs an agile manufacturing system and requires a proactive capacity selection policy rather than a reactive policy.

Along with Druehl et al.'s (2009) work, Hendricks and Singhal (2008) show the impact of new product delay for firms. They conclude that delay in releasing new product, statistically, has significant negative impact on profitability. The importance of agility becomes more visible when the correlation between the product lifecycle and capacity reaction is taken to account.

2.2.2 Disruptions

A short and frequent product lifecycle is not the only factor requiring system agility; the occurrence of disruption could also change the decision towards the capacity type, which requires faster reaction and recovery. For example, Toyota, Nissan and Honda closed` their plants in Japan and General Motors suspended the production in its assembly plant in USA due to the part shortage (Ghadge et al, 2011) because of Japan tsunami in 2011.

Disruption in supply chains is defined as “random events that cause a supplier or other elements of the supply chain to stop functioning, either completely or partially, for a typically random period of time” (Snyder et al. (2010))

The effect of disruption and capacity diversification usually appears in the context of supply chain (Chopra and Sodhi (2004)) and encourages the decision maker to plan for capacity diversification. The decision maker can usually take advantage of scatter capacity allocation in different geographical regions. Tang (2006) introduces several strategies for dealing with disruption where a prefunding advantage is given to robust strategies. Robust strategies are defined as those strategies which works cost-efficiently both in normal and abnormal situations. Wilson (2008) introduces time, inventory and excess capacity as three different buffers that could be used against uncertainty in a manufacturing system which can be generalized for a supply chain as well.

There are several researchers who have tried to apply simulation techniques to evaluate the supply chain against unpredictable events. Tomlin (2006) considers a situation where two different types of supplier exist, one reliable and the other one unreliable. The author investigates different strategies in order to identify which supply chain configuration can be robust against disruptions and develops some insights on, which strategy can maintain a reasonable trade-off between cost and service level. Schmitt (2009) tries to simulate a real case to investigate how a supply chain reacts to possible supply chain disruptions. Deleris (2005) provides a decision support tool based on simulation to evaluate risk exposure of a supply chain. One of the solutions for minimizing the disruption effect is contingency strategy. In this strategy, supply network should be reactive to disruption and try to minimize the negative effects in minimum possible time. The main issue in identifying this recovery strategy is how responsiveness of manufacturing system could benefit the supply network at the time of disruption. The responsiveness of the manufacturing system is related to its agility.

In summary, it can be claimed that the optimal capacity level of any firm is impacted by the trend of product lifecycle and reaction capability to market dynamics. Table 2-5 summarizes all the scholar works from different level of decision making in capacity management. In this table, all the important factors are categorized at each level.

The main question is how fast the company should adjust the capacity level and update the amount of capacity as the market demand changes. While the strategic level approach focuses on capacity investment decisions from the supply chain perspective and strategic interactions between different players, the operational level focuses on product and firm-specific operational environment. The differentiating factor of scalability and ramp up pattern will have the most visible impact on tactical level decision making in terms of capacity expansion decisions and production allocation to each capacity type.

Therefore, in section 2.3, we critically assess the literature from different decision making levels by focusing on the tactical level analysis of capacity planning.

Table 2-5 Capacity management most important factors

Factors Scholars	Stochastic demands	Investment	Product life	Serviceability	Lead time	Multi products	Technology	Product revenue	Forecast	Risk	Prices	Other Costs	New product development	Disruption
Rocklin et al (1984)	✓	✓										✓		
Angelus et al (2002)	✓		✓											
Netessine et al (2002)	✓			✓										
Ryan (2004)	✓			✓	✓							✓		
Fine et al (1990)	✓	✓					✓							
Van Miegham (1998)		✓					✓				✓			
Narongwanich et al (2002)	✓	✓				✓	✓						✓	
Ceryan et al (2009)		✓				✓		✓	✓					
Chen et al (2002)	✓		✓				✓							
Schmidt et al (2005)											✓	✓	✓	
Druehl et al (2009)												✓	✓	
Hendricks et al (2008)													✓	
McAllister et al (2000)	✓								✓	✓		✓		
Van Miegham (2007)							✓	✓		✓				
Bi et al (2008)			✓		✓			✓			✓		✓	
Spicer et al (2007)		✓			✓							✓		
Kuzgunkaya(2007)		✓			✓		✓	✓						
Metta et al (2008)	✓				✓		✓						✓	
Deleris (2005)		✓			✓					✓				✓
Wilson (2008)		✓			✓					✓				✓
Tomlin (2006)		✓		✓	✓									✓
Schmitt (2009)		✓								✓				✓

2.3 Impact of reconfiguration characteristics for capacity investment strategies

Capacity planning and management usually consists of determining the type of production systems as well as capacity expansion/contraction times. The first opportunities in capacity planning area falls in expanding the set of factors deemed important for capacity expansion (Julka et al. (2007)). With the increasing volatility of demand and more frequent product introductions, the planning of capacity becomes even more important for capital intensive industries. This problem can be analyzed at the strategic, tactical and operational levels (Wu et al., 2005).

At the strategic level, most of the studies are performed using dynamic stochastic optimization models to incorporate randomness and to account for the trade-off between excess capacity costs and lost sales during capacity expansions. Van Mieghem (2003) provides a detailed review on capacity management where factors such as risk aversion, multiple capacity types, hedging, and demand stochasticity are modeled. In Ryan and Marathe (2009), authors formulate a model to minimize expected discounted expansion cost under a service level constraint for infinite horizon. The authors consider only the capacity expansion and ignore the effects of capacity reduction. Moreover, the capacity expansion lead time is considered fixed; therefore, these studies ignore the partial capacity that can be available during the expansion period.

In addition to incorporating lead time effects, the capacity scalability or lumpiness of capacity of manufacturing systems is also considered at the strategic level by several authors. In the model developed by Narongwanich et al. (2002), equality of DMS and

RMS modules is not a valid assumption since RMS aims to provide better scalability. In order to highlight the importance of the scalability factor, Deif and ElMaraghy (2007) propose a model to manage capacity scalability on the RMS at system level according to total investment cost. The proposed model relaxes the assumption of fixed capacity increments, thereby giving the system designers ability to decide when to reconfigure the system according to the scale of capacity and by how much to scale it in order to meet the market demand in a cost effective way. However, this model assumes that the lead time is zero and ignores the ramp up period.

At the tactical and operational level, most of the previous studies focus on multiple period problems using mixed integer programming or stochastic programming approach to account for the demand uncertainty. Ceryan and Koren (2009) show how a range of investment cost parameters, product revenues, and demand uncertainties influence capacity portfolio by considering both DMS and FMS which have different scalabilities .Authors analyze multiple products demand for three consecutive periods using stochastic approach; however they do not integrate the lead times for capacity modifications. The optimal control theory based works by Asl and Ulsoy (2003), Matta et al. (2007) develop an optimal policy where reconfiguration periods are considered in a single product with random demand environment. In the model proposed by Matta et al. (2007), the ramp up is limited to a maximum of 50% of the available period. While this work is one of the better representations of ramp up periods, the duration of the ramp up is independent of the amount of capacity increase. According to Terwiesch and Bohn (2001), who investigate the impact of learning on the duration of ramp up, the time to reach full capacity decreases as learning is achieved through the experiments performed during ramp up periods. These prior works show that the throughput performance of manufacturing systems is affected by the activities during the ramp up period.

At the operational level, the works by Kuzgunkaya and ElMaraghy (2007), Spicer and Carlo (2007) provide more detailed capacity planning models by integrating reconfiguration characteristics. Spicer and Carlo (2007) propose a model which investigates the optimal configuration path of a scalable RMS in order to minimize investment and reconfiguration costs over a finite horizon with known demand. The assumption of identical capacity types and single product environment does not allow for a comparison of different scalabilities of manufacturing systems on the long run.

Moreover, at the operational level, the production environment is subject to variations in the production rate or customer arrival rate. These variations increase the resource utilization which leads to the longer lead time due to the congestion. The system throughput decreases over a certain period of time as the lead time increases. Ignoring the impact of the congestion in decision stage may lead to the overestimation of the production capability (Pahl et al., 2007).

Another aspect affecting the operational level decisions is the arrangement of machines and layout facility and their impact on reconfiguration time. Optimal line design always look for the better configuration of machinery and allocation of tasks to satisfy criteria such as maximum service level and minimum cost (Tang et al., 2003). Koren et al. (1998), consider different system configurations. System configurations involve changing process routes, relocation of machines, sharing machines, retooling machines and/or using multi-directional material handling system. Authors conclude that different configurations impact adaptability, reliability, productivity, product quality, and cost.

Abdi (2009) investigates the criteria which influences RMS layout configuration. The author develops an Analytical Hierarchical Process (AHP) model that considers layout re-configurability, cost, quality and reliability as different criteria. In this model, the criteria are applied to three possible layouts: serial configuration, parallel configuration, and hybrid configuration (Figure 2-1). The solution of the model, which is sensitive to firm priority, could reveal the best layout re-configurability.

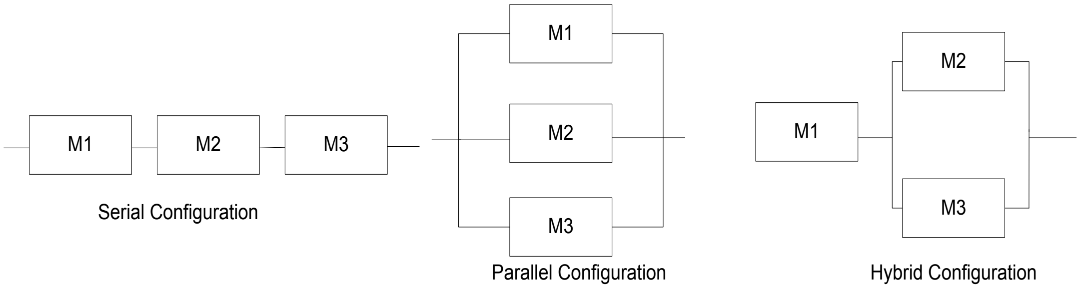


Figure 2-1 System layout configuration

Therefore, the selection of a good and reliable configuration is a must for manufacturer which influences the life cycle cost of the manufacturing system. In conclusion, the factors could have major impact on capacity planning at tactical level are reconfiguration characteristic, system layout configuration, and production throughput at each period.

2.4 Conclusion

In order to respond the market change quickly, one of the important characteristics of any manufacturing system especially RMS should be proper reconfiguration speed. The speed of reconfiguration depends on manufacturing system configuration such as interaction of RMS with other types of systems or its configuration layout. Therefore, the initial configuration and selection of any manufacturing system has a profound effect on the system adjustment step size speed and its cost over any product life cycle.

The impact of the scalability and RMS ramp up behavior should be considered simultaneously in manufacturing system selection. Moreover, instead of fixing the ramp up period length, the ramp up duration should be considered as a function of the capacity change level. This difference in system characteristics affects the availability of DMS, FMS, and RMS capacity during the planning time horizon. The proposed work in chapter 3 consider these specifications of ramp up characteristics and closely relates the ramp up model developed by Matta et al. (2008) and the works on capacity planning by Kuzgunkaya and ElMaraghy (2007), Spicer and Carlo (2007).

Moreover, besides system characteristic, initial configuration of manufacturing system could affect system agility. In other words, the ramp up time of a system is also dependent on system layout. In chapter 4, different ramp up patterns gained from different system configuration is investigated on service level during reconfiguration period. This subject is important since any ramp up pattern has major impact on available capacity during reconfiguration. Therefore, ignoring the capacity level during reconfiguration period may lead to inaccuracies of the actual capability of a manufacturing system. For example, the overestimation of capacity may lead to losing demand and reduction of service level, whereas underestimating the capacity causes the firm to carry extra capacity. By considering the shape of ramp up from one type of configuration to another, the impact of reconfiguration on demand service rate is investigated.

In addition to all mentioned ramp up characteristics, a better representation of available capacity during reconfiguration would incorporate the congestion. Production congestion analysis helps decision maker avoiding the overestimation of the available capacity during reconfiguration and provides a better picture of required ramp up speed to achieve required capacity. The effect of response speed in improving the service rate should be analyzed from capacity planning decision perspective.

Chapter 3: Impact of reconfiguration characteristics for capacity investment strategies in manufacturing systems

In this chapter, a decision model is developed based on DMS, FMS, and RMS characteristics to explain how product life cycle and frequency of new product introductions could affect the selection of manufacturing systems. The ramp up time and reconfiguration period of RMS is incorporated in the model as a function of the amount of added or removed capacity. It is examined how the capacity mix of manufacturing systems is affected by the changes in excess capacity cost, shortage cost, reconfiguration speed.

Ramp up time and speed depends on the manufacturing system characteristics. In order to analyze the impact of the various manufacturing system capacity characteristics, especially RMS reconfiguration feature, it is assumed that a company, currently producing one product, called (A), and the company is going to introduce new product (B) and (C) in the future based on deterministic pace. The decision maker has a choice between Dedicated, Flexible, and Reconfigurable Technology or a portfolio of those to invest. Scalability and functionality of these technologies are considered dissimilar.

DMS provides a large scale capacity just for one product family. The unit purchasing cost of DMS is less than both RMS and FMS as a result of the economies of scale. FMS has the ability to produce all products concurrently. The cost of purchasing FMS is higher than both DMS and RMS because of redundant functionality and capacity that a Flexible system provides through process flexibility. Flexible system provides better scalability than DMS. Since FMS is designed based on a product family in the anticipation of future changes, its complexity does not provide an easy option for capacity changes. Since all of FMS's capabilities may not be fully utilized by the manufacturers, the investment in redundant capability and capacity in anticipation of future product designs might impose a financial risk to the firm. Based on these characteristics it is assumed that FMS can modify its capacity in larger scale.

Reconfigurable Technology has the better scalability Compared to DMS and FMS. This is achieved thanks to the machine structure which consists of a base on which product specific modules could be added/removed in later periods when it is necessary. This allows capacity and capability to be updated according to market demand. The systems' scalability is determined with a parameter and this parameter is set as the lower bound of capacity that is added to each system.

Adding/removing capacity causes RMS to go under reconfiguration and some amount of capacity becomes unavailable due to downtime. This characteristic can also be associated with the expansion flexibility of a manufacturing system. Therefore, the assumptions made for FMS and RMS in this model allows comparing the manufacturing systems that have two different type of flexibility in meeting the demand changes.

Capacity unavailability during reconfiguration depends on the level of responsiveness. In this chapter an improved model of capacity modification is presented by considering the amount of modified capacity as a function of time and amount of capacity. This improvement not only helps firms to consider ramp up time in a linear trend but it also enables them to analyze ramp up time when capacity modification follows a nonlinear trend. For example, at the early stage of reconfiguration period the increase in capacity will be in small increments. As the system inefficiencies are solved in the ramp up phase, the desired capacity level will be reached at a faster rate. A linearization approach is developed as an approximate way of modeling the capacity modification during reconfiguration. This approach is explained in detail in section 3.2.

The capacity cost profile of each manufacturing system can be another factor in the investment decisions. Dedicated, Flexible, Reconfigurable unit capacity costs is chosen according to the complexity of each manufacturing system (Spicer et al. 2005). These cost ratios are chosen based on their scalability and capability to accommodate multiple products. Flexible System is purchased with a higher cost ratio since it is designed with process flexibility to produce all product families at the time of purchase. RMS comes with lower capacity cost compared to FMS thanks to its modular structure. DMS has the lowest cost ratio since it is dedicated to only one product family.

Since the modular structure of RMS capacity is achieved by decomposing it into modules, the allocation of the capacity cost between the modules and the base can impact the scalability profile of RMS. Therefore, DMS, FMS and base of RMS could be purchased instantaneously with the lower bound of their capacities.

Finally without loss of generality, it is assumed that either capacity expansion or contraction is allowed at each period. Each purchased capacity is depreciated completely after five consecutive periods and the amount of capacity reduction for Dedicated and Flexible Capacity in future periods must be equal to the exact purchased amounts in past periods.

In addition to system characteristics, the demand trends also have a major impact on capacity selection. For example, in electronic industry, new products are usually released annually whereas in the auto industry they are released every three to four years. These trends can be industry specific. The capacity selection is analyzed based on three main trends seen in the consumer products. Our objective is to observe the impacts of different system scalability characteristics on capacity selection. Therefore, each system is built based on the forecasted demand information. Since DMS and FMS systems are built based on anticipated forecasts due to their low scalability, proposed model assumes that these alternatives may build capacity ahead without allowing for the inventory to carry over to future periods. On the other hand, RMS has higher scalability for which allows the capacity change only in the required period. Proposed model does not allow any inventory carry over to the following period for any manufacturing system; this assumption allows the comparison of manufacturing alternatives based on their responsiveness. In addition to above assumptions, a discount factor of 2% percent is assumed at each period and the unmet demand is considered as lost in the time horizon of T.

In summary the assumptions of the problem are:

- DMS provides a large scale capacity just for one product family.
- Unmet demand is considered as lost.
- Unit purchasing cost of DMS is less than both RMS and FMS.
- Either capacity expansion or contraction is allowed at each period.
- No inventory is carried over to the following period.
- Cost ratios are chosen based on each system scalability and capability.
- RMS is the only system that goes under reconfiguration.

Based on these assumptions, the objective is to analyze the system selection according to product life cycle and new product introduction patterns, and to maximize net present value of cash flows. The costs of product shortage, excess capacity holding cost, and technology acquisition costs are considered as the main considerations of the decision maker. In order to analyze this research problem a mixed integer programming formulation this is described in the next section.

3.1 Proposed model and description

This section describes the objective function and system related constraints. The complementary indices are shown in chapter 3 list of acronyms. For clarity purposes, in this section the constraints related to capacity increases is explained and the explanation of constraints related to the removal of capacity for DMS, FMS, and RMS is discussed in appendix A. The following section presents each group of the objective function:

The objective function is set based on cash flow maximization for a predetermined time horizon T. Sales revenue (3-1) and salvage value of removed capacity are the firm's positive cash flows. On the other hand, investment cost, and reconfiguration cost are the firm's negative cash flows. The shortage cost (3-2) and the excess capacity cost (3-3) in the objective function are considered as two opportunity costs to incorporate the decision maker's attitude towards risk in selecting capacity allocations.

Maximize

Production sale, Shortage cost, and Excess Capacity cost

$$+\sum_{i=1}^{T}\sum_{p=1}^{P}\beta_i \mathrm{PP}_{i,p}\ \left(X_{i,p}+Z_{i,p}+Q_{i,p}\right) \tag{3-1}$$

$$-\sum_{i=1}^{T}\sum_{p=1}^{P}\beta_i\,\gamma_{i,p}\mathrm{SA}_{i,p} \tag{3-2}$$

$$-\sum_{i=1}^{T}\sum_{p=1}^{P}\beta_i\,(EPC_{i,p}^{d}EC_{i,p}^{d}+EPC_{i,p}^{r}\,EC_{i,p}^{r})-\sum_{i=1}^{T}\beta_i EPC_{i}^{f}\,EC_{i}^{f} \tag{3-3}$$

DMS

$$-\sum_{i=1}^{T}\sum_{p=1}^{P}\beta_i\, CC_{i,p}^{d} PC_{i,p}^{d} \tag{3-4}$$

$$+\sum_{i=1}^{T}\sum_{t=1}^{i}\sum_{p=1}^{P}\beta_i\, SCF_{i,t,p}^{d} RC_{i,t,p}^{d} \tag{3-5}$$

FMS

$$-\sum_{i=1}^{T}\beta_i CC_i^{f} PC_i^{f} \tag{3-6}$$

$$+\sum_{i=1}^{T}\sum_{t=1}^{i}\beta_i SCF_{i,t}^{f} RC_{i,t}^{f} \tag{3-7}$$

RMS

$$-\sum_{i=1}^{T}\beta_i RBC_i MRC_i \tag{3-8}$$

$$-\sum_{i=1}^{T}\sum_{t=1}^{i}\sum_{p=1}^{P}\beta_i\, RMC_{i,p} ADDMLE_{i,t,p} - \sum_{i=1}^{T}\sum_{p=1}^{P}\beta_i\, RMC_{i,p} ARMC_{i,i,p} \tag{3-9}$$

$$+\sum_{i=1}^{T}\sum_{t=1}^{i}\sum_{p=1}^{P}\beta_i\, RMSCF_{i,t,p} RMDMLE_{i,t,p} + \sum_{i=1}^{T}\sum_{t=1}^{i}\beta_i RBSCF_{i,t} RC_{i,t}^{r} \tag{3-10}$$

$$-\sum_{i=1}^{T}\beta_i \left(\sum_{p=1}^{P} RTC1\, RL1_{i,p} + RTC2\, RL2_{i,p} + RTC3\, RL3_{i,p} + RTC4\, RL4_{i,p} + RTC5\, RL5_{i,p}\right) \tag{3-11}$$

Capacity investment could be done on each of DMS, FMS, and RMS or a mix of those systems. In DMS and FMS capacity cost (3-4, 3-6) and capacity salvage revenue (3-5, 3-7) are included. RMS structure differs from DMS and FMS. In RMS, the base cost as well as the module acquisition cost is included whereby the modules of each base could be purchased in later periods (3-8, 3-9) and then removed with specific salvage revenue (3-10). Also, RMS has the reconfiguration cost (3-11) for the modules which are integrated to RMS at later periods.

In the constraint section of the model the demand balance constraint is included (3-12) whereby demand is either satisfied with available capacity (DMS, FMS, or RMS) or lost. Furthermore, each group of manufacturing system constraints is discussed separately.

Demand Satisfaction

$$Z_{i,p} + X_{i,p} + Q_{i,p} + SA_{i,p} = D_{i,p} \qquad \forall\, i \in T, \forall\, p \in P \qquad \textbf{(3-12)}$$

3.1.1 Dedicated capacity constraints

DMS scalability is worse than FMS and RMS. It provides the largest step increase in capacity among all other systems (3-17). Since DMS produce one product family (3-13), the capacity is purchased separately for each product. Furthermore, a dedicated capacity purchase can be removed only at a later period by the same amount (3-14... 3-16, 3-18).

$$\alpha^{p} X_{i,p} + EC^{d}_{i,p} = \sum_{t=1}^{i} PC^{d}_{t,p} - \sum_{l=1}^{i} \sum_{t=1}^{l-1} RC^{d}_{l,t,p} \qquad \forall\, i \in T, \forall\, p \in P \qquad \textbf{(3-13)}$$

$$RC^{d}_{i,t,p} \le PC^{d}_{t,p} + \boldsymbol{M} * (1 - SD^{d}_{i,t,p}) \qquad \forall\, i \in \{2,..T\}, \forall\, t \in \{1,..,i-1\}, \forall\, p \in P \qquad \textbf{(3-14)}$$

$$RC^{d}_{i,t,p} \ge PC^{d}_{t,p} - \boldsymbol{M} * (1 - SD^{d}_{i,t,p}) \qquad \forall\, i \in \{2,..T\}, \forall\, t \in \{1,..,i-1\}, \forall\, p \in P \qquad \textbf{(3-15)}$$

$$RC^{d}_{i,t,p} \le \boldsymbol{M} * (SD^{d}_{i,t,p}) \qquad \forall\, i \in \{2,..T\}, \forall\, t \in \{1,..,i-1\}, \forall\, p \in P \qquad \textbf{(3-16)}$$

$$PC^{d}_{t,p} \ge ScalarD * (SU^{d}_{t,p}) \qquad \forall\, t \in T, \forall\, p \in P \qquad \textbf{(3-17)}$$

$$\sum_{i=t+1}^{T} RC^{d}_{i,t,p} \le PC^{d}_{t,p} \qquad \forall\, t \in T, \forall\, p \in P \qquad \textbf{(3-18)}$$

DMS variables

$PC^{d}_{i,p}$	Purchased Dedicated Capacity at Time i for product p
$SU^{d}_{i,p}$	1 Dedicated Capacity is Scale Up at time i for product p 0 Otherwise
$SD^{d}_{i,t,p}$	1 Purchased Dedicated Capacity at time t for product p is scaled Down at time i 0 Otherwise

$RC_{i,t,p}^{d}$	Removed Dedicated Capacity which is purchased at time t for product p at time i
$EC_{i,p}^{d}$	Dedicated Excess Capacity at time i for product p
$X_{i,p}$	The amount of product p which is produced by Dedicated Capacity at time i

3.1.2 FMS and RMS capacity constraints

FMS provides better scalability than DMS (3-20) and it is able to produce multiple products' families based on its process flexibility (3-19).

$$\sum_{p=1}^{P} \vartheta^{p} Z_{i,p} + EC_{i}^{f} = \sum_{t=1}^{i} PC_{t}^{f} - \sum_{l=1}^{i} \sum_{t=1}^{l-1} RC_{l,t}^{f} \qquad \forall\, i \in T \tag{3-19}$$

$$PC_{t}^{f} \geq ScalarF * (SU_{t}^{f}) \qquad \forall\, t \in T \tag{3-20}$$

FMS variables

PC_{i}^{f}	Purchased Flexible Capacity at time i
SU_{i}^{f}	1 Flexible Capacity is Scaled Up at time i 0 Otherwise
$SD_{i,t}^{f}$	1 Purchased Flexible Capacity at time t is Scaled Down at time i 0 Otherwise
$RC_{i,t}^{f}$	Removed Flexible Capacity which is purchased at time t at time i
EC_{i}^{f}	Flexible Excess Capacity at time i
$Z_{i,p}$	The amount of product p which is produced by Flexible Capacity at time i

RMS is able to produce multiple product families similar to FMS (3-21).However, in terms of scalability, RMS acts better than FMS because of its modular structure. Each product's capacity module is installed on a base (3-22), allowing new modules to be integrated to RMS in later periods (3-25) according to market demand. The base of RMS provides a capacity envelope for the modules that could be added to machines in later periods (3-23, 3-24). It is assumed that the reconfiguration is a time consuming process and its duration depends on the number of modules which are modified. In order to identify the loss of capacity during reconfiguration, two types of capacity levels called nominal capacity and actual capacity is defined.

A nominal capacity shows the amount of desired capacity level for the system when the reconfiguration period is over (3-26). The actual capacity represents the amount of available capacity during the reconfiguration period (3-27, 3-28). As a result of nonzero reconfiguration period the actual capacity is less than nominal capacity in ramp up and more than nominal capacity in the ramp down. In addition, the reconfiguration time has a direct relationship to the amount of modified capacity. It is assumed that reconfiguration time can take from one-fifth of a period to a whole period depending on the amount of capacity change. In the following section the constraints that are related to the actual capacity is presented.

$$Q_{i,p} + EC_{i,p}^{r} = \sum_{t=1}^{i} ARMC_{i,t,p} \qquad \forall\, i \in T\,, \forall\, p \in P \tag{3-21}$$

$$\sum_{p=1}^{P} ARMC_{t,t,p} + \sum_{i=t+1}^{T} \sum_{p=1}^{P} ADDMLE_{i,t,p} - \sum_{i=t+1}^{T} \sum_{p=1}^{P} RMDMLE_{i,t,p} \leq MRC_{t} \qquad \forall\, t \in T \tag{3-22}$$

$$AMC_{i} \geq ScalarR * (SUB_{i}^{r}) \qquad \forall\, i \in T \tag{3-23}$$

$$MRC_{i} \leq M * (SUB_{i}^{r}) \qquad \forall\, i \in T \tag{3-24}$$

$$ADDMLE_{i,t,p} \leq MRC_{t} - IRMC_{i-1,t,p} \qquad \forall\, t \in T\,, \forall\, i \in \{t+1, .., T\}, \forall\, p \in P \tag{3-25}$$

$$IRMC_{i,t,p} = IRMC_{i-1,t,p} + ADDMLE_{i,t,p} - RMDMLE_{i,t,p} \qquad \forall\, t \in T\,, \forall\, i \in \{t+1, .., T\}, \forall\, p \in P \tag{3-26}$$

$$ARMC_{i,t,p} \leq IRMC_{i-1,t,p} + ADDMLE_{i,t,p} \qquad \forall\, t \in T\,, \forall\, i \in \{t+1,..,T\}, \forall\, p \in P \tag{3-27}$$

$$ARMC_{i,t,p} \geq IRMC_{i-1,t,p} - RMDMLE_{i,t,p} \qquad \forall\, t \in T\,, \forall\, i \in \{t+1,..,T\}, \forall\, p \in P \tag{3-28}$$

RMS Variables

$Q_{i,p}$	The amount of product p that is produced by Reconfigurable Capacity at time i
$EC^{r}_{i,p}$	Reconfigurable Excess Capacity at time i for product p
$ARMC_{i,t,p}$	Actual module capacity for product p at time i for base purchased at time t
$IRMC_{i,t,p}$	Nominal module capacity for product p at time i for purchased base at time t
$ADDMLE_{i,t,p}$	Added module capacity for product p module at time i for purchased base at time t
$RMDMLE_{i,t,p}$	Removed module capacity for product p module at time i for purchased base at time t
MRC_{i}	Maximum Reconfigurable Capacity is purchased at time i
$RC^{r}_{i,t}$	Removed Reconfigurable Capacity purchased at time t at time i
$SU^{r}_{i,p}$	1 Module Capacity is Scaled Up at time i for product p 0 Otherwise
$SD^{r}_{i,p}$	1 Module Capacity is Scaled Down at time i for product p 0 Otherwise
SUB^{r}_{i}	1 Reconfiguration Base is Scaled Up at time i 0 Otherwise
$SDB^{r}_{i,t}$	1 Purchased Reconfiguration Base is Scaled Down at time i 0 Otherwise
$RC_{i,p}$	1 Reconfiguration occurs at time i for product p 0 Otherwise
$RL1_{i,p},..,RL5_{i,p}$	1 if Reconfiguration occurs at level (1,..,5) at time i for product p 0 Otherwise

3.2 Reconfiguration technology ramp up constraints

The modular structure of RMS improves scalability and enables system capacity to gradually reach its new level. Since adding/removing capacity is time consuming, it will take time for the capacity to reach its desired nominal level. In order to consider this difference in modeling, a method is developed to estimate the available capacity in reconfiguration period.

Each time period is divided to five equal time slots. For example, if a period represents a year, each time slot represents 2.4 months. Specific amount of capacity is able to added or removed for each product where the reconfiguration time is related to all capacity modifications. For example, if adding 20 units of capacity takes one time slot, adding 40 units of capacity takes two time slots in a linear fashion. In the worst case scenario, when the reconfiguration takes the whole time stage for scaling up capacity, it is assumed half of the added capacity would be available for that reconfiguration period. As the reconfiguration speeds up, the actual capacity, represented by the area under the capacity curve, increases accordingly as shown in Figure 3-1. The transition from current capacity to the desired nominal capacity is directly related to system characteristics such as RMS layout and technology. The proposed model can provide the decision maker with a good estimation of the actual capacity during reconfiguration period. The estimated capacity during this period can be explained as follows:

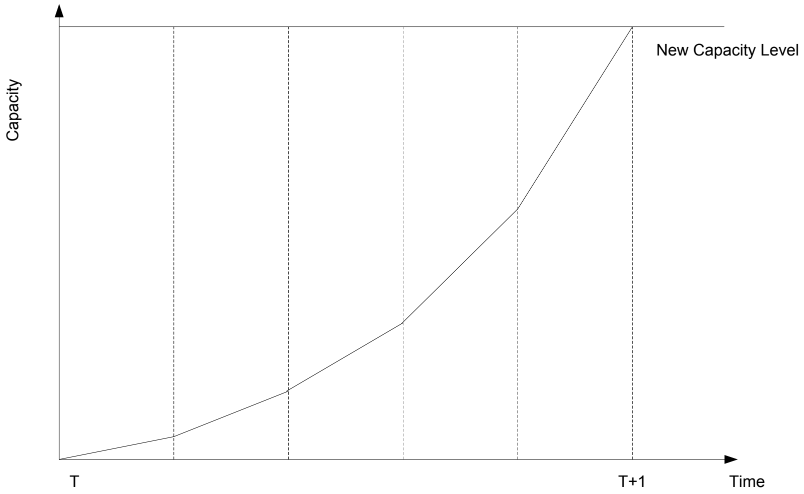


Figure 3-1 Available capacity during the reconfiguration period

Since the actual capacity is less than the nominal capacity due to the reconfiguration during ramp up, the nominal capacity of the following period is used as an upper bound (3-29). Depending on the amount of capacity that is integrated to RMS, an appropriate time interval is assigned for reconfiguration (40). Using the amount of capacity change and the time interval, the model estimates the actual capacity during reconfiguration period within the upper and lower bounds of available capacity during reconfiguration (3-30,..,3-39). The binary variables in (3-41,..,3-45) are set in such a way that the total reconfiguration length is identified by a set of these being equal to one. For example, if reconfiguration time is equal to 40% of the reconfiguration period, then $RL4_{i,p}$, $RL5_{i,p}$ should be equal to one and $RL1_{i,p}$,$RL2_{i,p}$, $RL3_{i,p}$ should be equal to zero. Ramp down is similar to ramp up and is discussed in Appendix A.

Reconfiguration (Scaling up) Constraints:

$$\sum_{t=1}^{i-1} ARMC_{i,t,p} \leq \sum_{t=1}^{i-1} IRMC_{i-1,t,p} + .5(\sum_{t=1}^{i-1} ADDMLE_{i,t,p}) + SU_{i,p}^{r} \qquad \forall\, i \in T, \forall\, p \in P \qquad \textbf{(3-29)}$$

$$SU_{i,p}^{r} \leq .1 * \sum_{t=1}^{i-1} ADDMLE_{i,t,p} - \boldsymbol{M} * RL1_{i,p} + \boldsymbol{M} \qquad \forall\, i \in T, \forall\, p \in P \qquad \textbf{(3-30)}$$

$$SU_{i,p}^{r} \geq .1 * \sum_{t=1}^{i-1} ADDMLE_{i,t,p} - \boldsymbol{M} * RL1_{i,p} \qquad \forall\, i \in T, \forall\, p \in P \qquad \textbf{(3-31)}$$

$$SU_{i,p}^{r} \leq .2 * \sum_{t=1}^{i-1} ADDMLE_{i,t,p} - \boldsymbol{M} * RL2_{i,p} + \boldsymbol{M} \qquad \forall\, i \in T, \forall\, p \in P \qquad \textbf{(3-32)}$$

$$SU_{i,p}^{r} \geq .2 * \sum_{t=1}^{i-1} ADDMLE_{i,t,p} - \boldsymbol{M} * RL2_{i,p} \qquad \forall\, i \in T, \forall\, p \in P \qquad \textbf{(3-33)}$$

$$SU_{i,p}^{r} \leq .3 * \sum_{t=1}^{i-1} ADDMLE_{i,t,p} - \boldsymbol{M} * RL3_{i,p} + \boldsymbol{M} \qquad \forall\, i \in T, \forall\, p \in P \qquad \textbf{(3-34)}$$

$$SU_{i,p}^{r} \geq .3 * \sum_{t=1}^{i-1} ADDMLE_{i,t,p} - \boldsymbol{M} * RL3_{i,p} \qquad \forall\, i \in T, \forall\, p \in P \qquad \textbf{(3-35)}$$

$$SU_{i,p}^{r} \leq .4 * \sum_{t=1}^{i-1} ADDMLE_{i,t,p} - \boldsymbol{M} * RL4_{i,p} + \boldsymbol{M} \qquad \forall\, i \in T, \forall\, p \in P \qquad \textbf{(3-36)}$$

$$SU_{i,p}^{r} \geq .4 * \sum_{t=1}^{i-1} ADDMLE_{i,t,p} - \boldsymbol{M} * RL4_{i,p} \qquad \forall\, i \in T, \forall\, p \in P \qquad \textbf{(3-37)}$$

$$SU_{i,p}^{r} \leq .49 * \sum_{t=1}^{i-1} ADDMLE_{i,t,p} - \boldsymbol{M} * RL5_{i,p} + \boldsymbol{M} \qquad \forall\, i \in T, \forall\, p \in P \qquad \textbf{(3-38)}$$

$$SU_{i,p}^{r} \leq \sum_{t=1}^{i-1} ADDMLE_{i,t,p} \qquad \forall\, i \in T, \forall\, p \in P \qquad \textbf{(3-39)}$$

$$RT_1 RL1_{i,p} + RT_2 RL2_{i,p} + RT_3 RL3_{i,p} + RT_4 RL4_{i,p} + RT_5 RL5_{i,p} \geq \sum_{t=1}^{i-1} ADDMLE_{i,t,p} + \varepsilon \sum_{t=1}^{i-1} RMDMLE_{i,t,p} \qquad \forall\, i \in T, \forall\, p \in P \qquad \textbf{(3-40)}$$

Staircase Reconfiguration steps

$$RL4_{i,p} \leq RL5_{i,p} \qquad \forall\, i \in T, \forall\, p \in P \qquad \textbf{(3-41)}$$

$$RL3_{i,p} \leq RL4_{i,p} \qquad \forall\, i \in T, \forall\, p \in P \qquad \textbf{(3-42)}$$

$$RL2_{i,p} \leq RL3_{i,p} \qquad \forall\, i \in T, \forall\, p \in P \qquad \textbf{(3-43)}$$

$$RL1_{i,p} \leq RL2_{i,p} \qquad \forall\, i \in T, \forall\, p \in P \qquad \textbf{(3-44)}$$

$$RL5_{i,p} \leq SU_{i,p}^{r} + SD_{i,p}^{r} \qquad \forall\, i \in T, \forall\, p \in P \qquad \textbf{(3-45)}$$

By relating reconfiguration time to the amount of modified capacity, a better estimation of actual capacity during ramp up time is presented. This benefits the decision maker by incorporating the responsiveness of RMS. In order to determine the suitable conditions for investing in each manufacturing technology, the proposed model has been implemented under various demands and investment cost parameters.

3.3 Numerical results

In order to conduct the numerical study, it is assumed a firm selects its optimal capacity portfolio for a planning horizon of nine periods. In assessing the capacity selection of each manufacturing system technology, the major factors that will impact the scalability and capacity purchase cost are considered. The reconfiguration length and the cost ratio of module and base for an RMS represent the critical factors in determining the scalability and responsiveness. The ratio of the excess capacity cost to the cost of lost sales represents the attitude of the decision maker towards this trade-off and will impact the capacity scalability preference of the decision maker. The capacity costs and the demand scenario data are selected from the literature based on the relative comparison of manufacturing systems (Spicer et al. 2005) and the characteristics of each demand scenario (Rink and Swan, 1979). The change in the selected set of parameters will help us distinguish between different systems characteristics in terms of scalability and investment cost. Depending on a market demand trend, the change in the range of these parameters will help us understand the significance of these parameters. A total of 5 criteria have been selected for our analysis as shown in Table 3-1.

Table 3-1 Main parameters for the analysis

Parameters			
Demand Pattern	Classic	Growth-plateau	Cycle-Recycle
Unit Capacity Cost Ratio		$DC^*=1, RC^*=1.5, FC^*=2.5$	
Module to Base Ratio	0.25	1	4
Reconfiguration Time	Short	Medium	Long
Excess/Shortage Ratio	1		3
DC=Dedicated Capacity, RC=Reconfigurable Capacity, FC=Flexible Capacity			

First, three different demand scenarios include Classical product life cycle, Growth-plateau product life cycle and Cycle-Recycle patterns (Table 3-2).

Each of these product life cycles represent a specific industry which is explained in detail later in this section. Second, Dedicated, Flexible, and Reconfigurable unit capacity costs values are chosen in a way that RMS unit capacity cost lies within FMS and DMS unit capacity cost (Spicer et al. 2005).

Table 3-2 Different product life-cycle evolution

		Time periods (i)								
Demand pattern	Products	1	2	3	4	5	6	7	8	9
Classical	A	65	100	250	300	300	250	100	0	0
	B	0	0	0	65	100	250	300	300	250
	C	0	0	0	0	0	0	65	100	250
Cycle–recycle	A	100	300	300	250	200	200	250	300	300
	B	0	0	100	300	300	250	200	200	250
	C	0	0	0	100	250	300	300	250	200
Growth-plateau	A	50	180	280	300	300	275	225	190	200
	B	0	0	50	180	280	300	300	275	225
	C	0	0	0	0	50	180	280	300	300

As a third factor it is observed the cost ratio of a base and different modules installed on RMS. The objective is to analyze the impact of cost allocation between a base and a module of RMS. Three different modules to base cost ratios are considered. The total cost of RMS is computed as the summation of the Base cost and the Module cost. While the total RMS cost is kept constant, the percentage of the cost allocation between a module and a base is changed to observe how this cost structure affects the selection of RMS. For example, if the total cost of unit capacity of RMS is considered at \$5, then \$1 is assigned to module and \$4 is assigned to RMS base, based on the following formula:

$$\left\{\begin{matrix} M + B = 5 \\ \frac{M}{B} = 0.25 \end{matrix}\right\} \tag{3-46}$$

Moreover, three possible reconfiguration times are considered as short, medium, and long reconfiguration times. As shown in Figure 3-2, when the reconfiguration time is short, more capacity could be added for a specific period ($\Delta t : t_1 - t_0$) with lower reconfiguration cost, but when the reconfiguration time is long for that specific period (Δt), less capacity could be added or removed from the system with higher reconfiguration cost.

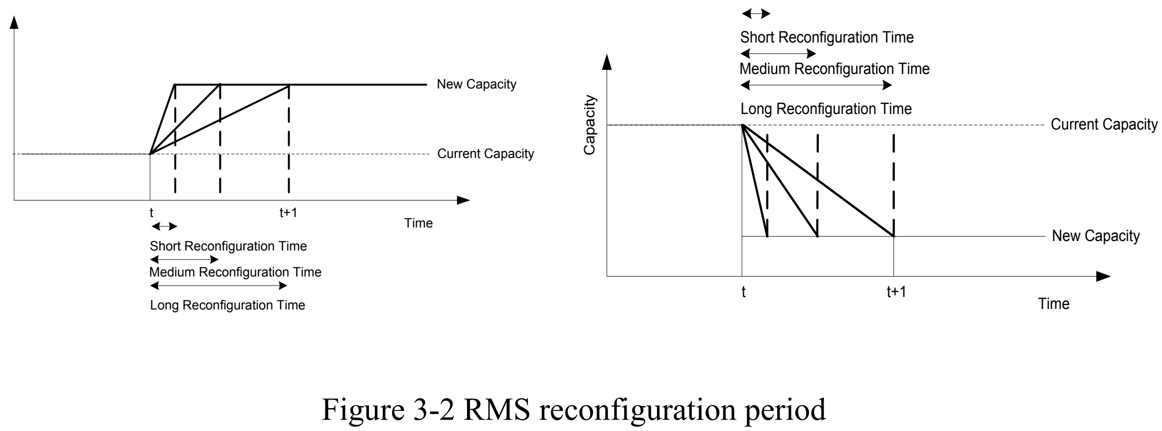


Figure 3-2 RMS reconfiguration period

Finally, two different excess capacity/shortage cost ratios are evaluated. By changing this ratio from 1 to 3, it could be observed how capacity portfolio is selected for different product demand life cycles. Different excess/shortage cost ratios could measure the risk attitude of a decision maker towards the risk of both product shortage and idle capacity. A higher percentage of excess capacity cost represents the attitude of decision maker to keep capacity at the lowest possible level. In contrast, a higher product shortage cost indicates that the decision maker wishes to keep serviceability at the highest level.

The experiments identified in Table 3-1 are implemented in AMPL software package and solved to optimality within MIPGAP set to 1E-04 using CPLEX 11.0. Each problem instance has 3818 decision variables and 6636 constraints. The experiments have been implemented on HPC Cluster Environment at Concordia University which uses 608 2.2 GHz AMD Opteron 64-bit processor cores.

Out of the fifty-four instances of the proposed model, one set of results is presented in Appendix B for illustrative purposes. In the following sections t the results on capacity portfolio selection is presented based on changes in the demand pattern and capacity related parameters. For each demand pattern the takeaways from the analysis is presented and give its explanation thereafter.

3.3.1 Classical product life cycle

Classical product life cycle for given dataset of Table 3-2 is shown in Figure 3-3. Based on input dataset and the sensitivity analysis on the reconfiguration time, Shorter product life cycles require responsive capacity in the form of RMS only or as a mix of DMS and

FMS: The classical product life cycle (Rink and Swan, 1979) considered in this study represents mainly markets having highly frequent new product introductions such as color television (Rink and Swan, 1979) and auto industries (Volpato and Stocchetti, 2008). In this scenario, products are introduced to market with a higher rate of diffusion and each product reaches to its maturity level quickly. These products diminish from the market when a new generation of products enters. In the Classical demand pattern, the products as well as their required demands vary in each period due to shorter product life cycle and increased frequency of new products to market.

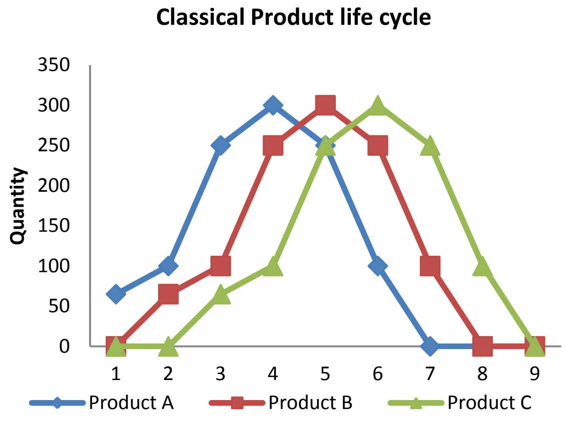


Figure 3-3 Classical product life cycle

The results for capacity portfolio selection for Classical demand pattern are shown in Table 3-3. Each solution represents the average level of allocated capacity over the planning horizon for each manufacturing system. When the reconfiguration time relatively increases, the percentage of RMS decreases; thus, RMS gets substituted with a mix of FMS and DMS. As the reconfiguration period lasts longer, FMS is more justifiable than RMS since it provides the process flexibility to switch between products despite the higher investment cost.

Based on the provided DMS scalability, DMS is usually purchased at a peak demand period and the amount of DMS, which is purchased or salvaged, depends on the amount of these peak instances as shown in Figure 3-4.

Table 3-3 Classic demand capacity portfolio for cost ratio DC=1, RC=1.5, FC=2.5

Classic Demand										
	Short Rec.			Medium Rec.			Long Rec.			
E/S	R	F	D	R	F	D	R	F	D	M/B
E1	100%	0%	0%	100%	0%	0%	0%	54%	46%	0.25
	100%	0%	0%	100%	0%	0%	0%	54%	46%	1
	100%	0%	0%	83%	17%	0%	10%	49%	41%	4
E3	100%	0%	0%	100%	0%	0%	0%	67%	33%	0.25
	100%	0%	0%	76%	24%	0%	26%	57%	17%	1
	100%	0%	0%	83%	17%	0%	33%	53%	14%	4

Moreover, increasing the excess/shortage ratio will result in allocating more capacity to FMS since DMS is less scalable and comes with higher percentage of excess capacity. Therefore, the capacity portfolio shifts from DMS to FMS.

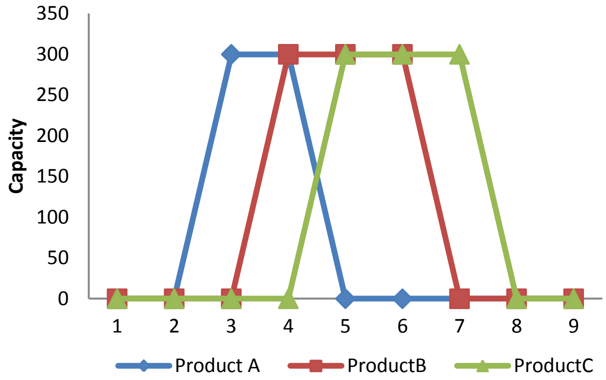


Figure 3-4 Dedicated capacity purchase in classical demand pattern

Based on the provided scalability for each system that is adapted from literature (Mehrabi et al., 2000), it is seen that RMS is selected in Classical demand pattern if RMS reconfiguration is short; otherwise, a mix of FMS and DMS is selected.

3.3.2 Growth-plateau product life cycle

Growth-plateau product life cycle schematic pattern for given dataset of Table 3-2 is shown in Figure 3-5. The sensitivity analyses performed with growth-plateau life cycle show that a mix of all manufacturing systems is selected. A growth-plateau life cycle is an example of the food industry products (Rink and Swan, 1979). In this scenario, products usually diffuse to market rapidly but when a new generation of product is introduced, the demand of the older version declines slowly until it remains constant. In these industries disappearance of product is not an issue from the market in several years. By solving the model for these kinds of products, the following results are obtained as shown in Table 3-4.

Table 3-4 Growth-plateau demand capacity portfolio for cost ratio DC=1, RC=1.5, FC=2.5

Growth-Plateau Demand										
E/S	Short Rec.			Medium Rec.			Long Rec.			
	R	F	D	R	F	D	R	F	D	M/B
E1	77%	0%	23%	49%	7%	44%	47%	9%	44%	0.25
	100%	0%	0%	49%	7%	44%	38%	18%	44%	1
	100%	0%	0%	83%	0%	17%	49%	7%	44%	4
E3	100%	0%	0%	76%	24%	0%	61%	22%	17%	0.25
	100%	0%	0%	79%	21%	0%	61%	22%	17%	1
	100%	0%	0%	100%	0%	0%	73%	27%	0%	4

In almost all instances during the sensitivity analysis of growth-plateau life cycle, RMS capacity constitutes a large portion of the capacity mix. However, the dedicated Capacity increases in case of low excess cost and long reconfiguration. Figure 3-6 represents the typical evolution of dedicated and flexible capacities in the results for long reconfiguration.

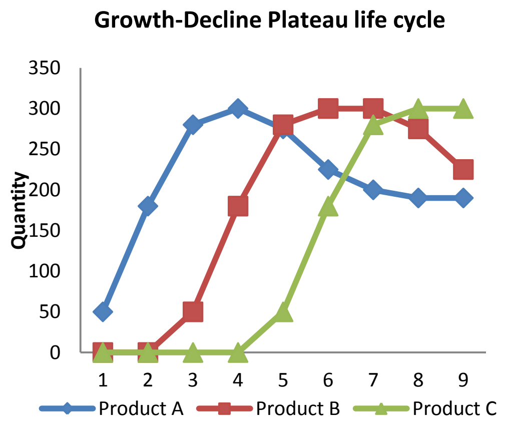


Figure 3-5 Growth-plateau product life cycle

Moreover, it is observed that dedicated capacity is chosen at later periods when all products have reached their maturities. However, flexible capacity is chosen at early stages to provide the required flexibility.

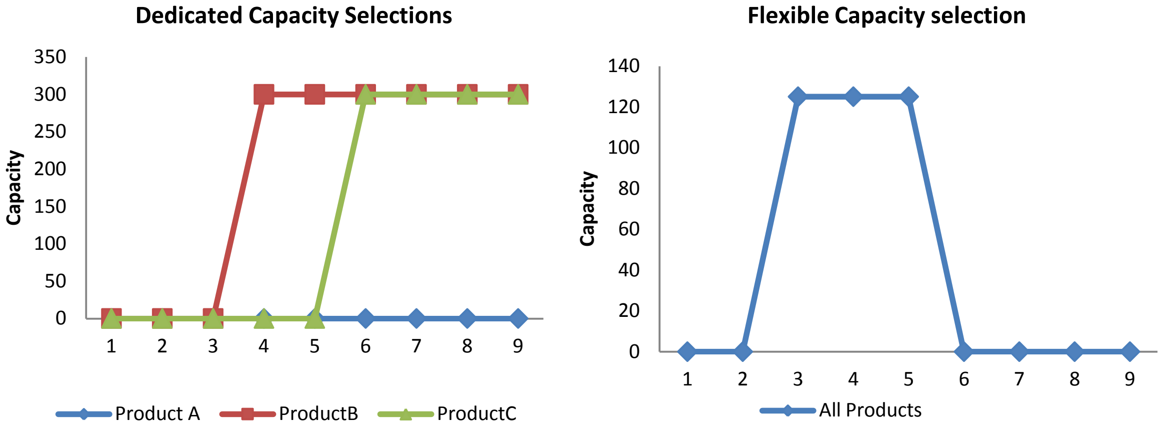


Figure 3-6 Capacity selections in growth-plateau demand pattern

From the excess and shortage ratio perspective, RMS is the dominant mix of capacity even with a long reconfiguration time. This can be explained by the better scalability of RMS over DMS.

3.3.3 Cycle-recycle product life cycle

Cycle-recycle product life cycle schematic pattern for given dataset of Table 3-2 is shown in Figure 3-7. With the assumption of low scalability of DMS, our sensitivity analysis indicates that frequent product design changeover makes DMS unsuitable for Cycle-Recycle demand: Cycle-Recycle life cycle is a representative of pharmaceutical and seasonal dependent products (Rink and Swan, 1979). In this product life cycle scenario, product demand changes from one period to another period. However, demolishing of a product is not an issue but a fraction of total demand varies among products.

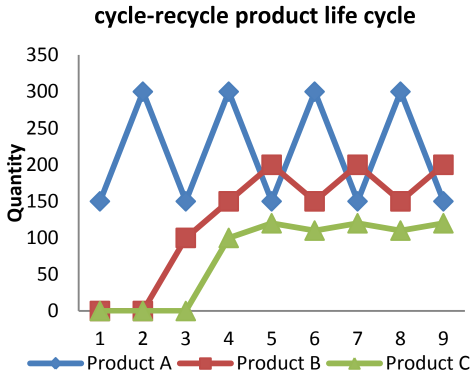


Figure 3-7 Cycle-Recycle product life cycle

The result in Table 3-5 shows that it is beneficial to have a mix of fixed and variable capacity in order to simultaneously meet stable and volatile demand. The fixed part of demand is satisfied by FMS and variable part of demand is met by RMS since RMS is highly scalable and has the ability to adapt (Figure 3-8).

Table 3-5 Cycle-Recycle demand capacity portfolio for cost ratio DC=1, RC=1.5, FC=2.5

Cycle-Recycle Demand										
E/S	Short Rec.			Medium Rec.			Long Rec.			
	R	F	D	R	F	D	R	F	D	M/B
E1	81%	19%	0%	73%	27%	0%	80%	20%	0%	0.25
	79%	21%	0%	73%	27%	0%	80%	20%	0%	1
	79%	21%	0%	77%	23%	0%	73%	27%	0%	4
E3	81%	19%	0%	73%	27%	0%	72%	28%	0%	0.25
	77%	23%	0%	75%	25%	0%	72%	28%	0%	1
	79%	21%	0%	77%	23%	0%	72%	28%	0%	4

RMS's better scalability and ability of adding different modules is another reason for selecting RMS over DMS. This scalability is also convenient for demand conditions where frequent changes in the demand mix and quantities are observed. In the case of low excess/shortage cost ratio, even more capacity is allocated to RMS, allowing the system to compensate for the cost difference by reducing the reconfiguration cost. For the fixed part of demand, the selection of flexible capacity depends on how effective the reconfiguration period length is. In other words, if RMS reconfiguration is done at a higher speed, then the amount of capacity allocated to FMS decreases. On the other hand, when the reconfiguration time and excess capacity cost ratio increase, the allocation to Flexible capacity increases.

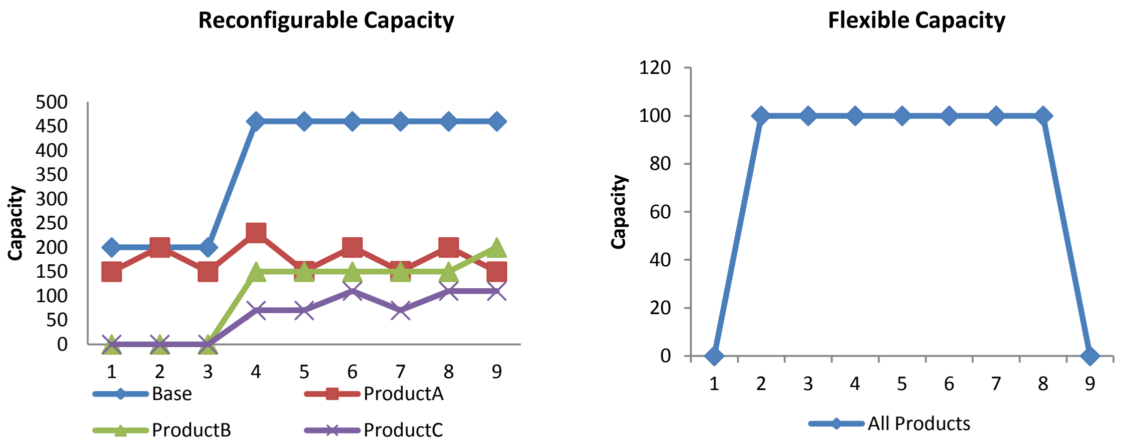
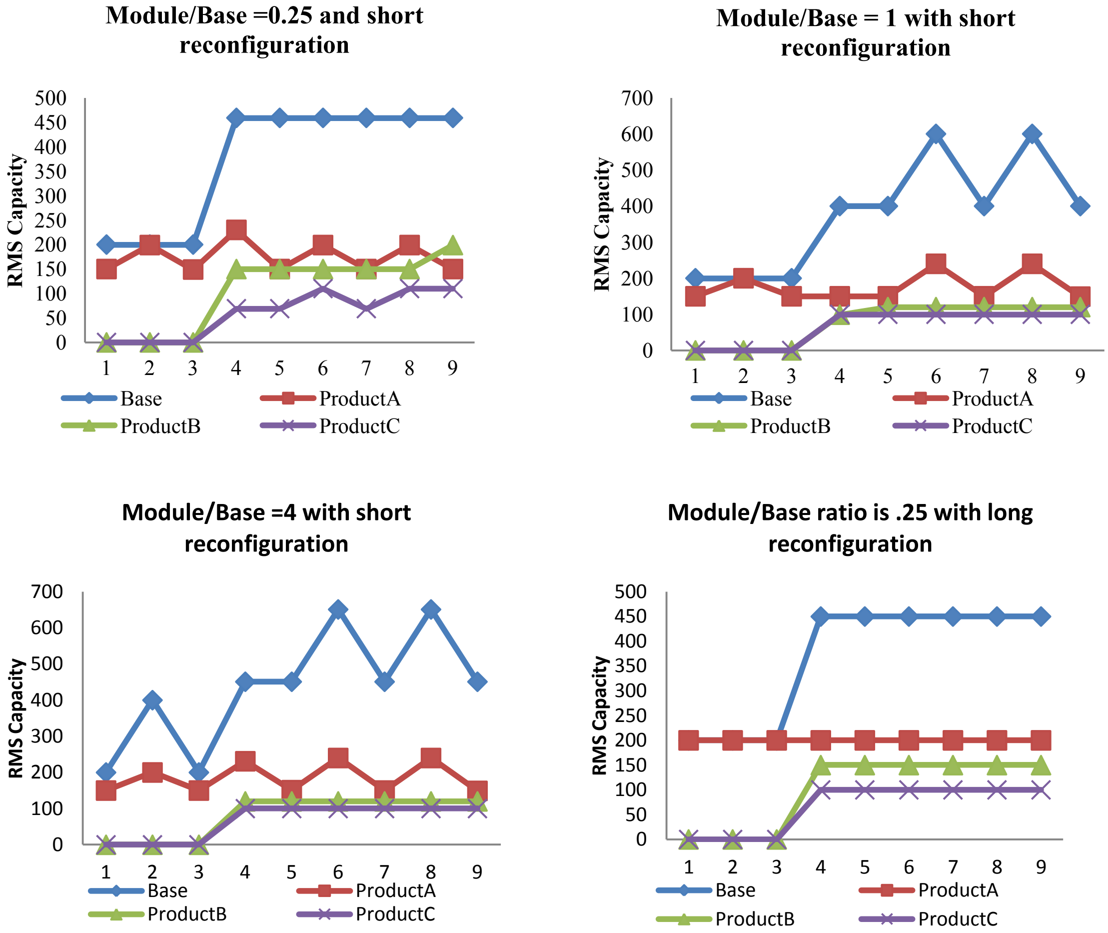


Figure 3-8 Flexible capacity selections in cycle-cecycle demand pattern

3.3.4 Effect of RMS module and base cost profile

The sensitivity analysis on module and base costs of RMS reveals that if module to base ratio cost is kept low in RMS, then reconfiguration tendency is increased due to RMS's better scalability. The impact of changing the module to base ratio results in the same behavior in each product life cycle scenario. In a short reconfiguration time, as the module to base ratio increases from 0.25 to 4, the reconfiguration activity is reduced leading to instantaneous purchase of reconfigurable capacity as represented in Figure 3-9.

The variation in the module to base cost ratio of reconfigurable capacity implies that more reconfiguration activity is justifiable whenever the cost of module is decreased in the total cost of reconfigurable capacity.


Module/Base =0.25 and short reconfiguration

Module/Base = 1 with short reconfiguration

Module/Base =4 with short reconfiguration

Module/Base ratio is .25 with long reconfiguration

Figure 3-9 Impact of RMS different module to base ratio

By increasing the module to base ratio level, modules are purchased in smaller increments because of the higher cost ratio and they are removed as soon as demand decreases. When reconfiguration is done over a longer period, reconfigurable capacity remains constant and no reconfiguration is done at module and base levels.

Through this sensitivity analysis, it is concluded that short reconfiguration time and low module to base cost ratio provides a competitive advantage to RMS over DMS and FMS as a result of better scalability. These two aspects enable RMS to behave as a DMS or FMS according to the demand requirements.

3.3.5 Effect of RMS responsiveness on capacity portfolio

According to the sensitivity analysis on reconfiguration time, it is observed that reconfiguration time has negative correlation with reconfiguration activity in RMS. Shorter reconfiguration time has a positive correlation with reconfiguration activity in RMS. The impact of changing the reconfiguration time per unit capacity on RMS capacity levels is represented in Figure 3-10. As expected, increasing reconfiguration time results in the reduction of reconfiguration activity for RMS. Nonetheless, the percentage of RMS does not decrease in cycle-recycle demand due to the better scalability of RMS compared to DMS and ability to produce multiple product families.

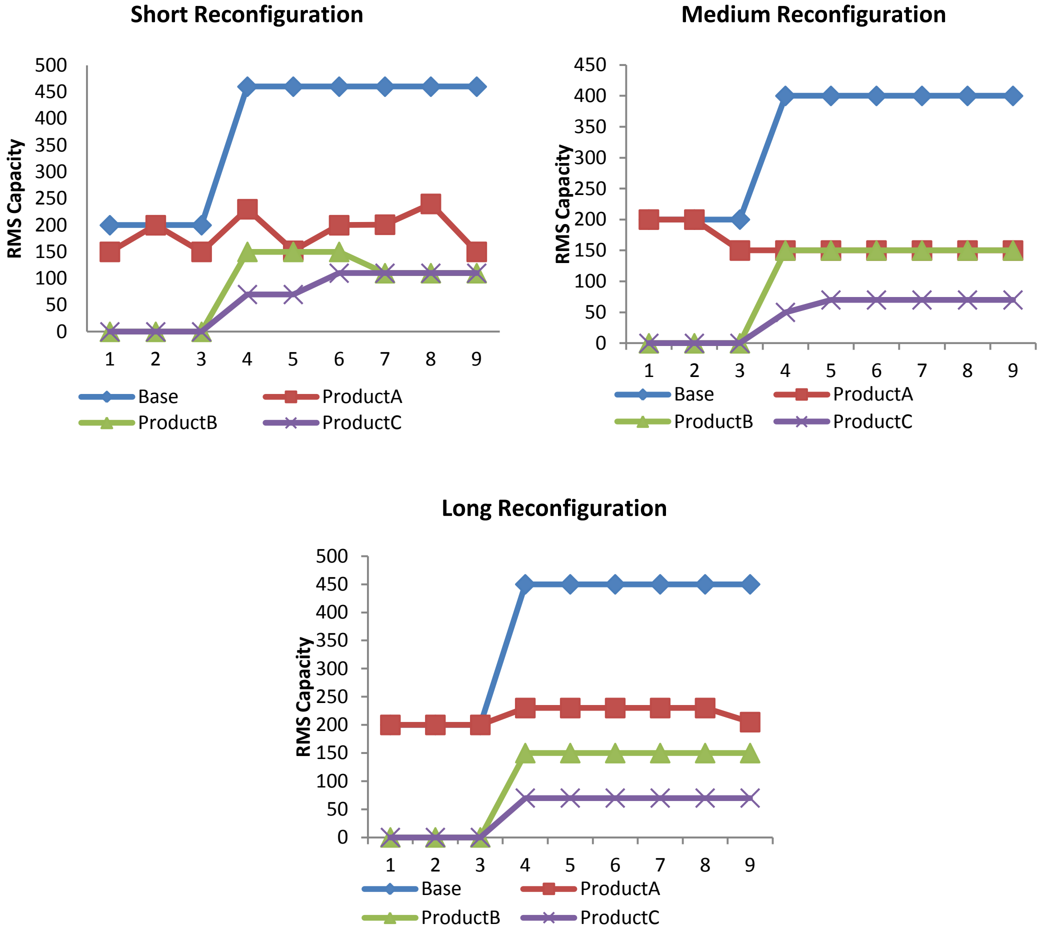


Figure 3-10 Impact of RMS reconfiguration time

3.4 Summary and discussion

The results obtained from the input data in this research shows that RMS could be a holistic system if it can be reconfigured efficiently in a short time period. In all demand life cycles it is observed better responsiveness of RMS, indicated by the increased service levels. Moreover, a minimum module to base ratio cost increases the tendency of reconfiguration in RMS. In this manner, reconfiguration by RMS is more desirable and it enables RMS to follow aggregate demand with minimum excess capacity.

For the selected data set provided in Table 3-1, results show that a mix of RMS and FMS is selected for cycle-recycle life cycle demand. By increasing reconfiguration time, percentage of RMS decreases and percentage of FMS increases. In the Classical life cycle demand, while reconfiguration time is kept short, RMS is considered as the main manufacturing system. In long reconfiguration time, a mix of DMS and FMS is preferred. In the growth-plateau life cycle demand, capacity portfolio changes from RMS to a mix of all systems as the reconfiguration time is increased. By increasing of reconfiguration time, RMS percentage is decreased from 100% to 50% in low and from 100% to 70% in high excess cost. Table 3-6 represents a summary of our numerical results and shows how portfolio selection is affected by the parameters considered in this study.

Table 3-6 Summary of manufacturing system selection

E/S	Reconfiguration Length	M/B	Classical Demand	Growth-plateau demand	Cycle-recycle demand
1	Short	0.25	Reconfigurable system selection	Reconfigurable system selection	Mix of reconfigurable and flexible manufacturing system
		1			
		4			
	Medium	0.25		mix of dedicated, reconfigurable and flexible manufacturing system	
		1			
		4	Mix of dedicated and flexible manufacturing system		
	Long	0.25			
		1			
		4			
3	Short	0.25	Reconfigurable system selection	Reconfigurable system selection	Mix of reconfigurable and flexible manufacturing system
		1			
		4			
	Medium	0.25			
		1		mix of dedicated, reconfigurable and flexible manufacturing system	
		4			
	Long	0.25	mix of dedicated, reconfigurable and flexible manufacturing system		
		1			
		4			

The system agility may not only depend on the machining features or manufacturing system characteristics, but also the layout of facility and machining configuration. For example, a product may follow many processes such as drilling, turning, milling, and assembly. A manufacturing system where each machine has the capability to perform all the operations will create a parallel configuration by adding identical machines to increase capacity. On the other hand, an equivalent system can be created by using one machine per operation, which results in a serial configuration. While the capacity increase of a parallel configuration can be done smaller increments and faster, a serial configuration will require all stages to be completely reconfigured in order to achieve a new capacity level. Therefore, the configuration can also facilitate the production throughput if a flexible capacity is used either in all processes or at bottleneck stages. The comparison of reconfigurable and flexible capacity showed that reconfigurable capacity could outweigh flexible capacity if it could do the reconfiguration in shorter time period.

While a parallel system means faster reconfiguration; it also means more investment in manufacturing system and costlier production. Therefore, in using reconfigurable capacity, there is a tradeoff for manufacturer between the cost and the response speed as a function of the selected configuration layout. It is possible that the required agility is obtained if reconfigurable capacity is used at key manufacturing processes.

In the next chapter, the main focus is on the reconfiguration speed based on the facility layout to investigate how reconfiguration speed could benefit manufacturer while demand is not deterministic.

Chapter 4: The effect of system configuration and ramp up time on manufacturing system acquisition under uncertain demand

In this chapter, the relation of different ramp up patterns on achieving a better customer service level for a predetermined time horizon is investigated. One of the desired RMS characteristics is fast reconfiguration capability. However, the speed of reconfiguration depends mainly on manufacturing system configuration which is determined by machine configurations and how these machines are allocated into stages. Considering its lifecycle, the initial configuration of the system has a profound effect on the system adjustment step size and its cost. Therefore, the ramp up time is dependent on system layout and displacement of stages. In this chapter, the objective is to take different ramp up patterns into account and analyze how initial configuration of a system influences the demand satisfaction during reconfiguration period. In capacity planning, the omission of the capacity levels during reconfiguration period may lead to inaccuracies of the actual capability of a manufacturing system. The overestimation of capacity leads to losing demand and reduction of service level, whereas underestimating the capacity causes the firm to carry extra capacity. Therefore, by considering the difference in ramp up behavior from one type of configuration to another, it is possible to analyze how the demand during reconfiguration is impacted.

In this chapter, it is assumed that a manufacturing plant currently produces one product, called (A), and the company anticipates that new product (B) will emerge some time in future. Assume that the time horizon of problem is T, and the decision maker has a choice between Dedicated and Reconfigurable Technology or a portfolio of those to invest. Scalability and functionality of those technologies are considered dissimilar. For example, the DMS scalability is low and DMS reconfiguration is similar to series reconfiguration. It can only produce one product at a time efficiently and it requires longer conversion time. RMS is able to produce multiple products in a scalable fashion. However, the extent of this scalability changes according to the RMS layout. When RMS system moves toward parallel configuration, the scalability of RMS increases but the system becomes more expensive (Abdi, 2009).

In order to differentiate the ramp up characteristic of each configuration, four main patterns representing the capacity evolution as shown in Figure 4-1 is identified. In the first plot, the system configuration is a less costly series configuration, but it takes longer time for new capacity to be operational. Second plot shows series-parallel configuration whereby only one or two processes will have parallel machines such as bottlenecks. Third plot, in line reconfiguration, represents linearly increasing current system capacity which is a parallel-series configuration with an increased number of parallel stages, and parallel configuration could be presented by fourth plot. Due to parallel configuration, more capacity is available during reconfiguration period, but system configuration is more expensive (Koren et al., 1998).

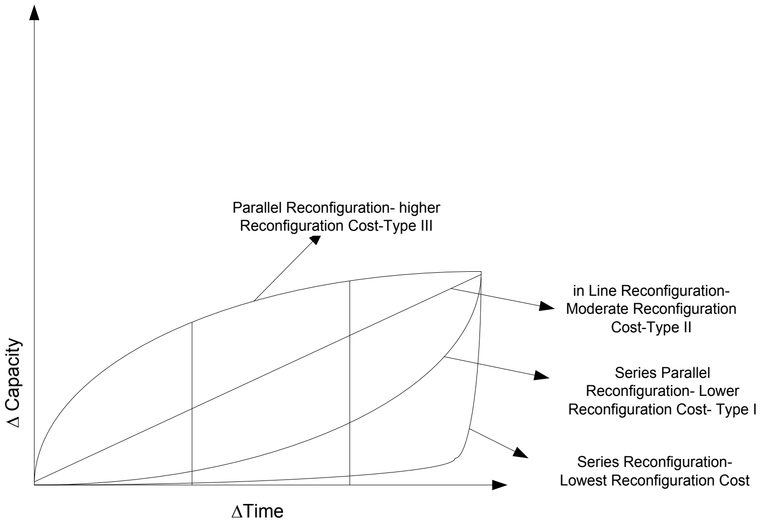


Figure 4-1 Reconfiguration ramp up time pattern

The low cost advantage of series reconfiguration may be offset by the unavailability of partial capacity during ramp up, resulting in the need for adding capacity well in advance than needed. On the other hand, parallel reconfiguration allows on time reconfiguration at the expense of increased reconfiguration cost. By modeling this reconfiguration pattern behavior, the objective is to see how system configuration could benefit the decision maker in providing the highest service level with optimal level of capacity. In this model, the cost of product shortage, excess capacity cost, technology acquisition cost, and reconfiguration cost are considered as the main concerns of decision maker.

It is assumed the demand at each period is uncertain and follows a specific mean and standard deviation. In order to satisfy the uncertain portion of the demand, a safety capacity based on the predetermined service level at each time period is considered. In addition, a discount factor of ς_t percent at each period is assumed. The unmet demand is considered to be lost. And either capacity expansion or contraction is allowed at each period.

Dedicated Technology provides a large scale capacity just for one product family. This means that for different products, different Dedicated Machines must be purchased. The unit purchasing cost of DMS is less than RMS as a result of economies of scale. DMS reconfiguration lasts a fixed period of time and added capacity is not available during reconfiguration period. The reconfiguration cost and time of adding new RMS modules are represented as a function of the amount of capacity change, following a specific ramp up trend as explained in 4.2 and 4.2.3.

We can summarize the assumptions as follows:

- Decision maker has a choice between Dedicated and Reconfigurable Technology or a portfolio of those to invest.
- RMS is able to produce multiple products in a scalable fashion.
- Demand at each period is uncertain and follows normal distribution with a specific mean and standard deviation.
- A safety capacity based on the predetermined service level at each time period is considered.
- A discount factor of ς_t percent at each period is assumed.
- Reconfiguration cost and time of adding new RMS modules are represented as a function of the amount of capacity change.

In the next section, the proposed methodology has been described by considering the aforementioned assumptions.

4.1 Proposed methodology and model description

In assessing the impact of configuration at the tactical level of decision making process, a two-phase process is introduced where the first phase is a multi-period MIP model. In the second phase, the MIP results are validated in a simulation environment by incorporating the randomness in demand and ramp up behavior. The MIP model is developed to optimize the configuration of the systems based on the operational costs and associated opportunity costs. The operational costs include the costs associated with the reconfiguration period related costs, and the opportunity costs include the loss sale costs associated with the ramp up period. Integration of these costs allows observing how the capacity of RMS and DMS is evaluated from one period to another period based on the assigned reconfiguration pattern. As explained, a capacity update could follow a non-linear trend depending on the layout configuration (Figure 4-1). A linearization approach is developed as an approximate way of modeling the capacity expansion and contraction during this time. This approach is explained in detail in 4.2.3. The output from the MIP model such as the amount of DMS or RMS capacity, reconfiguration period and capacity evolution are used as an input to the simulation model with random demand and ramp up duration. Although the randomness could also be modeled through the stochastic programming, the complexity of ramp up transition in continuous flow prevents modeling the scalability of manufacturing systems appropriately. A better approach for estimation of ramp up transition under uncertain demand could be achieved by discrete event simulation. By modeling the demand generation and manufacturing system capacity evolution separately and running with simulation model the effect of ramp up and system scalability could be modeled appropriately. By validating the results of the MIP model in simulation, it could be observed which reconfiguration type provides better service level. The flow of the methodology is represented in Figure 4-2.

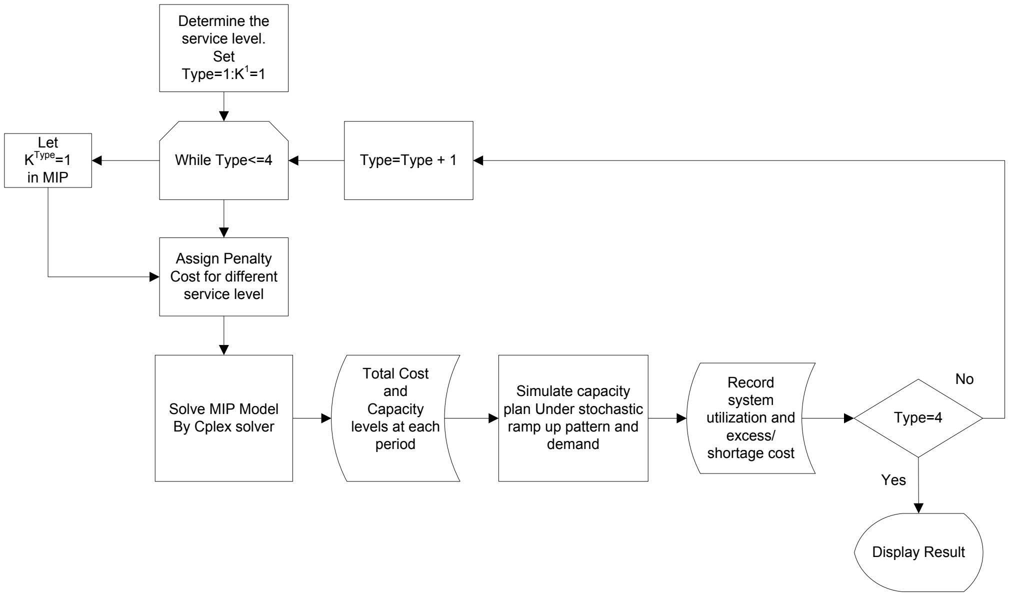


Figure 4-2 Capacity and reconfiguration pattern selection flowchart

4.2 MIP model

The objective of the MIP model is to minimize capacity investment and operational costs by selecting appropriate amount of DMS and RMS. In addition, opportunity costs associated with purchasing and updating the capacity during product lifecycle are considered in the objective function. In developing the proposed capacity planning model, the objective function is subject to a series of constraints which are explained in section 4.2.2. In the following section, the objective function and its terms are described in detail.

4.2.1 Objective function

The terms of the objective functions include the production cost (4-1), capacity investment cost (4-2), system reconfiguration cost (4-3), capacity excess cost, and lost demand (4-4). It is assumed that each unit of the reconfigurable system capacity cost is greater than its dedicated system counterpart (Van Mieghem, 2003, Ceryan & Koren, 2009). Also, a cost value is assigned to each unit of demand that is not satisfied and a cost to each unit of resource that has not been utilized at the end of each period.

$$Min(Z)=\sum_{t\in T}\sum_{p\in P}(CP_p^d * D\lambda_{t,p}+CP_p^r * R\lambda_{t,p}) \tag{4-1}$$

$$+(C^r+C_2^K K^2+C_3^K K^3) * R\xi_1+\sum_{t=2}^{T}\varsigma_t *(C^r+C_2^K K^2+C_3^K K^3) * R\Delta\xi_t^{+}+\sum_{p=1}^{P}C_p^d * D\xi_{1,p}+\sum_{t=2}^{T}\sum_{p=1}^{P}\varsigma_t * C_p^d * D\xi_{t,p} \tag{4-2}$$

$$+\sum_{t\in T}(C_1^T(Y_t^1+Y_t^4+Y_t^7)+C_2^T(Y_t^2+Y_t^5+Y_t^8)+C_3^T(Y_t^3+Y_t^6+Y_t^9+\sum_{p=1}^{P}Y_{t,p}^D)) \tag{4-3}$$

$$+\sum_{t\in T}(EC * E\xi_t^r+\sum_{p\in P}(SC * D_{t,p}^l+EC * E\xi_{t,p}^d)) \tag{4-4}$$

The parameters and the variables of the model are listed below with a brief description.

4.2.2 Constraints

This objective function is minimized subject to a set of constraints. In identifying the capacity requirements, the product demand is forecasted by a specific mean (μ) and variance (σ) at each period. In order to satisfy the uncertain part of the demand, a specific amount of safety capacity is assumed (4-20) at each period by the critical fractile ratio, u, based on following formula:

$$u = N^{-1}\left(\frac{SC}{SC+EC}\right) \tag{4-5}$$

After the demand is realized for a period, it is satisfied by a mix of RMS and DMS production, or it is lost (4-6). The characteristics of each manufacturing system are represented by their respective set of constraints. For instance, a DMS is dedicated to one product. Therefore, available dedicated capacity is allocated to one product's demand and some excess capacity at each period (4-7). Moreover, according to DMS specifications, it is assumed that increasing the capacity of DMS takes one period and no amount of added capacity is available during ramp up period, which means a step increase after one period (4-8). For a reconfigurable system, the total capacity is allocated to all products along with the excess capacity at each period (4-15).

Based on the reconfigurable system's better responsiveness to changes, it is assumed that some of the added capacity is available during reconfiguration. Therefore, during reconfiguration period, two characteristics of reconfigurable capacity are considered: nominal capacity and actual capacity. The nominal capacity determines the amount of capacity that the system is desired to reach (4-16). Actual capacity represents the amount of capacity that is available during reconfiguration. Actual capacity is different from the nominal capacity, because some capacity during reconfiguration is either lost during the ramp up period or considered as excess capacity during ramp down (4-17), as the system is not able to reach to desired capacity instantly.

Another aspect that is taken into account in the model is the reconfiguration cost. This cost includes labor cost, re-arrangement cost, and setup cost. The reconfiguration cost is measured based on the duration of the reconfiguration period. The constraint set (4-8) to

(4-14), and (4-16) to (4-20) have been introduced to determine this duration for DMS and RMS respectively. Constraints (4-9... 4-10) force binary variable $Y_{t,p}^{D}$ to get the value one during ramp up and ramp down period, which represents the step change for DMS. In RMS, the appropriate amount of reconfiguration time, which is based on the amount of added or removed capacity, is presented by the binary variable Y_t^i, through the constraint (4-20). Based on DMS specification, it is assumed that DMS is less scalable than RMS and a larger step of capacity is added/removed at each period (4-9). This assumption is justified based on the economies of scale characteristic of DMS. Therefore, the amount of capacity that can be added or removed from a DMS is in larger steps. In addition, the amount of capacity that is removed from DMS must be less than its current capacity (4-11). At each period it is assumed that either capacity is increased (4-12, 4-18) or decreased (4-13, 4-19) for both DMS and RMS.

Demand Requirements:

$$\mu_{t,p} = D\lambda_{t,p} + R\lambda_{t,p} + D_{t,p}^{l} \qquad \forall t \in T, p \in P \tag{4-6}$$

Dedicated System:

$$D\lambda_{t,p} + E\xi_{t,p}^{d} = D\xi_{t,p} \qquad \forall t \in T, p \in P \tag{4-7}$$

$$D\xi_{t,p} = D\xi_{t-1,p} + D\Delta\xi_{t-1,p}^{+} - D\Delta\xi_{t,p}^{-} \qquad \forall t \in \{2..T\}, p \in P \tag{4-8}$$

$$D\Delta\xi_{t,p}^{+} + D\Delta\xi_{t,p}^{-} \geq \vartheta_{R}^{d} + M * Y_{t,p}^{D} - M \qquad \forall t \in T, p \in P \tag{4-9}$$

$$D\Delta\xi_{t-1,p}^{+} + D\Delta\xi_{t,p}^{-} \leq M * Y_{t,p}^{D} \qquad \forall t \in T, p \in P \tag{4-10}$$

$$D\Delta\xi_{t,p}^{-} \leq D\xi_{t,p} \qquad \forall t \in T, p \in P \tag{4-11}$$

$$D\Delta\xi_{t,p}^{+} \leq M * (Y_{t,p}^{11}) \qquad \forall t \in T, p \in P \tag{4-12}$$

$$D\Delta\xi_{t,p}^{-} \leq M * (1 - Y_{t,p}^{11}) \qquad \forall t \in T, p \in P \tag{4-13}$$

$$Y_{t,p}^{D} \leq K^{4} \qquad \forall t \in T, p \in P \tag{4-14}$$

Reconfigurable System:

$$R\lambda_{t,p} + E\xi_t^r = R\xi_t \qquad \forall t \in T \tag{4-15}$$

$$IR\xi_t = IR\xi_{t-1} + R\Delta\xi_t^+ - R\Delta\xi_t^- \qquad \forall t \in \{2..T\} \tag{4-16}$$

$$R\xi_t = IR\xi_{t-1} + U\xi_t^r - L\xi_t^r \qquad \forall t \in \{2..T\} \tag{4-17}$$

$$R\Delta\xi_t^+ + U\xi_t^r \le M * Y_t^{10} \qquad \forall t \in T \tag{4-18}$$

$$R\Delta\xi_t^- + L\xi_t^r \le M * (1 - Y_t^{10}) \qquad \forall t \in T \tag{4-19}$$

$$R\Delta\xi_t^+ + U\xi_t^r + R\Delta\xi_t^- + L\xi_t^r \le M * \sum_{i=1}^{9} Y_t^i \qquad \forall t \in T \tag{4-20}$$

Safety Capacity:

$$\sum_{p\in P} (u * \sigma_{t,p} + D\lambda_{t,p} + R\lambda_{t,p}) \le \sum_{p\in P} D\xi_{t,p} + R\xi_t \qquad \forall t \in T \tag{4-21}$$

Auxiliary constraints

$$R\Delta\xi_1^+ = 0, R\Delta\xi_1^- = 0, U\xi_1^r = 0, L\xi_1^r = 0 \tag{4-22}$$

$$IR\xi_1 = R\xi_1 \tag{4-23}$$

$$\sum_{p=1}^{P} D\Delta\xi_{1,p}^- = 0 \tag{4-24}$$

Decision Variables:

$D\xi_{t,p}$	Dedicated system capacity at time t for product p
$D\lambda_{t,p}$	Dedicated system production at time t for product p
$D\Delta\xi_{t,p}^+$	Added capacity for Dedicated system at time t for product p
$D\Delta\xi_{t,p}^-$	Removed capacity for Dedicated system at time t for product p
$E\xi_{t,p}^d$	Excess Capacity of Dedicated system at time t for product p
$R\xi_t$	Actual capacity of Reconfigurable system at time t
$R\lambda_{t,p}$	Reconfigurable system production at time t for product p
$IR\xi_t$	Nominal capacity of Reconfigurable system at time t
$R\Delta\xi_t^+$	Added capacity for Reconfigurable system at time t
$R\Delta\xi_t^-$	Removed capacity for Reconfigurable system at time t
$U\xi_t^r$	Upper limit capacity during reconfiguration at time t for reconfigurable system
$L\xi_t^r$	Lower limit capacity during reconfiguration at time t for reconfigurable system

$E\xi_t^r$	Excess capacity of Reconfigurable system at time t
$\vartheta_R^r, \vartheta_R^d$	Maximum Capacity that could be added to a system in each period
$D_{t,p}^l$	Product p demand lost at time t
$Y_t^1..Y_t^3$	Number of sub intervals are used for reconfiguration as binary variable for Type (I) Reconfiguration
$Y_t^4..Y_t^6$	Number of sub intervals are used for reconfiguration as binary variable for Type (II) Reconfiguration
$Y_t^7..Y_t^9$	Number of sub intervals are used for reconfiguration as binary variable for Type (III) Reconfiguration

The configuration of a manufacturing system is the main indicator in identifying the reconfiguration time and the partial capacity that is available during this period. The ramp up pattern associated with each configuration is represented by a set of constraints as explained in the following section.

4.2.3 Representation of reconfiguration patterns

The system configuration pattern is determined through the binary variables K^1 to K^4. Binary variable K^4 represents DMS reconfiguration. In this reconfiguration, reconfiguration is only done on DMS and capacity is added or removed in a stairway shape. One can assume that RMS behaves as FMS in this configuration (K^4=1). It is able to produce multiple products at the same time with fixed capacity during time horizon.

In type I reconfiguration pattern (Figure 4-3), a predetermined percentage of capacity is available during reconfiguration time based on the maximum amount of capacity that could be added to a system at each period. For example, it is assumed $0 \le \Delta C \le 0.05C$ could be installed in Δt_1, $0.05C \le \Delta C \le 0.25C$ could be installed in Δt_2, and $0.25C \le \Delta C \le C$ could be installed in Δt_3 (4-31 to 4-36). In type I reconfiguration, available capacity of added/removed capacity falls between 25% and 60% of added or removed capacity (4-25 to 4-30). ΔC is presented by $R\Delta\xi_t^+$ and Δt is presented by Y_t in the constraints.

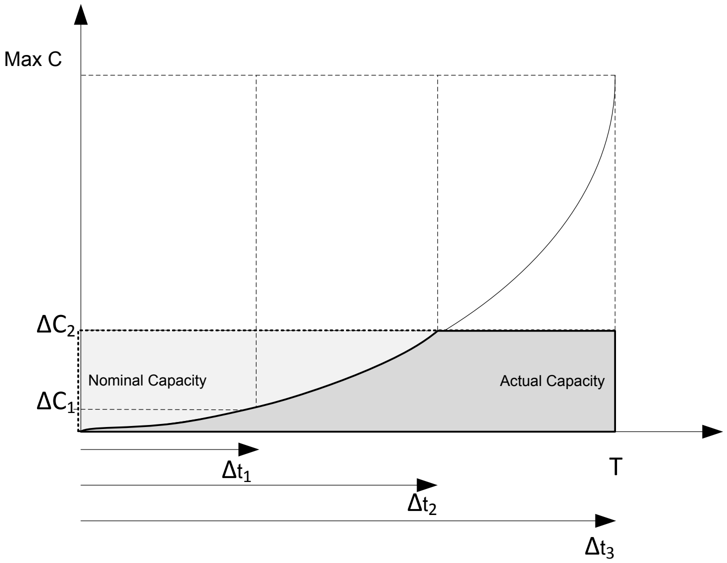


Figure 4-3 Reconfiguration type I, less capacity is available during reconfiguration

Capacity availability during reconfiguration type I:

$$U\xi_t^r + L\xi_t^r \le 0.6*\left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) + M*(1-Y_t^1) \qquad \forall t \in \{2..T\} \tag{4-25}$$

$$U\xi_t^r + L\xi_t^r \ge 0.45*\left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) - M*(1-Y_t^1) \qquad \forall t \in \{2..T\} \tag{4-26}$$

$$U\xi_t^r + L\xi_t^r \le 0.45*\left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) + M*(1-Y_t^2) \qquad \forall t \in \{2..T\} \tag{4-27}$$

$$U\xi_t^r + L\xi_t^r \ge 0.35*\left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) - M*(1-Y_t^2) \qquad \forall t \in \{2..T\} \tag{4-28}$$

$$U\xi_t^r + L\xi_t^r \le 0.35*\left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) + M*(1-Y_t^3) \qquad \forall t \in \{2..T\} \tag{4-29}$$

$$U\xi_t^r + L\xi_t^r \ge 0.25*\left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) - M*(1-Y_t^3) \qquad \forall t \in \{2..T\} \tag{4-30}$$

Reconfigurable System Responsiveness (Type I)

$$R\Delta\xi_t^+ + R\Delta\xi_t^- \le .05*\vartheta_R^r + M - M*(Y_t^1) \qquad \forall t \in \{2..T\} \tag{4-31}$$

$$R\Delta\xi_t^+ + R\Delta\xi_t^- \ge .05*\vartheta_R^r - M + M*(Y_t^2) \qquad \forall t \in \{2..T\} \tag{4-32}$$

$$R\Delta\xi_t^+ + R\Delta\xi_t^- \le .25*\vartheta_R^r + M - M*(Y_t^2) \qquad \forall t \in \{2..T\} \tag{4-33}$$

$$R\Delta\xi_t^+ + R\Delta\xi_t^- \ge .25*\vartheta_R^r - M + M*(Y_t^3) \qquad \forall t \in \{2..T\} \qquad (4\text{-}34)$$

$$R\Delta\xi_t^+ + R\Delta\xi_t^- \le \vartheta_R^r + M - M*(Y_t^3) \qquad \forall t \in \{2..T\} \qquad (4\text{-}35)$$

$$Y_t^1 + Y_t^2 + Y_t^3 \le K^1 \qquad \forall t \in T \qquad (4\text{-}36)$$

In type II reconfiguration pattern (Figure 4-4), it is assumed $0 \le \Delta C \le 0.33C$ could be installed in Δt_1, $0.33C \le \Delta C \le 0.66C$, could be installed in Δt_2, and $0.66C \le \Delta C \le C$, could be installed in Δt_3 (4-43 to 4-48). In type II reconfiguration, the available capacity of added or removed capacity falls between 40% and 80% of added/removed capacity (4-37 to 4-42).

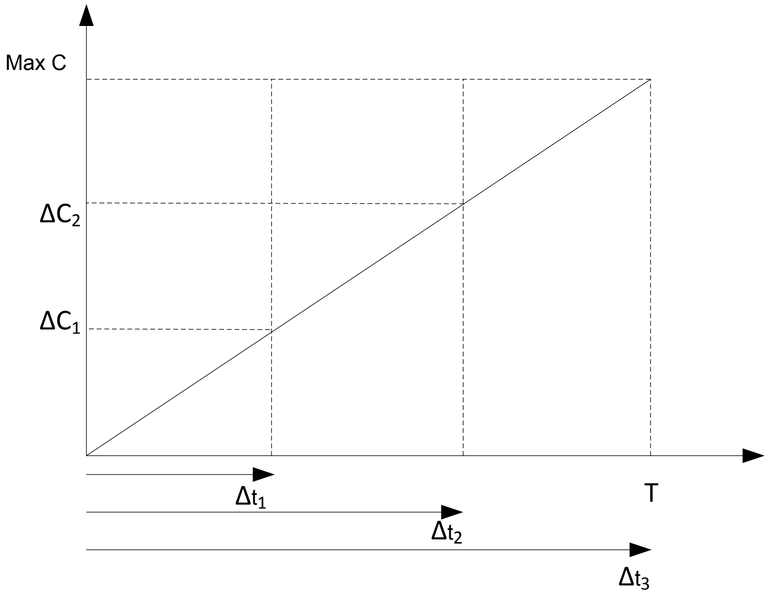


Figure 4-4 Reconfiguration type II, capacity is added linearly

Capacity availability during reconfiguration type II:

$$U\xi_t^r + L\xi_t^r \le .8*\left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) + M*(1-Y_t^4) \qquad \forall t \in \{2..T\} \qquad (4\text{-}37)$$

$$U\xi_t^r + L\xi_t^r \ge 0.7*\left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) - M*(1-Y_t^4) \qquad \forall t \in \{2..T\} \qquad (4\text{-}38)$$

$$U\xi_t^r + L\xi_t^r \le 0.7*\left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) + M*(1-Y_t^5) \qquad \forall t \in \{2..T\} \qquad (4\text{-}39)$$

$$U\xi_t^r + L\xi_t^r \geq 0.55*(R\Delta\xi_t^+ + R\Delta\xi_t^-) - M*(1-Y_t^5) \qquad \forall t \in \{2..T\} \qquad (4\text{-}40)$$

$$U\xi_t^r + L\xi_t^r \leq 0.55*\left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) + M*(1-Y_t^6) \qquad \forall t \in \{2..T\} \qquad (4\text{-}41)$$

$$U\xi_t^r + L\xi_t^r \geq 0.4*\left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) - M*(1-Y_t^6) \qquad \forall t \in \{2..T\} \qquad (4\text{-}42)$$

Reconfigurable System Responsiveness (Type II)

$$R\Delta\xi_t^+ + R\Delta\xi_t^- \leq .33*\vartheta_R^r + M - M*(Y_t^4) \qquad \forall t \in \{2..T\} \qquad (4\text{-}43)$$

$$R\Delta\xi_t^+ + R\Delta\xi_t^- \geq .33*\vartheta_R^r - M + M*(Y_t^5) \qquad \forall t \in \{2..T\} \qquad (4\text{-}44)$$

$$R\Delta\xi_t^+ + R\Delta\xi_t^- \leq .66*\vartheta_R^r + M - M*(Y_t^5) \qquad \forall t \in \{2..T\} \qquad (4\text{-}45)$$

$$R\Delta\xi_t^+ + R\Delta\xi_t^- \geq .66*\vartheta_R^r - M + M*(Y_t^6) \qquad \forall t \in \{2..T\} \qquad (4\text{-}46)$$

$$R\Delta\xi_t^+ + R\Delta\xi_t^- \leq \vartheta_R^r + M - M*(Y_t^6) \qquad \forall t \in \{2..T\} \qquad (4\text{-}47)$$

$$Y_t^4 + Y_t^5 + Y_t^6 \leq K^2 \qquad \forall t \in T \qquad (4\text{-}48)$$

In type III reconfiguration pattern (Figure 4-5), it is assumed $0 \leq \Delta C \leq 0.625C$, could be installed in Δt_1, $0.625C \leq \Delta C \leq 0.875C$, could be installed in Δt_2, and $0.875 \leq \Delta C \leq C$, could be installed in Δt_3 (4-55 to 4-60). In type III, the available capacity of added or removed capacity falls in 80% to 100% of added or removed capacity (4-49 to 4-54).

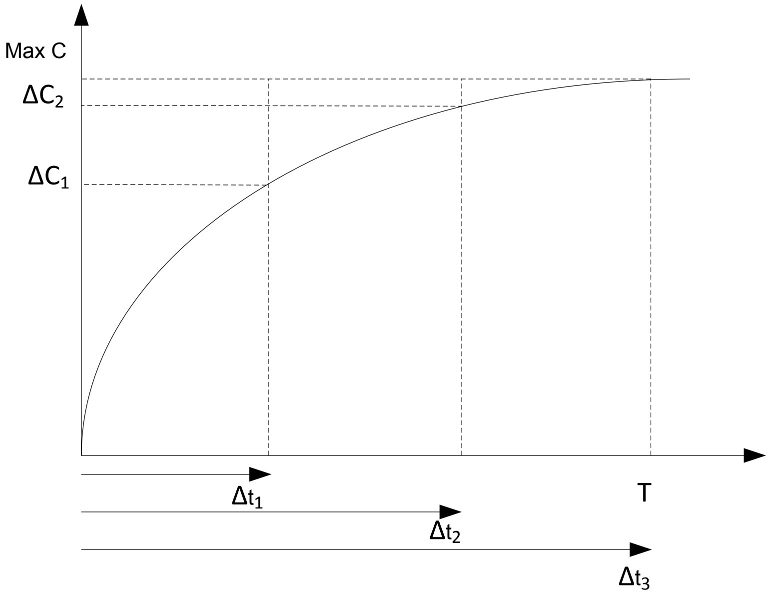


Figure 4-5 Reconfiguration type III more capacity is available during reconfiguration

Capacity availability during reconfiguration type III:

$$U\xi_t^r + L\xi_t^r \le \left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) + M*(1-Y_t^7) \qquad \forall t \in \{2..T\} \tag{4-49}$$

$$U\xi_t^r + L\xi_t^r \ge 0.95*\left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) - M*(1-Y_t^7) \qquad \forall t \in \{2..T\} \tag{4-50}$$

$$U\xi_t^r + L\xi_t^r \le 0.95*\left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) + M*(1-Y_t^8) \qquad \forall t \in \{2..T\} \tag{4-51}$$

$$U\xi_t^r + L\xi_t^r \ge 0.9*\left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) - M*(1-Y_t^8) \qquad \forall t \in \{2..T\} \tag{4-52}$$

$$U\xi_t^r + L\xi_t^r \le 0.9*\left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) + M*(1-Y_t^9) \qquad \forall t \in \{2..T\} \tag{4-53}$$

$$U\xi_t^r + L\xi_t^r \ge 0.8*\left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) - M*(1-Y_t^9) \qquad \forall t \in \{2..T\} \tag{4-54}$$

Reconfigurable System Responsiveness (Type III)

$$R\Delta\xi_t^+ + R\Delta\xi_t^- \le 0.625*\vartheta_R^r + M - M*(Y_t^7) \qquad \forall t \in \{2..T\} \tag{4-55}$$

$$R\Delta\xi_t^+ + R\Delta\xi_t^- \ge 0.625*\vartheta_R^r - M + M*(Y_t^8) \qquad \forall t \in \{2..T\} \tag{4-56}$$

$$R\Delta\xi_t^+ + R\Delta\xi_t^- \le 0.875*\vartheta_R^r + M - M*(Y_t^8) \qquad \forall t \in \{2..T\} \tag{4-57}$$

$$R\Delta\xi_t^+ + R\Delta\xi_t^- \ge 0.875*\vartheta_R^r - M + M*(Y_t^9) \qquad \forall t \in \{2..T\} \tag{4-58}$$

$$R\Delta\xi_t^+ + R\Delta\xi_t^- \le \vartheta_R^r + M - M*(Y_t^9) \qquad \forall t \in \{2..T\} \tag{4-59}$$

$$Y_t^7 + Y_t^8 + Y_t^9 \le K^3 \qquad \forall t \in T \qquad (4\text{-}60)$$

The MIP model is solved to optimality by CPLEX software (Academic version 12.1) set to 1E-04 MIPGAP on 2.4 GHz double processor cores CPU. The MIP model has 524 rows, 290 columns and 2237 nonzero coefficients. Also number of binary decision variables are 132 and number of general variables are 157. The solutions obtained from the MIP model identify the optimal capacity allocation by considering the safety capacity and some approximation regarding the ramp up period. In order to represent the randomness in these processes and to validate the results of the MIP, the optimal solutions are simulated in ARENA 13.5. In the following section, the simulation model flow and the associated parameters is described.

4.3 Simulation model

The simulation model developed to validate the MIP results consists of two sections of information flow. In the first section, the time period is controlled (Figure 4-6-Section A) and all required statistics at the end of each period is collected. Statistics that will be collected are the total amount of excess capacity, total demand lost, and total satisfied demand. In addition, series reconfiguration is updated at time period subsection because the series reconfiguration takes one period and no capacity is available during reconfiguration period.

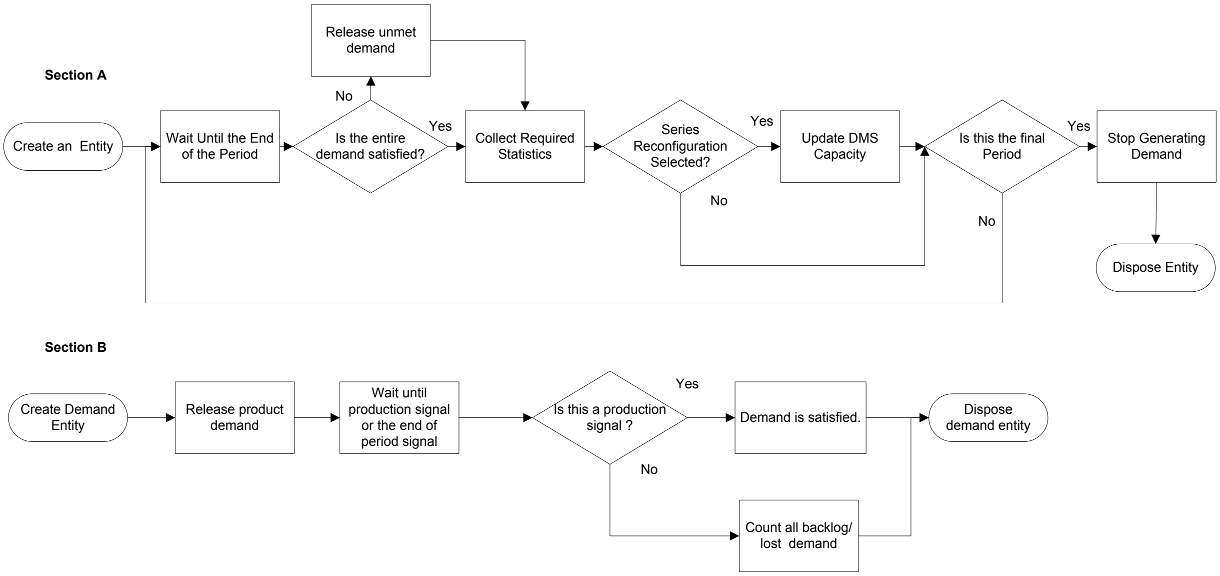


Figure 4-6 Simulation demand and time period control flowchart

Moreover, the demand of each product is generated (Figure 4-6-Section B) based on a given statistical distribution. The demand is kept up until the end of a period. If any demand is not satisfied by DMS or RMS at the end of a period, then it is considered as lost.

In the second section of the simulation module, the DMS and RMS production is modelled (Figure 7-Section A). DMS and RMS production levels are based on the results that are obtained from the MIP model. Furthermore, RMS capacity is updated based on the configuration pattern selected in the MIP (Figure 7-Section B). In a reconfiguration period, the ramp up pattern can be represented as follows: Type I, Type II and Type III reconfiguration pattern. The duration of the reconfiguration period is equivalent to MIP model.

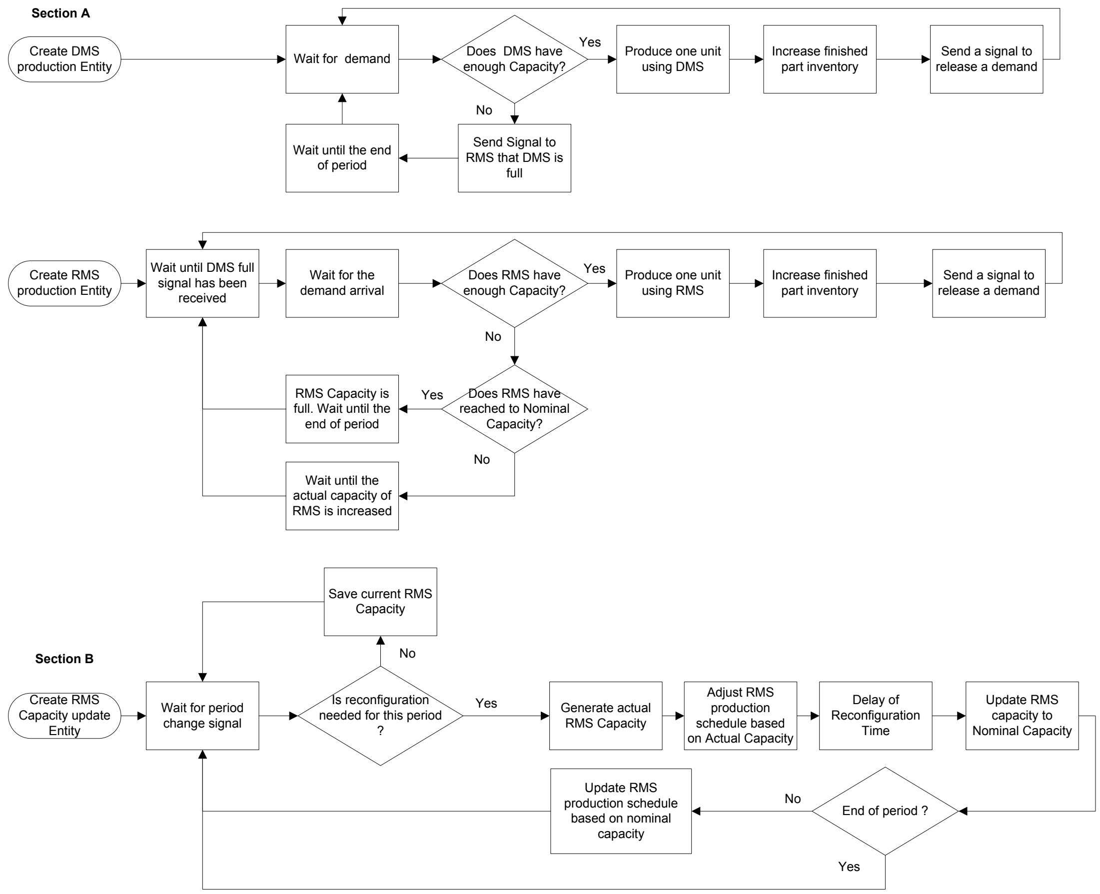


Figure 4-7 Simulation production system section and RMS capacity evolution

For the reconfiguration time, the output of the MIP is used in simulation as a constant parameter. However, the actual capacity that is available during this period is represented by the uniform distribution. The upper and lower bounds of the distribution are set according to the bounds determined for each configuration pattern. For example, in reconfiguration Type I, it is assumed that actual capacity is between 45% and 60% of nominal capacity if the reconfiguration length is one third of a period as indicated in constraints (4-25) and (4-26). For this case, the actual capacity is determined by a uniform distribution [45% $IR\xi_t$, 60% $IR\xi_t$], where $IR\xi_t$ represents the nominal capacity.

In the next section, a set of experiments are developed to analyze how system's capacity portfolio changes during multiple production periods in order to highlight the impact of layout configuration.

4.4 Numerical results

An illustrative example is presented in order to analyze the impact of configuration characteristics into the tactical level decision regarding the capacity allocation decisions. As indicated in section 4.2, the MIP model is developed to optimize the capacity allocation of manufacturing systems based on the operational costs and associated opportunity costs. There exist four main parameters for which a sensitivity analysis is conducted in the MIP phase. These parameters and their associated values are indicated in Table 4-1:

Table 4-1Critical parameters for the MIP

Parameter	**Value Range**
Configuration Characteristic	Type I, II, III, and IV
Desired Service Level	[70%, 80%, 90%]
Excess capacity cost	S, 2S, 3S
Response Range	σ, 3σ

A combination of these parameters is considered as a scenario to be run in the MIP model, i.e. a total of 72 scenarios were considered. The objective in performing this analysis is to analyze the impact of configuration responsiveness on the performance levels such as capacity allocation, achieved service level, and total cost.

In assessing the responsiveness of RMS, a maximum range of capacity that could be added, is identified. The lower and the higher response range correspond to the design approach of the modules and bases in setting the RMS capacity (Niroomand et al., 2012). An RMS system can be implemented in such a way that the average number of modules per machine base is kept low. This would represent a possibility to add a higher level capacity compared to another configuration with equivalent capacity which consists of bases that is limited in terms of adding modules. The first case represents a high response range where the second case represents a low response range. By changing the response range, ϑ^r, the boundary is adjusted for the amount of capacity that could be added or removed. At the low level, it is assumed that the RMS system is able to respond to a range equivalent to the standard deviation of all periods' demand. The high level is set to a value equivalent to three times the standard deviation.

In the second phase, the output of the MIP is validated in simulation environment where the demand and available capacity during reconfiguration are considered as random variables. The objective of the simulation phase is to test the capacity allocation and configuration decisions against the achieved service level and operational costs. In the simulation model, first the service level is verified to ensure that each capacity portfolio is able to meet the determined service level. If the target service level is not achieved the MIP model is solved again by increasing the value of u.

This experimental setup is implemented for a hypothetical firm that produces product A and B where product B is introduced to market later than product A. The mean demand for each product (μ) for ten consecutive periods is represented in Figure 4-8. It is assumed that demand follows normal distribution and demand variance (δ) changes depending on the stage in product lifecycle. A period demand has a higher variation during the introduction and the decline phase and less variation during the maturity phase.

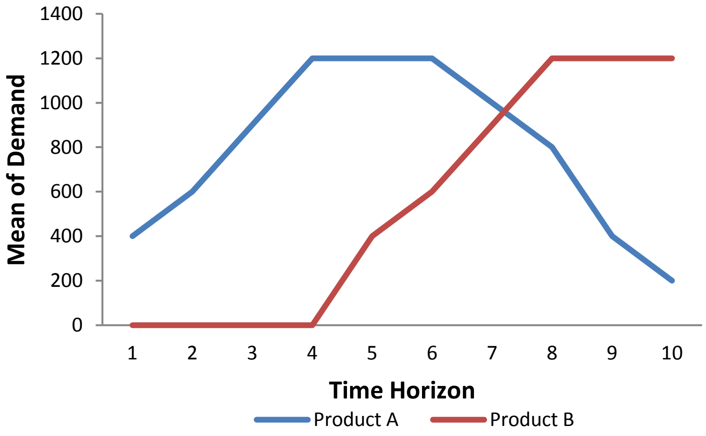


Figure 4-8 Product A and B evolution trend

4.4.1 Capacity allocation by MIP model

The percentage of RMS capacity allocation for each scenario is shown in Table 4-2. In all reconfiguration types, a higher level of capacity is allocated to the RMS system by increasing the excess cost within the same service level. For example, RMS investment increases from 46% to 77% at low response range and 90% service level. This indicates that the benefit of scalability outweighs the added investment cost compared to a DMS alternative.

With respect to the impact of response range, it is observed that the allocation to RMS increases as the response range increases. This increase is seen at a given service level and excess cost. Among reconfigurations Type I to Type III, Type III reconfiguration provides better responsiveness and enables RMS to reach the desired level of capacity faster. In low response range, higher reconfiguration speed is an advantage for RMS since the capacity evolution of RMS is able to chase the demand (Figure4- 9-(a)). In high response range, the rate of reduction in RMS investment is less than low response range as service level increases. This is mainly as a result of the improvement in actual capacity during reconfiguration when RMS response range increases. For example, at low excess cost and 3σ response range, RMS investment decreases from 76% to 74% in contrast to 58% to 46% in σ response range.

On the other hand, a higher requirement in the service level shifts the capacity allocation to DMS. The shift from RMS to DMS is significant especially in cases where the excess capacity cost is low, which allows DMS to maintain the service level through its excess capacity. As the excess capacity becomes expensive, an increase in the service level requirement does not change the capacity allocation. In this situation, the responsive capacity is preferred over the excess capacity allocation.

Table 4-2 RMS investment in three reconfiguration types

Response range	Excess cost	Type I			Type II			Type III		
		70%	**80%**	**90%**	**70%**	**80%**	**90%**	**70%**	**80%**	**90%**
$\vartheta^{r} = \sigma$	**S**	60%	46%	38%	58%	46%	46%	70%	67%	56%
	2S	68%	68%	65%	78%	75%	71%	83%	71%	68%
	3S	80%	80%	78%	82%	81%	77%	83%	82%	79%
$\vartheta^{r} = 3\sigma$	**S**	63%	63%	63%	76%	76%	74%	76%	76%	75%
	2S	84%	82%	82%	86%	85%	84%	84%	84%	75%
	3S	84%	83%	82%	86%	85%	84%	85%	84%	83%

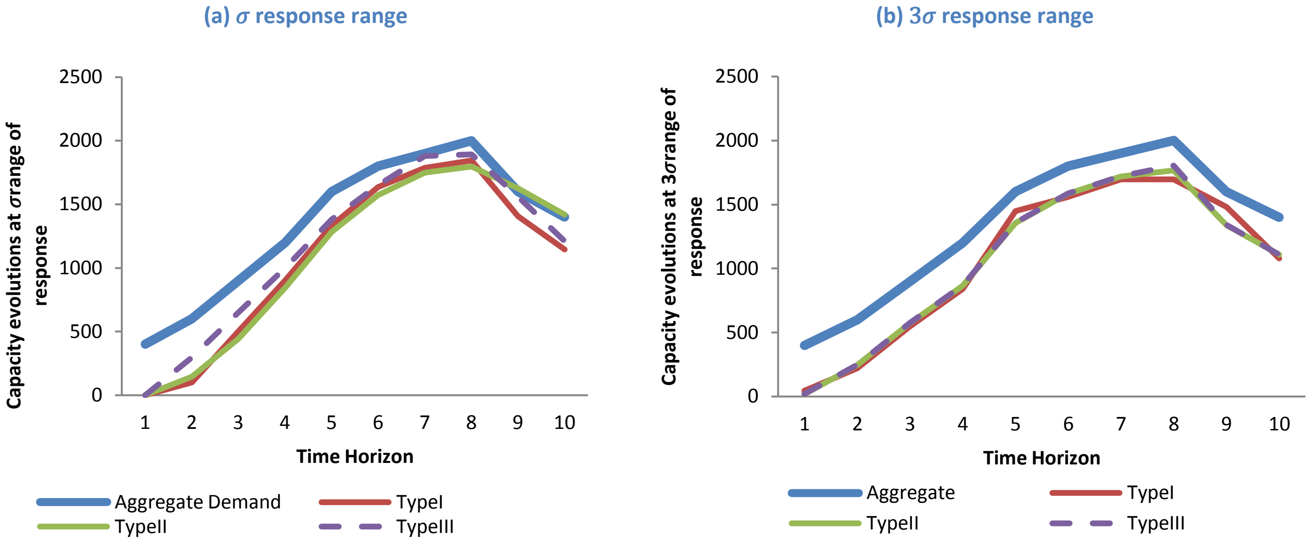


Figure 4-9 RMS capacity evolution of different configuration types

Since RMS is designed to chase capacity in achieving the desired service level, the configuration characteristics play an important role in this capability. As indicated in Figure 4-9.a), opting for a parallel configuration allows to better demand chasing in the case where the response range is limited. On the other hand, all configuration types are more or less capable to follow the demand in high response range (Figure 4-9.b). In cases where the response range is high, the system cost becomes more important since the difference in the speed of response is not significant between configuration characteristics. As a result of this, a higher portion of capacity is allocated to Type II configuration in high response range compared to other configurations (Table 4-2). In order to analyze the differences among configuration types, the MIP output is discussed in terms of reconfiguration characteristics in the following section.

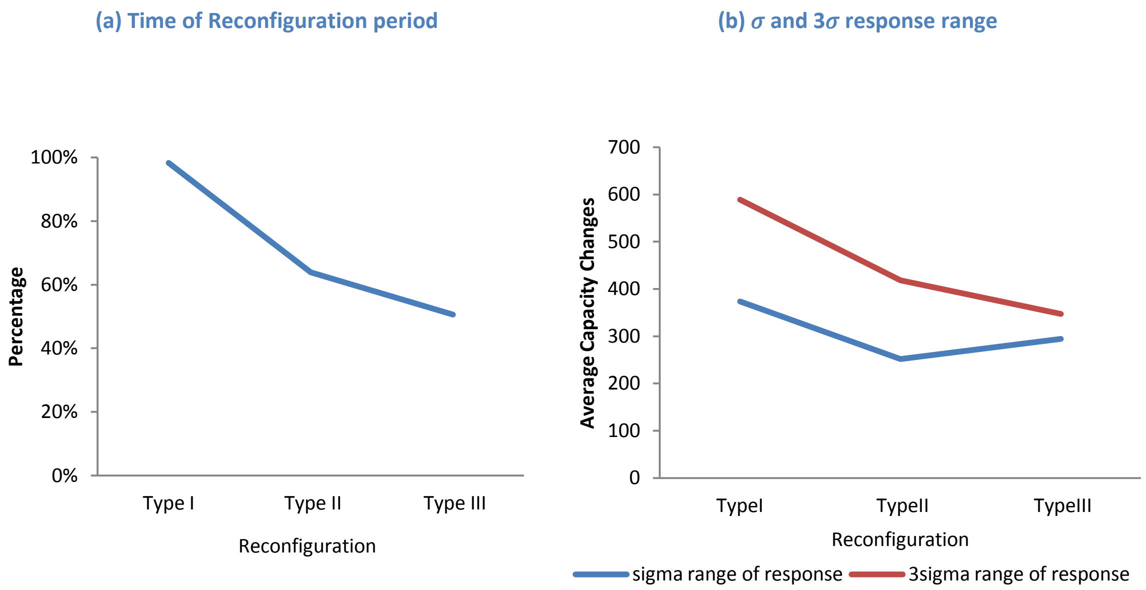
4.4.2 The impact of reconfiguration type on performance

Reconfiguration type has a major effect on the time and the amount of capacity that is added or removed in different stages of the products' life cycle. As expected, the reconfiguration time is decreased noticeably by moving from reconfiguration Type I to Type III (Figure 4-10.a). In addition, improving the reconfiguration speed increases the total number of reconfigurations. As indicated in Table 4-3, capacity is updated more frequently when it is highly responsive.

Table 4-3 Number of reconfigurations for Type I,II, and III

Response range	Excess cost	**Type I**			**Type II**			**Type III**		
		70%	**80%**	**90%**	**70%**	**80%**	**90%**	**70%**	**80%**	**90%**
$\vartheta^r = \sigma$	**S**	2	2	2	4	3	5	5	7	6
	2S	3	6	5	7	8	8	8	7	7
	3S	5	7	8	8	8	8	8	8	8
$\vartheta^r = 3\sigma$	**S**	1	2	3	4	5	5	5	5	7
	2S	4	4	6	6	6	7	8	8	7
	3S	4	5	6	6	7	7	9	8	8

The improvement in responsiveness not only increases the frequency of reconfigurations but also the average capacity change, i.e. the scalability. Changing the layout type towards a parallel configuration decrease the average amount of updated capacity as indicated in Figure 4-10.b.


(a) Time of Reconfiguration period

(b) σ and 3σ response range

Figure 4-10 Reconfiguration type's effect on capacity evolution and reconfiguration time from MIP model

The MIP results clearly indicate the improvement in responsiveness and changes in reconfiguration characteristics as a result of changes in the layout characteristics. However, the generated solutions must be validated subject to a random demand and reconfiguration process. In order to test the performance of the selected capacity configurations in terms of customer service level and operational cost, a comprehensive simulation study is conducted for each scenario.

4.4.3 Simulation results

In the simulation environment, the capacity during ramp up time and demand for each year are considered random. In achieving the simulation results, each scenario indicated in Table 4-1 is simulated with 30 replications. As a result of the randomness, the achieved service level will be different than the MIP results. As shown in Table 4-4, all the instances meet the target service level. Demand lost at each service level is better than expected. The amount of the service level achieved in simulation shows that considering safety capacity in the MIP model ensures that the desired service level is met.

Table 4-4 Demand loss

		$\vartheta^r = \sigma$				$\vartheta^r = 3\sigma$			
Service Level	Excess Cost	Series	Type I	Type II	Type III	Series	Type I	Type II	Type III
70%	S	6.2%	6.3%	6.9%	7.5%	6%	6%	7%	6%
	2S	6.2%	5.6%	5.3%	5.1%	6%	5%	4%	5%
	3S	6%	6.8%	5.1%	5.1%	6%	5.9%	4.7%	5%
80%	S	5.9%	5%	4.8%	3.8%	5.9%	3%	5%	4%
	2S	5.9%	2.6%	1.9%	3.9%	5.9%	3.6%	2.6%	3.5%
	3S	6.2%	3.6%	1.7%	1.9%	6.2%	3.8%	3.8%	3%
90%	S	3.8%	3.1%	2.6%	2.9%	3.8%	1.9%	3.6%	2.8%
	2S	3.5%	2.1%	1%	1.9%	3.5%	3.2%	1.7%	3%
	3S	3.5%	2.9%	3.1%	2.9%	3.5%	3.2%	2.6%	2.3%

In order to analyze the impact of responsiveness on operational costs, the data regarding excess capacity costs, shortage costs, and total cost have been collected in the simulation environment. The cost information for each scenario and cost category is provided as a percentage difference relative the minimum within that category.

The advantage of frequent reconfiguration with scalable capacity can be identified by the reduction in excess capacity cost. Excess capacity reduction helps manufacturers to decrease capacity investment cost and provide better utilization of available capacity. The simulation results for each reconfiguration type confirm this observation. According to Figure 4-11, the rate of reduction in excess capacity and shortage rate is in line with the faster reconfiguration speed. In other words, better reconfiguration speed not only helps the manufacturer to satisfy the predetermined service level but it also prevents the accumulation of capacity in advance.

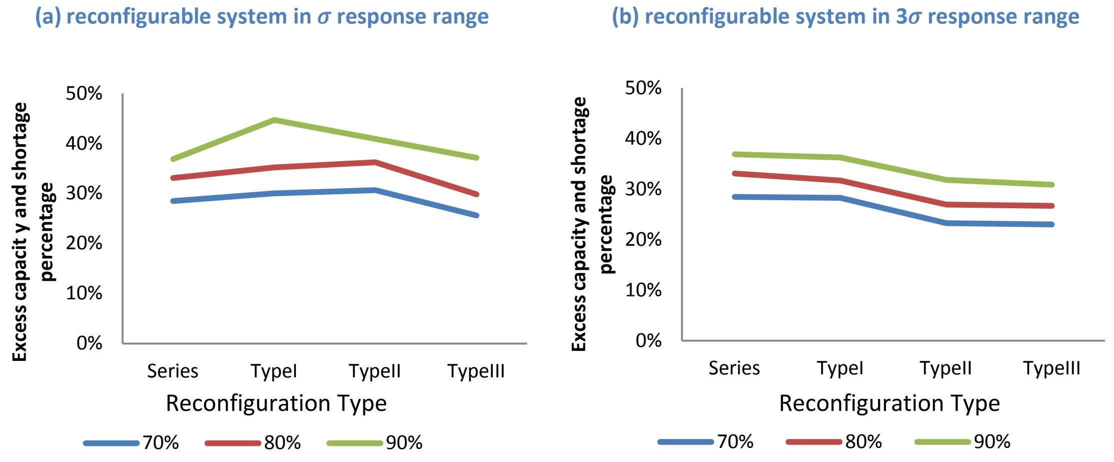
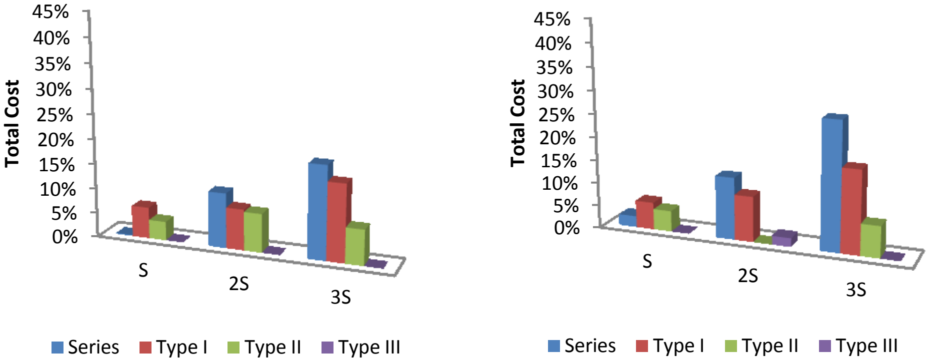


Figure 4-11 Excess capacity and shortage percentage of each type of reconfiguration based on simulation result

Simulation results for different configurations show that series reconfiguration comes with minimum total cost only at a low excess cost Figure 4-12.a. This can be explained by the demand fluctuation causing series reconfiguration to impose high level of excess capacity cost.


(a)- 70% Service level

(b)- 80% Service level

(c)- 90% Service level

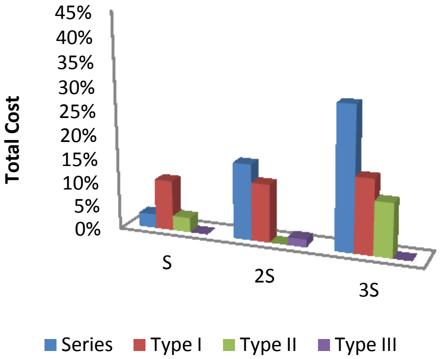


Figure 4-12 Simulation results of total cost for different configurations in **σ** response range

As it is shown in Figure 4-13, the total cost of series reconfiguration is only 2% higher than Type III reconfiguration; however, the excess capacity cost in series reconfiguration is 20% higher than the excess capacity cost identified in Type III reconfiguration.

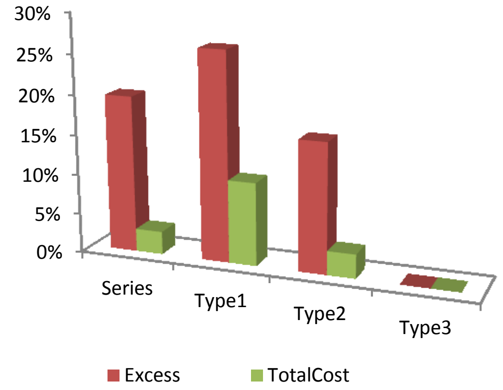
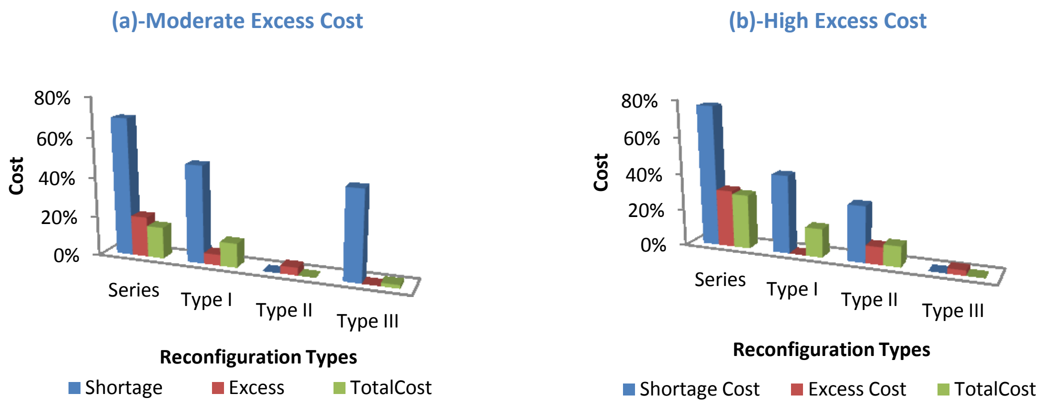


Figure 4-13 Excess cost vs. total cost at 90% Service level and **σ** response range

As indicated in Figure 4-12, the cost gap between series reconfiguration and Type III increases rapidly by increasing both the service level and excess capacity cost. For example, at 80% and 90% service level, the total cost of series reconfiguration is 30% more than Type III reconfiguration. Among different reconfiguration types, Type III reconfiguration provides minimum total cost at high excess capacity cost levels within low response range.

At low excess capacity cost, Type II reconfiguration acts better than Type III reconfiguration while service level is kept high (80% and 90%). At high service level, excess capacity of Type II reconfiguration could benefit the manufacturer during a ramp down phase if the demand in this period is above expectation. Therefore, at the moderate excess cost, excess capacity as a result of Type II reconfiguration is an advantage and reduces lost demand rate and total cost (Figure 4-14.a). By increasing excess cost, Type III reconfiguration comes with minimum total cost among all reconfigurations (Figure 4-14.b).

In low level response range, Type I reconfiguration is not selected at any scenario. Type I reconfiguration is similar to series reconfiguration, but with the disadvantage of higher capacity cost since RMS is more expensive than DMS. Also, during the reconfiguration period, Type I reconfiguration does not provide any competitive advantages for the manufacturer since the actual capacity during reconfiguration is minimum.


(a)-Moderate Excess Cost

(b)-High Excess Cost

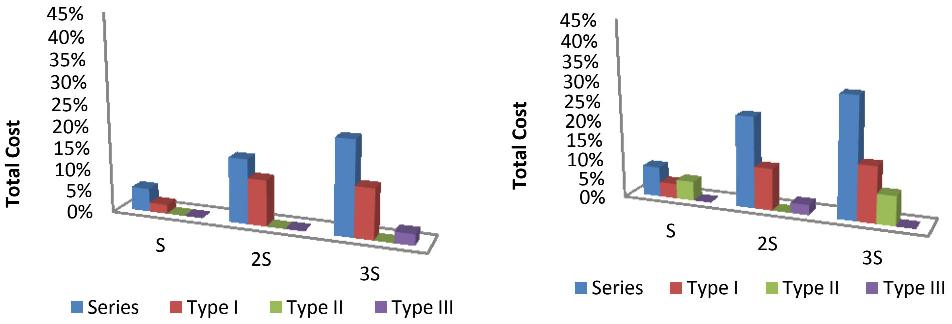
Figure 4-14 Different cost at 90% service level and **σ** response range

The simulation results regarding the total cost show that Type II reconfiguration provides minimum total cost at low service level (Figure 4-15). In addition, Type II configuration remains the best configuration at moderate excess cost for any service level. Here, the excess capacity in Type II reconfiguration increases fill rate and reduces total cost as observed in the case of low response range.

Also, a higher response range results in a reduced total cost for Type II compared to Type III reconfiguration. For example, at the low response range, the simulation result shows only 1% gap between Type II and Type III reconfiguration (Figure 4-12.c) at 90% service level. But, at the high response range this gap increases to 10% (Figure 4-15.c).

(a)- 70% Service level

(b)- 80% Service level



(c)- 90% Service level

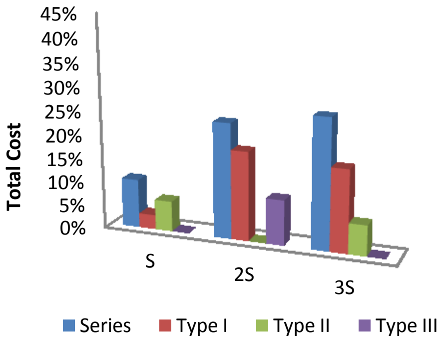


Figure 4-15 Total cost for different configurations in 3σ response range achieved by simulation

At the highest excess cost and highest service level, Type III reconfiguration is the better option than other configuration patterns. The summary of the simulation results are presented in Table 4-5

Table 4-5 Minimum cost configurations

Response range	Excess cost	**Service Level**		
		70%	**80%**	**90%**
$\vartheta^r = \sigma$	**S**	Series	Series	Series / Type III
	2S	Type II	Type II	Type II
	3S	Type II	Type II	Type III
$\vartheta^r = 3\sigma$	**S**	Type II	Type III	Type III
	2S	Type II/III	Type II	Type II
	3S	Type II	Type III	Type III

The simulation results show that at low response range, series reconfiguration could be selected when excess cost is low. This is based on the fact that the excess capacity is affordable in this situation compared to an RMS installation. As the excess capacity cost and service level requirement increase the minimum cost configuration switch to Type II and Type III.

At high response range, Type II reconfiguration becomes more appealing at a moderate excess cost or low service level. This can be interpreted as a consequence of more scalable capacity being added or removed with higher speed rate. Thus, the total cost performance of Type II reconfiguration is very close to Type III making it a preferable configuration at a higher service level and the highest excess cost.

Among all configurations, Type I reconfiguration is not justified since Type I reconfiguration shape is similar to series reconfiguration. Therefore, Type I reconfiguration does not provide any competitive advantage for the firm during reconfiguration period in terms of responsiveness. In addition, Type I reconfiguration is more costly than series reconfiguration since the capacity cost of RMS is higher than DMS. Therefore, even at low service rate and low excess cost; DMS system has more benefit for the firm.

It is seen that the reconfiguration speed has a direct effect on updating capacity and excess capacity amount. Especially, the frequent reconfiguration reduces the excess capacity and shortage rate simultaneously as a result of a responsive RMS. Simulation results also verify that the speed of the reconfiguration is an important factor in the reduction of opportunity cost. Even at low response range, moving from the Type I to Type III reconfiguration reduces the excess capacity. At 3σ response range, since the responsiveness of the system is much better than the σ response range, the scalability of RMS is improved. Therefore, more scalable capacity could be added in Type II reconfiguration. The result of this scalability is the reduction of excess capacity and shortage percentage. Therefore, the opportunity cost is reduced as it shown in Figure 4-11.b.

4.5 Summary and discussion

Based on the results, it could be concluded that series reconfiguration might be a good option at low excess cost and higher service level; however, under demand uncertainty, series reconfiguration results in higher percentage of excess capacity and increased total cost. By increasing the excess cost, the tendency of manufacturing system moves towards RMS.

At low response range in RMS, Type III reconfiguration (parallel reconfiguration) will benefit the system more than other types of configurations. Quick ramp up helps the firm to adjust capacity close to the demand in each period. Type II reconfiguration (Hybrid reconfiguration) is more desirable when the response range of RMS increases.

At higher response range, not only can the Type II reconfiguration follow the demand closely as a result of better scalability, but it can also reduce the total system cost. In other words, at low response range a higher RMS reconfiguration speed provides better service level for the manufacturer but at higher response range, a good service level is achieved in a cost effective manner.

Moreover, by moving from Type I reconfiguration to Type III reconfiguration, the number of reconfigurations increases and the amount of capacity change reduces. Therefore, Type II and III reconfigurations could help firms in competitive markets where the frequency of new products to market is high.

In addition to system layout configuration, the workload level can have an effect on capacity planning strategy on the long run. The total available capacity may not be fully utilized due to congestion. In order to analyse the effect of congestion on the capacity level, the reconfiguration speed is analyzed in the context of the supply chain network. In this context, a main supply node is considered to be disrupted, and a backup supplier will adjust its capacity to cover the capacity shortage. This may result in an overflow of demand towards the backup supplier, which may face with congestion. The reconfiguration speed of the backup supply node is selected in a way that not only covers the capacity shortage but also minimizes the effect of production congestion.

Chapter 5: Effect of response time on service level in supply chain network

In this chapter, the available capacity of manufacturing system is investigated according to response time characteristics and congestion impact. Considering the effects of congestion provides a better estimation of available capacity during reconfiguration period. In this context, a single product supply chain that includes a warehouse with dual sourcing is investigated (Figure 5-1). One supplier uses DMS and the other one takes advantage of more flexible capacity such as RMS. Since production by DMS is cheaper than RMS, DMS is the main supplier and the RMS is considered as a backup source.

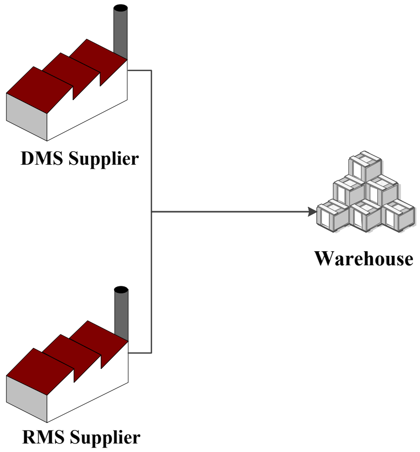


Figure 5-1 Two echelon supply chain network

The product lifecycle follows introduction, growth, maturity and decline phases and demand during each stage of life cycle is assumed to be deterministic (Rink and Swan, 1979). During the peak demand at growth stage or at the time that DMS supplier is disrupted, RMS supplier could compensate for the lost DMS production. The reconfiguration time and available capacity of RMS is analyzed in a contingency capacity planning scenario. The drivers of RMS capacity update are shortage cost, RMS reconfiguration cost, RMS excess capacity cost, and RMS production cost as described in sections 5.2 and 5.2.3.

It is assumed that a fraction of the RMS capacity is available during the reconfiguration period. However, in addition to ramp up behavior that makes the actual capacity less than nominal capacity, the effect of production congestion during reconfiguration also reduces the system throughput. In a situation where the main supplier is disrupted, its demand would be transferred to the backup supplier under a contingency strategy. This may create an overload of demand at the backup supplier despite the quick ramp-up characteristics. As a result of this overload, queues will build up, degrading performance due to the congestion. To represent this behaviour, clearing functions have been implemented as discussed in section 5.2.2.

RMS capacity within response time is important since the supply chain incurs shortage costs if the available capacity level during this period is lower than the required capacity. As result of these, the reconfiguration speed of the RMS should be selected with respect to the trade-off between reconfiguration cost and required available capacity.

The summary of assumptions is as follows:

- Demand levels follow the classical product lifecycle.
- Production cost of the backup supplier is higher than the regular supplier.
- Higher reconfiguration cost increases as reconfiguration speed increases.
- Excess capacity cost is increased at the decline phase of product life cycle.
- Shortage cost is decreased at the decline phase of product life cycle.

5.1 Solution Methodology

Through mixed integer programming (MIP) the interaction of supply chain network' echelon is determined. Afterwards, the capacity plan is subjected to a set of possible DMS disruption scenarios where each scenario's probability of occurrence is calculated using discrete Markov chain distributions (Figure 5-2). Three different response speeds are proposed $\mathrm{RS_k}, \mathrm{k} \epsilon \{1,2,3\}$ where a certain capacity level is available during the response time corresponding to each speed. For each response speed, the MIP generates the contingency capacity plans and their resulting costs corresponding to different disruption scenarios *(t,l)* where t represents the time of occurrence and *l* is the length of disruption. The costs of the contingency capacity plans as well as the probabilities of disruption scenarios are then represented in a decision tree

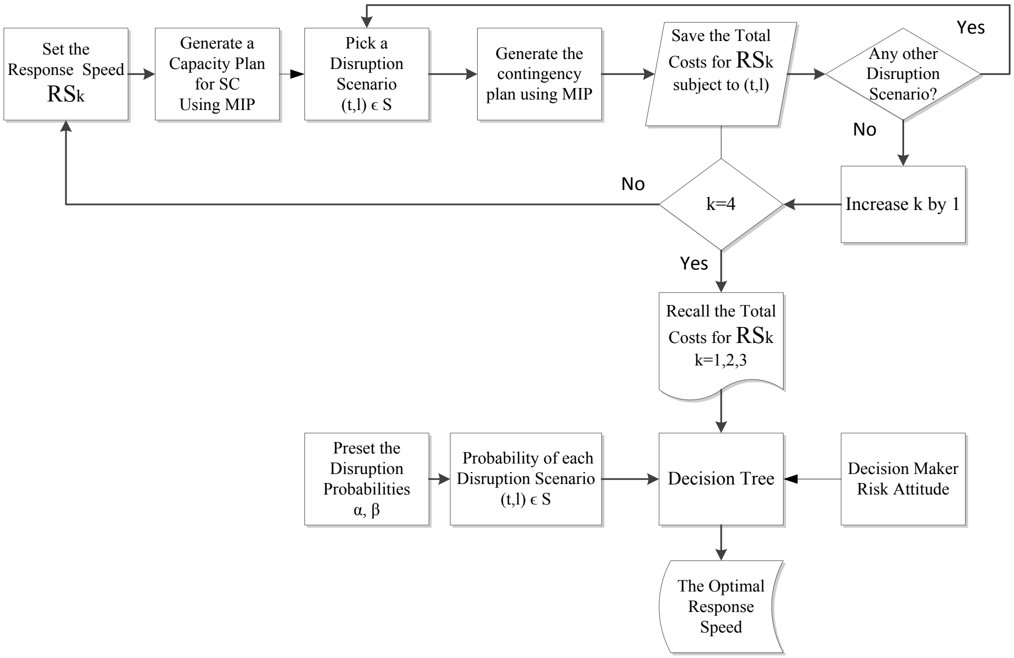


Figure 5-2 Solution methodology

For a given failure and recovery probability, a better response speed is selected through a decision tree analysis by considering the better capacity policy under risk neutral conditions. The risk neutral decision maker selects the optimal response speed with the objective of minimizing the expected cost under all plausible scenarios.

5.2 MIP capacity planning

Through mathematical programming, a relationship of capacity, production, inventory and WIP levels of DMS and RMS suppliers are modelled for a predetermined planning horizon. The impact of the reconfiguration on RMS capacity as well as the impact of congestion on the production capabilities is shown with their corresponding constraints.

The objective function includes the production cost (5-1), the system reconfiguration cost (5-2), the capacity excess cost and demand lost (5-3), the holding cost of the finished goods inventory (5-4), the WIP inventory holding cost (5-5) and the raw material holding cost (5-6).

Since the production cost of the flexible capacity supplier is higher than the fixed capacity supplier (Tomlin, 2006), it is assumed that the WIP cost and the holding cost of the products produced by RMS are more than the DMS. Any demand which is not satisfied at each period is considered as lost demand and it is not backordered. Also, it is assumed that any unutilized capacity is not manufacturer favor; therefore, an excess cost is calculated for any unutilized capacity at the end of each period.

$$Min(Z) = \sum_t (CP^d * D\lambda_t + CP^r * R\lambda_t) \tag{5-1}$$

$$+\sum_t RC * (R\Delta\xi_t^+ + R\Delta\xi_t^-) \tag{5-2}$$

$$+\sum_t (SC * D_t^l + EC^d * E\xi_t^d + EC^r * E\xi_t^r) \tag{5-3}$$

$$+\sum_t HC^d * I_t^d + HC^r * I_t^r \tag{5-4}$$

$$+\sum_t c\omega^d * \omega_t^d + c\omega^r * \omega_t^r \tag{5-5}$$

$$+\sum_t crm^d * rm_t^d + crm^r * rm_t^r \tag{5-6}$$

Any realized demand could be satisfied either through the inventory or the current RMS and DMS production (5-7, 5-8). The demand lost (5-9, 5-10) is occurred when the total demand is more than current production capacity and inventory level. Therefore, it is not possible to have both demand loss and the inventory at the end of any period (5-11, 5-12).

Furthermore, any unfinished goods inventory has impact on the production quantity of a facility in any period. Therefore, the current capacity of any system is a function of the WIP level and the released material within that period. This relation is shown by constraints (5-13, 5-14). The maximum workload in any period is bounded by the available capacity during that period (5-17, 5-18) and any unutilized capacity is considered as excess capacity (5-15, 5-16).

Constraints

$$I_t^d = I_{t-1}^d + D\lambda_t - D_t^d \qquad \forall\ t \in T \qquad (5\text{-}7)$$

$$I_t^r = I_{t-1}^r + R\lambda_t - D_t^r \qquad \forall\ t \in T \qquad (5\text{-}8)$$

$$D_t^d + D_t^r = D_t^s \qquad \forall\ t \in T \qquad (5\text{-}9)$$

$$D_t^s + D_t^l = D_t^{tot} \qquad \forall\ t \in T \qquad (5\text{-}10)$$

$$D_t^l \le M * (1 - Y_t^5) \qquad \forall\ t \in T \qquad (5\text{-}11)$$

$$I_t^d + I_t^r \le M * (Y_t^5) \qquad \forall\ t \in T \qquad (5\text{-}12)$$

$$\omega_t^d = \omega_{t-1}^d + rm_t^d - D\lambda_t \qquad \forall\ t \in T \qquad (5\text{-}13)$$

$$\omega_t^r = \omega_{t-1}^r + rm_t^r - R\lambda_t \qquad \forall\ t \in T \qquad (5\text{-}14)$$

$$D\lambda_t + E\xi_t^d = C_{\max}^d \qquad \forall\ t \in T \qquad (5\text{-}15)$$

$$R\lambda_t + E\xi_t^r = R\xi_t \qquad \forall\ t \in T \qquad (5\text{-}16)$$

$$\omega_t^d + rm_t^d \le C_{\max}^d \qquad \forall\ t \in T \qquad (5\text{-}17)$$

$$\omega_t^r + rm_t^r \le R\xi_t \qquad \forall\ t \in T \qquad (5\text{-}18)$$

Decision Variables:

D_t^s	Satisfied demand at time t
D_t^d	DMS satisfied demand at time t
D_t^r	RMS satisfied demand at time t
$E\xi_t^d$	DMS excess capacity at time t
$E\xi_t^r$	RMS excess capacity at time t
I_t^d	DMS finished good inventory at time t
I_t^r	RMS finished good inventory at time t
ω_t^d	DMS Work in Process at time t
ω_t^r	RMS Work in Process at time t
rm_t^d	Amount of material released to DMS at time t
rm_t^r	Amount of material released to RMS at time t

5.2.1 The impact of response time on RMS capacity

In order to have an appropriate estimation of the available capacity of the RMS during the reconfiguration, it is assumed that only a portion of the added capacity is available during reconfiguration. Therefore, during this period two characteristics of the reconfigurable capacity is considered: the nominal capacity and the actual capacity. The nominal capacity determines the amount of capacity that the system is set to reach for the following period (5-19).

$$IR\xi_t = IR\xi_{t-1} + R\Delta\xi_t^+ - R\Delta\xi_t^- \qquad \forall\ t \in T \qquad (5\text{-}19)$$

$$R\xi_t = IR\xi_{t-1} + U\xi_t^r - L\xi_t^r \qquad \forall\ t \in T \qquad (5\text{-}20)$$

$$IR\xi_t \le C_{\max}^r \qquad \forall\ t \in T \qquad (5\text{-}21)$$

Decision Variables:

$R\Delta\xi_t^+$	RMS added capacity at time t
$R\Delta\xi_t^-$	RMS removed capacity at t
$R\xi_t$	RMS actual capacity at time t
$IR\xi_t$	RMS nominal capacity at time t
$U\xi_t^r$	Upper limit for changes in RMS capacity at time t
$L\xi_t^r$	Lower limit for changes in RMS capacity at time t

Since capacity could not be added or removed instantly, some portion of capacity is lost during ramp up period or considered as excess capacity during the ramp down period. Therefore, the actual capacity is different from the nominal during reconfiguration period. The actual capacity represents the amount of capacity that is available during the reconfiguration period (5-20).

During the reconfiguration period, it is assumed that RMS capacity can be added or removed by changing the modules of the system. The Maximum number of modules that could be added to a system determines the maximum RMS capacity (5-21). Since adding or removing of the modules requires a new setup, it is assumed that adding or removing of each module incurs a reconfiguration cost.

The amount of RMS available capacity during the reconfiguration is a fraction of nominal capacity and is set through constraints (5-22... 5-27).

$$U\xi_t^r + L\xi_t^r \le \theta_1^U * \left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) + M*(1-Y_t^1) \qquad \forall\, t \in T \qquad (5\text{-}22)$$

$$U\xi_t^r + L\xi_t^r \ge \theta_1^L * \left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) - M*(1-Y_t^1) \qquad \forall\, t \in T \qquad (5\text{-}23)$$

$$U\xi_t^r + L\xi_t^r \le \theta_2^U * \left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) + M*(1-Y_t^2) \qquad \forall\, t \in T \qquad (5\text{-}24)$$

$$U\xi_t^r + L\xi_t^r \ge \theta_2^L * (R\Delta\xi_t^+ + R\Delta\xi_t^-) - M*(1-Y_t^2) \qquad \forall\, t \in T \qquad (5\text{-}25)$$

$$U\xi_t^r + L\xi_t^r \le \theta_3^U * \left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) + M*(1-Y_t^3) \qquad \forall\, t \in T \qquad (5\text{-}26)$$

$$U\xi_t^r + L\xi_t^r \ge \theta_3^L * \left(R\Delta\xi_t^+ + R\Delta\xi_t^-\right) - M*(1-Y_t^3) \qquad \forall\, t \in T \qquad (5\text{-}27)$$

For each capacity change, a portion of added capacity is available during reconfiguration. It is assumed this portion falls in the range of $[\theta_i^L,\theta_i^U]$ of added capacity. The same assumption applies to the case of capacity reduction. Each module could add a pre-determined amount of capacity to the system (5-28). Also, either ramp up or ramp down is allowed at any period (5-29, 5-30).The reconfiguration period is determined through some binary variables, in the case of no reconfiguration; no capacity could be added or removed (5-31,..,5-33).

$$\left(R\Delta\xi_t^{+} + R\Delta\xi_t^{-}\right) = C_{ml}^{r} * Y_t^1 + 2C_{ml}^{r} * Y_t^2 + 3C_{ml}^{r} * Y_t^3 \qquad \forall\, t \in T \qquad (5\text{-}28)$$

$$R\Delta\xi_t^{+} + U\xi_t^{r} \le M * Y_t^{10} \qquad \forall\, t \in T \qquad (5\text{-}29)$$

$$R\Delta\xi_t^{-} + L\xi_t^{r} \le M * (1 - Y_t^{10}) \qquad \forall\, t \in T \qquad (5\text{-}30)$$

$$\sum_{i=0}^{3} Y_t^i = 1 \qquad \forall\, t \in T \qquad (5\text{-}31)$$

$$R\Delta\xi_t^{+} + U\xi_t^{r} \le M * \sum_{i=1}^{3} Y_t^i \qquad \forall\, t \in T \qquad (5\text{-}32)$$

$$R\Delta\xi_t^{-} + L\xi_t^{r} \le M * \sum_{i=1}^{3} Y_t^i \qquad \forall\, t \in T \qquad (5\text{-}33)$$

The consideration of supply disruptions at the main supplier can result in an overflow of the demand towards the backup supplier. This overflow results in an accumulation of WIP despite the ramp up at the backup supplier. There are two drawbacks associated with this situation. First, the congestion created by this overflow will decrease the throughput. Second, the decreased throughput will then result in lost demand. Furthermore, the effects of congestion are also important in order to properly assess the actual capacity of the suppliers, especially in a contingency strategy.

5.2.2 The impact of the congestion on throughput

Production capability is affected by production congestion. In order to show congestion impact at higher level of supply chain, it is assumed that each supply facility is a single server system with Poisson arrivals and general service time distribution (M/G/1 system).

A solution for analysing the impact of congestion could be clearing function. The clearing function is introduced by Karmarkar (1989) and it presents the expected throughput of a resource over a planning period as a function of the expected work in process (WIP). Also, Kim and Uzsoy (2008) employ the clearing function in a multi work centers capacity expansion problem where the objective is to control the WIP level.

The clearing function (Missbauer, 2002) is employed to show the impact of the congestion over the system throughput. Based on this clearing function, the expected system throughput $E(X_t)$ (5-34) in any period is a function of the expected work load $E(\omega_{t-1} + rm_t)$, available capacity (C), and the mean and the variance of the processing time.

$$E(X_t) = \frac{1}{2}\left[C + k + E(\omega_{t-1} + rm_t) - \sqrt{C^2 + 2Ck + k^2 - 2CE(\omega_{t-1} + rm_t) + 2kE(\omega_{t-1} + rm_t) + E(\omega_{t-1} + rm_t)^2} \right] \quad (5\text{-}34)$$

Where the mean and variance of the processing time are presented through (k) where:

$$k = \frac{\mu\sigma^2}{2} + \frac{1}{2\mu} \quad (5\text{-}35)$$

The clearing function is concave and nonlinear (Missbauer, 2002).Thus, a linearization approximation is applied by using a set of lines. In order to minimize the error between the actual curve and the approximated lines, the tangent points and the number of lines are determined by a subtractive clustering method (Chiu, 1994). The detailed explanation of the method is presented in Appendix C.

It is important to mention that each of the suppliers has its own clearing function. This difference arises from different processing times and capacity levels. The production by the DMS supplier could not be more than the expected throughput which is estimated by its clearing function (5-36).

$$D\lambda_t \le \min_\eta (\psi^d_\eta * (\omega^d_{t-1} + rm^d_t) + \lambda^d_\eta) \qquad \forall\ \eta \in \mathrm{N}^d \qquad \forall\ \mathrm{t} \in \mathrm{T} \qquad \text{(5-36)}$$

Since the RMS has different capacity levels within the planning horizon, a set of binary variables are applied to activate the corresponded clearing function corresponding to each level (5-28, 5-37, and 5-38).

$$IR\xi_t = C^r_{ml} * Y^{100}_t + 2C^r_{ml} * Y^{200}_t + 3C^r_{ml} * Y^{300}_t + 4C^r_{ml} * Y^{400}_t \qquad \forall\ \mathrm{t} \in \mathrm{T} \qquad \text{(5-37)}$$

$$\sum_{j \in \{100,200,300,400\}} Y^j_t = 1 \qquad \forall\ \mathrm{t} \in \mathrm{T} \qquad \text{(5-38)}$$

The same type of constraint as in (5-36) can be utilized to represent the RMS clearing function for periods with fixed capacity levels (5-39,..,5-42).

$$R\lambda_t \le \psi^r_\eta * (\omega^r_{t-1} + rm^r_t) + \lambda^r_\eta + M * (2 - Y^0_t - Y^{100}_t) \qquad \forall\ \eta \in \mathrm{N}^r_{0,100} \qquad \forall\ \mathrm{t} \in \mathrm{T} \qquad \text{(5-39)}$$

$$R\lambda_t \le \psi^r_\eta * (\omega^r_{t-1} + rm^r_t) + \lambda^r_\eta + M * (2 - Y^0_t - Y^{200}_t) \qquad \forall\ \eta \in \mathrm{N}^r_{0,200} \qquad \forall\ \mathrm{t} \in \mathrm{T} \qquad \text{(5-40)}$$

$$R\lambda_t \le \psi^r_\eta * (\omega^r_{t-1} + rm^r_t) + \lambda^r_\eta + M * (2 - Y^0_t - Y^{300}_t) \qquad \forall\ \eta \in \mathrm{N}^r_{0,300} \qquad \forall\ \mathrm{t} \in \mathrm{T} \qquad \text{(5-41)}$$

$$R\lambda_t \le \psi^r_\eta * (\omega^r_{t-1} + rm^r_t) + \lambda^r_\eta + M * (2 - Y^0_t - Y^{400}_t) \qquad \forall\ \eta \in \mathrm{N}^r_{0,400} \qquad \forall\ \mathrm{t} \in \mathrm{T} \qquad \text{(5-42)}$$

During the periods where capacity of RMS is changed, the clearing function can be represented as a function of two variables: workload and service rate. In this situation, the clearing function is generated as a set of hyper planes as indicated in (5-43,..,5-48).

$$R\lambda_t \le \psi^r_\upsilon * (\omega^r_{t-1} + rm^r_t) + \lambda^r_\upsilon * (R\xi_t) - \Upsilon_\upsilon + M * (2 - Y^1_t - Y^{200}_t) \qquad \forall\ \upsilon \in \mathrm{V}^r_{1,200}\ \forall\ \mathrm{t} \in \mathrm{T} \qquad \text{(5-43)}$$

$$R\lambda_t \le \psi^r_\upsilon * (\omega^r_{t-1} + rm^r_t) + \lambda^r_\upsilon * (R\xi_t) - \Upsilon_\upsilon + M * (2 - Y^1_t - Y^{300}_t) \qquad \forall\ \upsilon \in \mathrm{V}^r_{1,300}\ \forall\ \mathrm{t} \in \mathrm{T} \qquad \text{(5-44)}$$

$$R\lambda_t \le \psi^r_\upsilon * (\omega^r_{t-1} + rm^r_t) + \lambda^r_\upsilon * (R\xi_t) - \Upsilon_\upsilon + M * (2 - Y^1_t - Y^{400}_t) \qquad \forall\ \upsilon \in \mathrm{V}^r_{1,400}\ \forall\ \mathrm{t} \in \mathrm{T} \qquad \text{(5-45)}$$

$$R\lambda_t \le \psi^r_\upsilon * (\omega^r_{t-1} + rm^r_t) + \lambda^r_\upsilon * (R\xi_t) - \Upsilon_\upsilon + M * (2 - Y^2_t - Y^{300}_t) \qquad \forall\ \upsilon \in \mathrm{V}^r_{2,300}\ \forall\ \mathrm{t} \in \mathrm{T} \qquad \text{(5-46)}$$

$$R\lambda_t \le \psi^r_\upsilon * (\omega^r_{t-1} + rm^r_t) + \lambda^r_\upsilon * (R\xi_t) - \Upsilon_\upsilon + M * (2 - Y^2_t - Y^{400}_t) \qquad \forall\ \upsilon \in \mathrm{V}^r_{2,400}\ \forall\ \mathrm{t} \in \mathrm{T} \qquad \text{(5-47)}$$

$$R\lambda_t \le \psi^r_\upsilon * (\omega^r_{t-1} + rm^r_t) + \lambda^r_\upsilon * (R\xi_t) - \Upsilon_\upsilon + M * (2 - Y^3_t - Y^{400}_t) \qquad \forall\ \upsilon \in \mathrm{V}^r_{3,400}\ \forall\ \mathrm{t} \in \mathrm{T} \qquad \text{(5-48)}$$

The above constraints are the clearing functions when RMS increases its capacity level within reconfiguration period. In order to represent the clearing functions that correspond to capacity reduction cases, the constraints (5-49,..,5-54) are employed.

$$R\lambda_t \le \psi_\upsilon^r *(\omega_{t-1}^r + rm_t^r) + \lambda_\upsilon^r *(R\xi_t) - \Upsilon_\upsilon + M*(2 - Y_t^1 - Y_t^{100}) \qquad \forall\ \upsilon \in \mathrm{V}_{1,100}^r\ \ \forall\ \mathrm{t} \in \mathrm{T} \tag{5-49}$$

$$R\lambda_t \le \psi_\upsilon^r *(\omega_{t-1}^r + rm_t^r) + \lambda_\upsilon^r *(R\xi_t) - \Upsilon_\upsilon + M*(2 - Y_t^1 - Y_t^{200}) \qquad \forall\ \upsilon \in \mathrm{V}_{1,200}^r\ \forall\ \mathrm{t} \in \mathrm{T} \tag{5-50}$$

$$R\lambda_t \le \psi_\upsilon^r *(\omega_{t-1}^r + rm_t^r) + \lambda_\upsilon^r *(R\xi_t) - \Upsilon_\upsilon + M*(2 - Y_t^1 - Y_t^{300}) \qquad \forall\ \upsilon \in \mathrm{V}_{1,300}^r\ \forall\ \mathrm{t} \in \mathrm{T} \tag{5-51}$$

$$R\lambda_t \le \psi_\upsilon^r *(\omega_{t-1}^r + rm_t^r) + \lambda_\upsilon^r *(R\xi_t) - \Upsilon_\upsilon + M*(2 - Y_t^2 - Y_t^{100}) \qquad \forall\ \upsilon \in \mathrm{V}_{2,100}^r\ \forall\ \mathrm{t} \in \mathrm{T} \tag{5-52}$$

$$R\lambda_t \le \psi_\upsilon^r *(\omega_{t-1}^r + rm_t^r) + \lambda_\upsilon^r *(R\xi_t) - \Upsilon_\upsilon + M*(2 - Y_t^2 - Y_t^{200}) \qquad \forall\ \upsilon \in \mathrm{V}_{2,200}^r\ \forall\ \mathrm{t} \in \mathrm{T} \tag{5-53}$$

$$R\lambda_t \le \psi_\upsilon^r *(\omega_{t-1}^r + rm_t^r) + \lambda_\upsilon^r *(R\xi_t) - \Upsilon_\upsilon + M*(2 - Y_t^3 - Y_t^{100}) \qquad \forall\ \upsilon \in \mathrm{V}_{3,100}^r\ \forall\ \mathrm{t} \in \mathrm{T} \tag{5-54}$$

While the presented MIP model generates the supply configurations under the normal operational condition of DMS, additional variables and constraints allow integrating the disruption scenarios and generate the performance information for each scenario. In order to represent the contingency capacity plan once the DMS fails, the following section describes the modifications to the MIP model defining the disruptions scenarios.

5.2.3 Representation of the disruption in MIP model

In this section it is investigated how RMS supplier could cover DMS failure. In order to model DMS failure, some of the constraints of MIP model are modified to represent DMS supplier malfunction.

The binary variable Y_t^{DMS} which is incorporated to show the DMS supplier failure, is defined as follows

$$Y_t^{DMS} = \begin{cases} 1 & \text{If DMS is available} \\ 0 & \mathit{Else} \end{cases} \qquad \forall\ \mathrm{t} \in \mathrm{T} \tag{5-55}$$

Once the DMS supplier is disrupted, the demand could be satisfied through current inventory and/or RMS production (5-56). For a given disruption scenario there should be no production and material release in DMS supplier when it is disrupted (5-57, 5-58). The DMS WIP level during the disrupted periods remains equal to the last period before the disruption (5-59). Also, the DMS clearing function is inactive during the disruption (5-60).

$$I_t^d = I_{t-1}^d + (Y_t^{DMS} * D\lambda_t) - D_t^d \qquad \forall\ t \in \mathrm{T} \qquad (5\text{-}56)$$

$$D\lambda_t + E\xi_t^d = (Y_t^{DMS} * D\xi_t) \qquad \forall\ t \in \mathrm{T} \qquad (5\text{-}57)$$

$$rm_t^r \le M * Y_t^{DMS} \qquad \forall\ t \in \mathrm{T} \qquad (5\text{-}58)$$

$$\omega_t^d = \omega_{t-1}^d + Y_t^{DMS} * (rm_t^d - D\lambda_t) \qquad \forall\ t \in \mathrm{T} \qquad (5\text{-}59)$$

$$D\lambda_t \le Y_t^{DMS} * f^d(\omega_{t-1}^d + rm_t^d) \qquad \forall\ t \in \mathrm{T} \qquad (5\text{-}60)$$

In order to generate the contingency plans, first, capacity planning model is solved without the disruption. Afterwards, since it is a reactive capacity planning, the inventory levels and the capacity of DMS and RMS are set up to disruption period according to initial plan. Then, the rest of remaining periods of time horizon are solved according to DMS failure. The interaction of disruption occurrence and RMS capacity is formulated through constraints (5-61... 5-63).

$$I_t^d = I_t^{d,ini} \qquad \forall\ t \in \{1,\dots,t_D - 1\} \qquad (5\text{-}61)$$

$$I_t^r = I_t^{r,ini} \qquad \forall\ t \in \{1,\dots,t_D - 1\} \qquad (5\text{-}62)$$

$$Y_t^i = Y_t^{i,ini} \qquad \forall\ t \in \{1,\dots,t_D - 1\} \qquad (5\text{-}63)$$

During the disruption the load of RMS increases. Therefore, the capacity of RMS should be updated according to length of disruption. The available capacity of RMS during the ramp up period has positive correlation with RMS response speed. In another words, by increasing the response speed, more RMS capacity is available during the reconfiguration. This is indicated through the coefficients of the upper and lower bounds in constraints 5-22 to 5-27. These coefficients are increased as the response speed gets faster (Table 5-1).

Table 5-1 The coefficients of capacity boundaries corresponding to different speeds

	Slow			Medium			Fast		
Number of modules	1	2	3	1	2	3	1	2	3
Upper bound	0.75	0.5	0.4	0.85	0.65	0.5	0.95	0.85	0.7
Lower bound	0.5	0.4	0.2	0.65	0.5	0.3	0.85	0.7	0.55

The MIP model generates the contingency capacity of the backup facility according to a certain response speed under different disruption scenarios. The total costs of these contingency plans and the probability of the each disruption scenario would be an input of a decision tree to find the better reconfiguration cost and response speed trade off.

5.3 Disruption distribution

In order to model the disruption scenarios, a finite Markov discrete time distributions is used. The parameter α in 5-64 represents the probability of a disrupted period following a non-disrupted period (failure probability). The parameter β in 5-65 defines the probability of a non-disrupted period following a disrupted period (recovery probability).

The length of the planning horizon is T. Based on these assumptions, the probability of a disruption at time t with the length of l is computed through the following formulas.

$$\text{P(No Disruption)} = (1-\alpha)^T \qquad (5\text{-}64)$$

$For\ all\ l \leq T$

$$\text{P}_{\text{Disruption}}\text{(t,l)}=\alpha\beta(1-\alpha)^{t-1}(1-\beta)^{l-1} \qquad l \in \{1,...,T-t\} \qquad (5\text{-}65)$$

$$\text{P}_{\text{Disruption}}\text{(t,l)}=\alpha(1-\alpha)^{t-1}(1-\beta)^{l-1} \qquad l = T-t+1 \text{ or more} \qquad (5\text{-}66)$$

The details regarding the derivation of these formulas could be found in Appendix D.

5.4 Decision analysis under risk

The decision tree is a graphical diagram which includes nodes and branches and is a well-known technique in decision making field (Berger et al., 2004). As indicated in Figure 5-3, the square nodes are the decision options and the circle nodes represent the chance events.

In this section, the appropriate reconfiguration speed is determined by representing the disruption probability scenario and their associated costs in a decision tree.

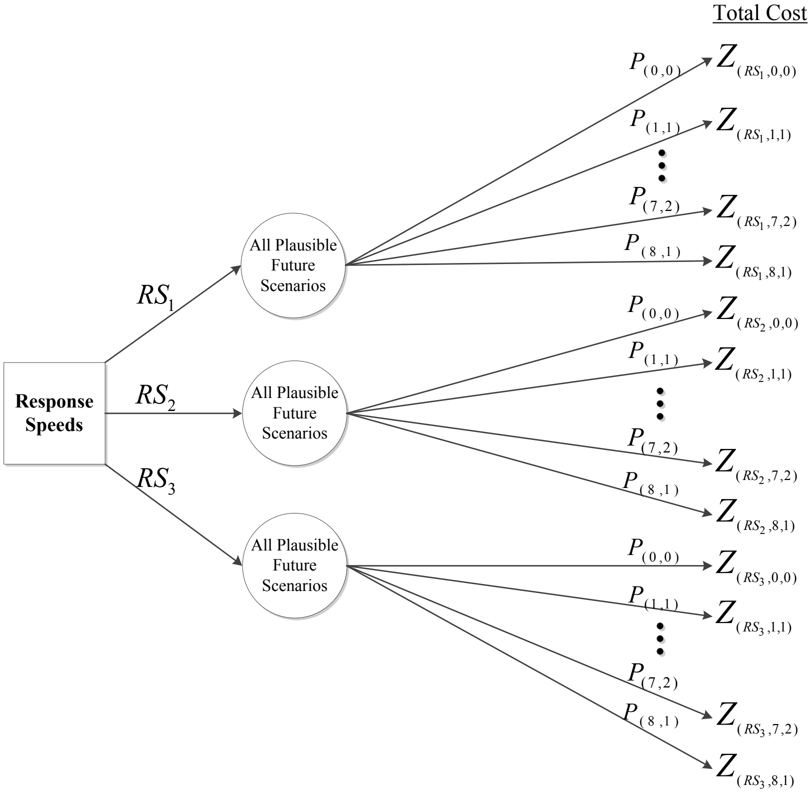


Figure 5-3 The decision tree for the optimal selection of the response speed

The decision set regarding the response speeds (RS_k) includes Fast speed (RS_1), Medium speed (RS_2), and Slow speed (RS_3). The supply chain is subject to a set of plausible disruption scenarios (S) that each of these response speeds associated with a backup source. The planning horizon is limited into T periods. For the aim of simplicity, only one disruption occasion with varying length within the planning horizon is considered. Based on this assumption, the following table represents the disruption scenarios. The index t presents the time of disruption’s occurrence while l is the length of the disruption (Table 5-3).

Table 5-2 All plausible future scenarios-major disruption

l t	1	2	3	.	.	.	T-1	T
1	(1,1)	(1,2)	(1,3)	.	.	.	(1,T-1)	(1,T)
2	(2,1)	(2,2)	(2,3)	.	.	.	(2,T-1)	
3	(3,1)	(3,2)	(3,3)	.	.	.		
.	.	.	.	.	.			
.	.	.	.	.				
.	.	.	.					
T-1	(T-1,1)	(T-1,2)						
T	(T,1)							

The expected cost corresponding to each decision is computed through the following formula:

$$EXC_{RS_k} = \sum_{(t,l)\in S} P_{(t,l)} \times Z_{(RS_k,t,l)} \qquad \forall k \in \{1,2,3\} \tag{5-67}$$

The term $P_{(t,l)}$ is the probability of occurrence of the scenario (t,l) and $Z_{(RS_k,t,l)}$ is the objective function of the MIP capacity planning model for a given response speed RS_k and the disruption scenario (t,l) . The expected cost is a selection tool which belongs to a risk neutral decision maker albeit the decision maker could be risk averse. Through the decision tree analysis, appropriate response speed of the backup supplier with different disruption scenarios is selected. The solution methodology is based on the DMS failure and recovery probabilities. Since these probabilities depends on situation such as the hazard exposure level of the geographical zone where the facility is located as well as the ability of the facility to return to the operational condition once it is disrupted (Klibi et al., 2010), numerical section presents response speed selection with respect to different failures and recovery probabilities of DMS supplier.

5.5 Numerical results

This section presents an example in order to illustrate the selection of the RMS reconfiguration speed through the solution methodology which was proposed in section 5.1. The planning horizon is divided in to 8 periods and the demand follows the classical pattern in Figure 4.

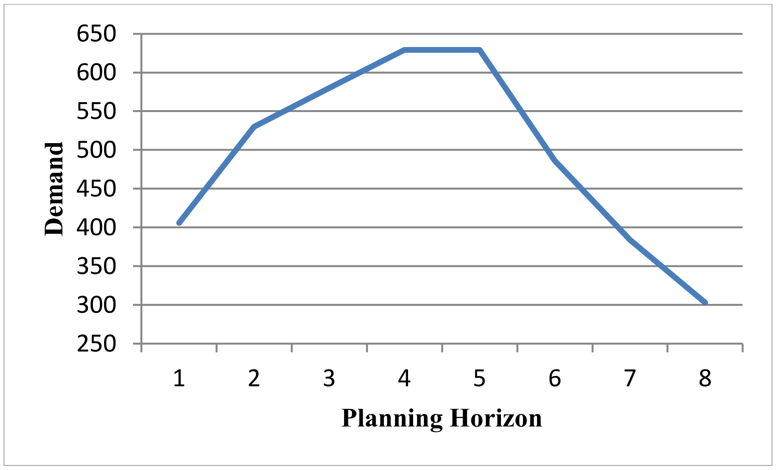


Figure 5-4 The classical demand pattern

Through the MIP model, the supply chain configuration and its features such as capacity amount, production, raw material, inventory, and WIP levels is determined. The supply chain configuration is selected based on the supplier's costs parameters (Table 5-3), the product shortage cost and the structure of the supplier's capacity (Table 5-4, 5-5).

Table 5-3 Supplier's costs parameters

Cost Parameters	Value (£: unit of money)
DMS Raw Material Release cost	2£
RMS Raw Material Release cost	2£
DMS production cost	2£
RMS production cost	10£
DMS WIP cost	3£
RMS WIP cost	10£
DMS Holding cost	4£
RMS Holding cost	12£
RMS Reconfiguration Cost-Slow	2£
RMS Reconfiguration Cost-Medium	3£
RMS Reconfiguration Cost-Fast	6£

While the raw material purchasing cost is the same for both suppliers, the production cost of the RMS is higher than that of the DMS (Tomlin, 2006). Therefore the WIP and the finished goods inventory holding cost of the RMS are higher than for the DMS. There are three different RMS reconfiguration costs corresponding to three different speed levels. The reconfiguration costs increase as the response speed levels are improved.

The RMS excess capacity costs and the product's shortage costs are presented in Table 5-4. The excess cost increase in time due to the depreciation and increased maintenance costs. Also, shortage cost is defined with respect to the demand pattern. In introduction and growth periods shortage cost is higher compared to the maturity periods but in the decline periods shortage cost is lower.

Table 5-4 RMS excess capacity costs

Periods	1	2	3	4	5	6	7	8
RMS supplier Excess capacity Costs	2£	2.5£	3£	3.5£	4£	5£	6£	7£
Shortage Cost	70£	70£	70£	65£	60£	55£	40£	30£

Moreover, Since DMS facility has higher production capacity compare to RMS, it is assumed that DMS capacity is fixed and equals to 500 units of products per period while the RMS facility could have a variable production capacity according to number of existing modules (Table 5-5). The initial configuration of the RMS is a base which provides a 100 units of capacity and it can raise its capacity level by adding modules.

Table 5-5 RMS capacity levels with respect to its configurations

RMS Configuration	Base	1 Module	2 Modules	3 Modules
Production Capacity per period	100	200	300	400

Based on the stated assumptions regarding the supply chain and input data, the following experiments are conducted. The MIP model to generate the regular capacity plans as well as the contingency plans has been implemented in ILOG CPLEX version 12.5. The MIP model has 240 decision variables and 1456 constraints. By setting the desired optimality gap to 0.0001, the results of contingency plans of disruption scenarios have been obtained with average optimality gap of 0.0015 at an average computation time of 4.48 seconds. First, the effect of congestion in evaluating the performance of a contingency strategy is considered. Second, an optimal contingency strategy is assessed by identifying the performance of RMS response speed within a range of failure and recovery probabilities. The selection of optimal response speeds are then evaluated based on the total expected cost value.

5.5.1 The impact of the congestion over the available capacity

In this section, the impact of considering the congestion is evaluated by observing the supply chain service level under two conditions. First, the MIP model is used to determine the capacity plan, the production quantities, WIP and inventory levels corresponding to DMS and RMS suppliers without considering the impact of congestion (load independent model). For this purpose, the constraints (5-36), (5-39) to (5-54) are relaxed. Afterwards, the clearing functions present the actual production quantity of the DMS and RMS based on the capacity and WIP levels which have been determined in the load independent model. The actual demand losses are then computed by the difference between demand and production quantities obtained using clearing function.

Second, in order to compute the supply chain service level once the congestion impact is considered (load dependent model), the proposed MIP model is executed. To illustrate the results, we present the case for a DMS disruption scenario at time 3 with a length of 3 periods, in Table 5-6.

The production quantities ($D\lambda_t, R\lambda_t$) in the load independent model are overestimated as a result of ignoring the congestion. Once the impact of congestion is considered (load dependent model), the MIP model would increase the RMS capacity ($IR\xi_t, R\xi_t$) to a higher level compared to the load independent model to cover the shortages. As a result of this, the service level of the load dependent model would be higher than its load independent counterpart. This behavior is observed in all plausible scenarios. Figure 5-5 represents the service level of the load independent model and load dependent model for disruptions which might occur at time 3 at varying lengths, with an RMS at medium response speed.

Table 5-6. Supply chain configurations in load independent versus load dependent models

Decision Variables	1	2	3	4	5	6	7	8
	MIP results in load independent capacity plan (no congestion effects)							
$D\lambda_t$	474	500	0	0	0	486	384	303
$IR\xi_t$	100	100	400	400	400	100	100	100
$R\xi_t$	100	100	250	400	400	250	100	100
$R\lambda_t$	0	0	250	400	400	0	0	0
	Actual production levels due to congestion effects							
ACT $D\lambda_t$	419	432	0	0	0	424	358	290
ACT $R\lambda_t$	0	0	186	333	333	0	0	0
D_t^l	55	68	356	296	296	62	26	13
Service Level	0.70							
	MIP results with load dependent capacity plan (with congestion effects)							
$D\lambda_t$	431	405	0	0	0	425	379	302
$IR\xi_t$	100	200	400	400	400	100	100	100
$R\xi_t$	100	184	330	400	400	250	100	100
$R\lambda_t$	0	100	262	333	333	61	5	1
D_t^l	0	0	318	296	296	0	0	0
Service Level	0.77							

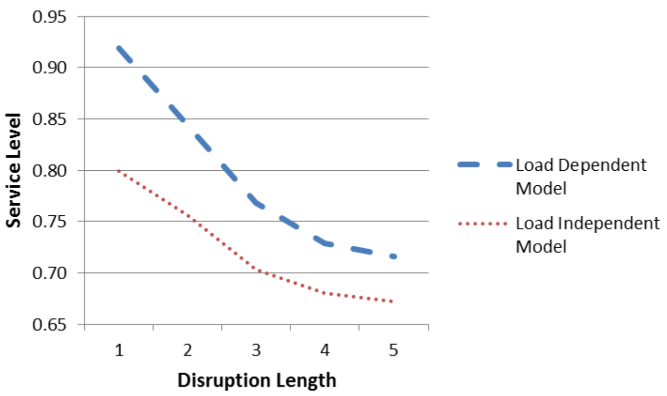


Figure 5-5.The impact of considering congestion effects on service level.

The results show that considering the congestion effects in developing a contingency plan for a supply chain improves the service level. This is due to the fact that the backup supplier capacity and its response speed can be planned accordingly. As indicated in

Figure 5-5, the service level decreases in both cases as the length of the disruption increases. This happens due to losing the main supplier, which has a higher capacity level compared to the backup supplier. As the disruption length increase we observe that the service level difference between two cases decreases. This is due to the fact that the backup supplier can't replace the main supplier over long periods of disruption.

The results presented so far show improvement in the service level of the supply chain by considering congestion. Furthermore, the supply chain responsiveness improves once the appropriate response speed of RMS is determined. The optimal selection of the response speed depends on the accurate understanding of the required RMS capacity, which depends on the realistic estimation of the DMS and RMS production capabilities. Therefore, the impact of congestion is considered in the selection of the RMS response speed. At the planning stage of a supply chain configuration, it is important to consider an appropriate level of responsiveness to recover from major disruptions. The following section allows demonstrating this importance and the use of the proposed methodology towards this objective.

5.5.2 The optimal selection of the RMS response speeds

In identifying an optimal response speed at the planning stage of a supply chain design, the trade-off between the investment cost of responsiveness and lost sales can be considered as main determinants.

In a risk neutral behavior, the optimal response speed is selected by comparing the expected cost of the supply chain under all plausible future scenarios. The probability of occurrence for each scenario is determined by the failure and recovery probabilities of the DMS supplier. As illustrated in Figure 5-6, the expected cost of the supply chain grows as the failure probability increases and/or the recovery probability decreases.

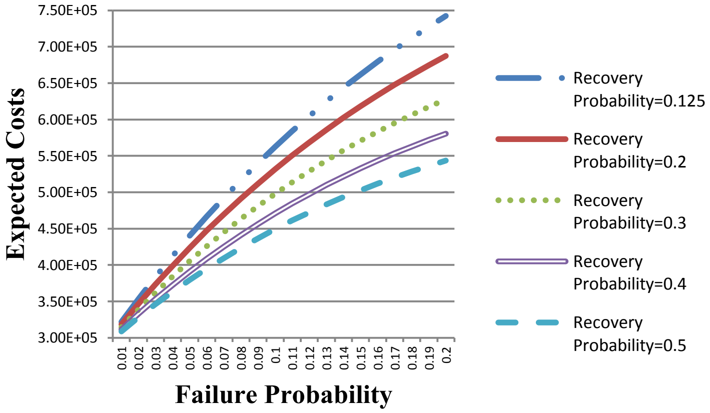


Figure 5-6 Sensitivity analysis of the expected costs of the supply chain

The probability of the scenarios with disruption increases as the failure probability increases. Since these scenarios have higher cost compared to the scenario without disruption, the expected cost of the supply chain increases. On the other hand, the probability of the scenarios with long disruption increases when the recovery probability decreases. These scenarios have higher cost compared to the scenarios with short disruption. Therefore the expected cost of the supply chain increases.

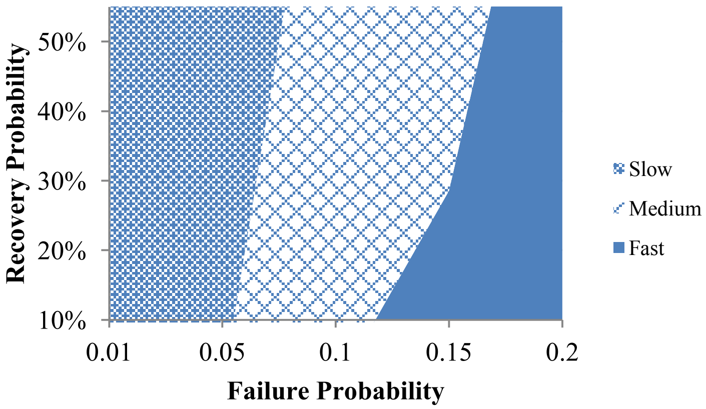


Figure 5-7 Optimal response speed-risk Neutral

Since the expected cost of the supply chain depends on the failure and recovery probabilities of DMS, the optimal response speed changes depending on these parameters as indicated in Figure 5-7.

The results indicate that slow speed is the optimal response speed for the low probabilities of DMS failure; it is not economical to provide the RMS supplier with costly faster recovery speeds since the probability of their deployment is low. When the failure probability increases and/or the recovery probability decreases, the available capacity within the response time becomes critical to minimize the shortages during the disrupted periods. As a result of that, faster response speeds are appropriate.

5.6 Summary

The first section of the numerical results shows the improvement in supply chain service level upon considering the congestion impact in planning stage. This happens because of triggering the RMS supplier to provide higher capacity level to cover the shortages due to congestion. Afterwards, the response speed of RMS is determined with the purpose of improving the supply chain responsiveness once DMS disrupts. In order to have an accurate analysis of the required capacity, the congestion impact is considered in selection process.

The numerical results show the optimality of the slower response speeds for the lower probability of DMS failure and higher probability of the recovery. However, as the failure probability of DMS increases or the recovery probability decreases, the tendency is toward the faster speeds.

Chapter 6: Conclusion and future research

In an era of global competition where companies strive to be the leader in the marketplace, it is important to consider the scalability and ramp up behaviour in selecting manufacturing systems. The objective of this thesis is to study ramp up characteristics in three main categories. First analysis is focusing on the way that any manufacturing system type is selected in different product life cycle scenarios. Second, the impact of system configuration on ramp up time and its effect on the long term capacity selection is studied. Finally, in case of a supplier disruption, the impact of reconfiguration speed on the service level is investigated by determining an appropriate response speed for a backup supplier.

In the first analysis, a mixed integer programming model, which considers all Dedicated, Flexible, and Reconfigurable Manufacturing Systems including their differentiating characteristics, is proposed. Multiple product families are considered, and Reconfigurable Capacity scalability lead time is taken into account. One of the contributions of proposed model is the improved modeling of the ramp up pattern and scalability of RMS capacity during reconfiguration. Thorough this model, the reconfiguration time can be presented in both linear and nonlinear fashions as a function of the amount of added/removed capacity. Moreover, each system's scalability is distinguished according to its specifications. Finally, including the shortage cost and the excess cost in the model provide a better option for manufacturers to come up with a capacity selection according to their attitude towards risk. The primary results show that RMS should have a low module to base cost ratio in order to justify the reconfigurations. Otherwise, instantaneous capacity purchase is substituted for reconfiguration. If reconfiguration does not occur in a short time, RMS would behave similar to DMS or FMS. A lack of responsiveness in RMS results in a remarkable decrease in the frequency of reconfigurations.

In the second study, by extending the mathematical model for different ramp up pattern, the duration of ramp up is modelled based on the configuration characteristics of the manufacturing system. This is especially important in cases where demand variations and new product introductions force companies to upgrade their capacity levels. The introduction of this ramp up period allows decision makers to consider the responsiveness of a capacity alternative by relating it into manufacturing system layout characteristics. The modified MIP model incorporates constraints that represent the ramp up behaviour of each reconfiguration pattern according to the system configuration layout. The considered system layouts are classified as a pure parallel configuration, in line reconfiguration, series parallel reconfiguration, and series reconfiguration. From the tactical decision making aspect, the actual and nominal capacities are presented based on each system configuration. The accurate representation of available capacity allows analyzing how capacity shortage or excess during reconfiguration could affect capacity investment selection and the required layout. The results of the MIP model have been validated through a simulation study. In the simulation, the capacity evolution of the RMS and DMS is tested through random demand and random actual capacity during the reconfiguration period. It is shown that omitting the configuration and responsiveness characteristics can lead to underestimating capacity requirements in the long term capacity selection. This oversight in capacity planning stage can negatively affect customer service level.

Finally, an MIP model is developed for capacity planning in a supply chain context to analyze the effectiveness of a contingency plan with a responsive supplier using RMS. A new model is applied in the context of supply chain when one of the suppliers fails to provide an acceptable service level to customers. The contribution of the proposed model is in presenting a better estimate of the available capacity within the response period by considering the congestion impact. Through a decision tree analysis, a better response speed for a given disruption profile is selected, and recovery scenarios are discussed. The final result shows that the faster response speed is better when the failure probability increases or recovery probability decreases.

In terms of future research directions, the frequency of product introduction to market and variability of demand at each period could be investigated. This phenomenon could affect the purchase of new capacity, selection of a new manufacturing system, and system layout configurations. By using the stochastic programming, the frequency of product to market could be modeled through different statistical distributions. This analysis can provide a better framework for the manufacturer to select the most relevant configuration for a firm and give insight about how capacity evolution could affect the contingency capacity planning and thus the optimal selection of the response and capacity towards demand satisfaction.

Moreover, excess holding cost and shortage cost of a product is a function of the product life cycle stage, which could be incorporated in the analysis. As well, considering stochastic product demand would enable companies to analyze the impact of market uncertainty and determine how RMS reconfiguration speed profile could decrease the risk of both excess capacity and demand loss for entire supply network. Finally, as one of our assumptions is known timing of future product introduction without considering the market behavior and competitor's activity in the market, the failure risk of new products could have a great impact on capacity selection and it could be modeled through Monte Carlo risk simulation. Future research can incorporate these issues in capacity selection.

References

1. Abdi, M.R., 2009. Fuzzy multi-criteria decision model for evaluating reconfigurable machines. *International Journal of Production Economics* 117 (1), 1-15.
2. Angelus, A., Porteus, E.L., 2002. Simultaneous capacity and production management of short-life-cycle, produce-to-stock goods under stochastic demand. *Management Science* 48 (3), 399-413.
3. Asl, F.M., Ulsoy, A.G., 2003. Stochastic optimal capacity management in reconfigurable manufacturing systems. *CIRP Annals - Manufacturing Technology* 52 (1), 371-374.
4. Beamon, B.M. 1998. Supply chain design and analysis: Models and Methods. *International Journal of Production Economics* 55 (3), 281-294.
5. Berger, P. D., Gerstenfeld, A., Zeng, A. Z., 2004. How many suppliers are best? A decision-analysis approach. *Omega* 32 (1), 9-15.
6. Bernstein, F., DeCroix, G.A., 2004. Decentralized pricing and capacity decisions in a multitier system with modular assembly. *Management Science* 50 (9), 1293-1308.
7. Bi, Z.M., Lang, S.Y.T., Shen, W., Wang, L., 2008. Reconfigurable manufacturing systems: The state of the art. *International Journal of Production Research* 46 (4), 967-992.
8. Black, J.T., 1991. The Design of The Factory with A Future. McGraw-Hill Inc., New York.

9. Boyaci, T., Ray, S., 2003. Product Differentiation and Capacity Cost Integration in Time and Price Sensitive Markets. *Manufacturing and Service Operations Management* 5 (1), 18-36.
10. Buffa, E.S., 1983. Modern Production/Operations Management. Wiley, New York.
11. Ceryan, O., Koren, Y., 2009. Manufacturing capacity planning strategies. *CIRP Annals - Manufacturing Technology* 58 (1), 403-406.
12. Chauhan, S.S, Nagi, R., Proth, J.M, 2004.Strategic capacity planning in supply chain design for a new market opportunity. *International Journal of Production Research* 42 (11), 2197-2206
13. Chen, Z., Li, S., Tirupati, D., 2002. A scenario-based stochastic programming approach for technology and capacity planning. *Computers and Operations Research* 29 (7), 781-806.
14. Chiu, S.L, 1994. Fuzzy model identification based on cluster estimation. *Journal of Intelligent and Fuzzy Systems* 2, 267-278.
15. Chopra, S., Sodhi, M. S., 2004. Managing Risk To Avoid Supply-chain breakdown. *MIT Sloan Management Review* 46 (1), 53-61.
16. Deif, A.M., ElMaraghy, W., 2007. Investigating optimal capacity scalability scheduling in a reconfigurable manufacturing system. *International Journal Of Advanced Manufacturing Technology* 32 (5), 557-62.
17. Deleris, L. A., Erhun, F., 2005. Risk management in supply networks using monte-carlo simulation. In Proceedings of the 2005 Winter Simulation

Conference. Institute of Electrical and Electronics Engineers, Inc. Piscataway, New Jersey, 1643–1649.

18. Druehl, C.T., Schmidt, G.M., Souza, G.C., 2009. The optimal pace of product updates. *European Journal of Operational Research* 192 (2), 621-33.
19. Fine, C.H., Freund, R.M., 1990. Optimal investment in product-flexible manufacturing capacity. *Management Science* 36 (4), 449-66.
20. Freidenfelds, J., 1981. Capacity expansion: analysis of simple models with applications. North Holland: Elsevier Science.
21. Ghadge,A., Dani,S., Kalawsky,R., 2011. Systems Thinking for Modeling Risk Propagation in Supply Networks. IEEE International Conference, Singapore, 1685-1689.
22. Goyal, M., Netessine, S., 2007. Strategic Technology Choice and Capacity Investment Under Demand Uncertainty. *Management Science* 53 (2), 192-207.
23. Graham, G.A, 1988. Automation Encyclopedia. Society of Manufacturing Engineers, Dearborn, MI.
24. Hendricks, K.B., Singhal, V.R., 2008. The effect of product introduction delays on operating performance. *Management Science* 54(5), 878-892.
25. Hu, S. J., 1997. Stream of Variation Theory for Automotive Body Assembly. *Annals of the CIRP* 46(1), 1-4.
26. Huh, W.T, Roundy, R.O., Cakanyidirim, M., 2005. A General Strategic Capacity Planning Model under Demand Uncertainty. *Naval Research Logistics* 53 (2), 137-150

27. Julka, N., Baines, T., Tjahjono, B., Lendermann, P., Vitanov, V., 2007. A review of multi-factor capacity expansion models for manufacturing plants: Searching for a holistic decision aid. *International Journal of Production Economics* 106(2), 607-621.
28. Karmarkar, U. S., 1989. Capacity loading and release planning with work-in-progress (WIP) and leadtimes. *Journal of Manufacturing and Operations Management* 2, 105-123.
29. Kim, S., Uzsoy, R., 2008. Exact and heuristic procedures for capacity expansion problems with congestion. *IIE Transactions* 40, 1185-1197.
30. Klibi, W., Martel, A., Guitouni, A., 2010. The design of robust value-creating supply chain networks: a critical review. *European Journal of Operational Research* 203, 283-293.
31. Koren, Y., Hu, S. J., Weber, T. W., 1998. Impact of manufacturing system configuration on performance. *CIRP Annals - Manufacturing Technology* 47 (1), 369-372
32. Koren, Y.,Shpitalni, M., 2010. Design of reconfigurable manufacturing systems. *Journal of Manufacturing Systems* 29 (4), 130-141.
33. Kuzgunkaya, O., ElMaraghy, H.A., 2007. Economic and strategic perspectives on investing in RMS and FMS. *International Journal of Flexible Manufacturing Systems* 19 (3), 217-46.
34. Lalic, B., Cosic,I., Anisic, Z., 2005. Simulation Based Design and Reconfiguration of Production Systems. *International Journal of Simulation Modelling* 4 (4), 173-183.

35. Luss, H., 1982. Operations research and capacity expansion problems: a survey. *Operations Research* 30 (5), 907-47.
36. McAllister, C.D., Ryan, S.M., 2000. Relative risk characteristics of rolling horizon hedging heuristics for capacity expansion. *Engineering Economist* 45 (2), 115-28.
37. Matta, A., Tomasella, M., Clerici, M., Sacconi, S., 2008. Optimal reconfiguration policy to react to product changes. *International Journal of Production Research* 46 (10), 2651-2673.
38. Matta, A., Tomasella, M. & Valente, A., 2007. Impact of ramp-up on the optimal capacity-related reconfiguration policy. *International Journal of Flexible Manufacturing Systems* 19 (3), 173-94.
39. Mehrabi, M.G., Ulsoy, A.G., Koren, Y., 2000. Reconfigurable manufacturing systems: key to future manufacturing. *Journal of Intelligent Manufacturing* 11 (4), 403-419.
40. Mehrabi, M.G., Ulsoy, A.G., Koren, Y., Heytler, P., 2002. Trends and perspectives in flexible and reconfigurable manufacturing systems. *Journal of Intelligent Manufacturing* 13 (2), 135-46.
41. Mincsovics, G., Tan, T., Alp, O., 2009. Integrated capacity and inventory management with capacity acquisition lead times. *European Journal of Operational Research*, 196 (3), 949-958.
42. Missbauer, H., 2002. Aggregate order release planning for time-varying demand. *International Journal of Production Research*, 40, 699-718.

43. Niroomand, I., Kuzgunkaya, O., Asil Bulgak, A., 2012. Impact of reconfiguration characteristics for capacity investment strategies in manufacturing systems. *International Journal of Production Economics* 139 (1), 288-301.

44. Netessine, S., Dobson, G., Shumsky, R.A., 2002. Flexible service capacity: optimal investment and the impact of demand correlation. *Operations Research* 50(2), 375-88.

45. Narongwanich, W., Duenyas, I., Birge, J.R., 2002. Optimal portfolio of reconfigurable and dedicated capacity under uncertainty, Technical report, University of Michigan.

46. Noaker, P.M, 1994. The search for agile manufacturing. *Manufacturing Engineering* 13, 40-34.

47. Pahl, J., VoB, S., Woodruff, D. L., 2007. Production planning with load dependent lead times: an update of research. *Annals of Operations Research* 153, 297-345.

48. Pine, B.J.I., 1993. Mass Customization: The new frontier in business competition. Technical report, Harvard Business School Press, Boston.

49. Rink, D. R., Swan, J. E., 1979. Product life cycle research: A literature review. *Journal Of Business Research* 7, 219-242.

50. Rocklin, S.M., Kashper, A., Varvaloucas, G.C., 1984. Capacity expansion/contraction of a facility with demand augmentation dynamics. *Operations Research* 32 (1), 133-47.

51. Ryan, S.M., 2004. Capacity expansion for random exponential demand growth with lead times, *Management Science* 50 (6), 740-748.

52. Ryan, S.M., Marathe, R.R. 2009. Capacity expansion under a service-level constraint for uncertain demand with lead times. *Naval Research Logistics* 56 (3), 250-63.
53. Sawik, T., 2013. Selection of resilient supply portfolio under disruption risks. *Omega* 41(2), 259-269.
54. Schmidt, G.M., Druehl, C.T., 2005. Changes in product attributes and costs as drivers of new product diffusion and substitution. *Production and Operations Management* 14 (3), 272-85.
55. Schmitt, A. J., 2009. Strategies for customer service level protection under multi-echelon supply chain disruption risk. *Transportation Research Part B: Methodological* 45, 1266-1283.
56. Slack, N., Chambers, S., Herland, C., Harrison, A., Johnson, R., 1995. Operation Management, Pitman Publishing, London (Melbourne).
57. Snyder, L., V., Atan, Z., Peng, P., Rong, Y., Schmitt, A. J., Sinsoysal, B., 2010. OR/MS models for supply chain disruptions: A review. *Social Science Research Network*, working paper.
58. Spencer, Michael S., 1997. The impact of JIT on capacity management: a case study and analysis. *Production Planning & Control* 8 (2), 183-193.
59. Spicer, P., Yip-hoi, D., Koren, Y., 2005. Scalable reconfigurable equipment design principles. *International Journal of Production Research*, 43(22), 4839-4852.

60. Spicer, P., Carlo, H.J. 2007. Integrating reconfiguration cost into the design of multi-period scalable reconfigurable manufacturing systems. *Journal of Manufacturing Science and Engineering* 129 (1), 202-210.
61. Tang, C.S., 2006. Robust strategies for mitigating supply chain disruptions. *International Journal of Logistic Researches and Applications: A Leading Journal of Supply Chain Management* 9, 33-45.
62. Tang,Li, 2005. Design and Reconfiguration of RMS for part Family. A dissertation for the degree of Doctor of Philosophy, University of Michigan
63. Tang, Li, Yip-Hoi, D. M., Wang, W., Koren, Y., 2003. Concurrent line-balancing, equipment selection and throughput analysis for multi-part optimal line design. Proceedings of the 2nd CIRP Conference on Reconfigurable Manufacturing Systems, Ann Arbor USA.
64. Tolio, T., Matta, A., 1998. A Method for Performance Evaluation of Automated Flow Lines. *Annals of the CIRP* 47 (1).
65. Tomlin, B., 2006. On the value of mitigation and contingency strategies for managing supply chain disruption risks. *Management Science* 52, 639-657.
66. Van Mieghem, J.A., 2003. Capacity management, investment, and hedging: review and recent developments. *Manufacturing & Service Operations Management* 5(4), 269-302.
67. Van Mieghem, J.A. 2007. Risk mitigation in newsvendor networks: Resource diversification, flexibility, sharing, and hedging, *Management Science* 53 (8), 1269-1288.

68. Van Mieghem, J.A. 1998. Investment strategies for flexible resources, *Management Science* 44 (8), 1071.
69. Van Mieghem, J.A., Dada, M., 1999. Price Versus Production Postponement: Capacity and Competition. *Management Science* 45 (12), 1631-1649.
70. Wang, W., Koren, Y. 2012. Scalability planning for reconfigurable manufacturing systems. *Journal of Manufacturing Systems* 31(2), 83-91.
71. Wilson, L., 2010. How to implement lean manufacturing. McGraw-Hill Companies, Inc. ISBN: 978-0-07-162508-1
72. Wu, S.D., Erkoc, M., Karabuk, S., 2005. Managing Capacity in the High-Tech Industry: A Review of Literature. *The Engineering Economist: A Journal Devoted to the Problems of Capital Investment*, 50(2), 125.
73. Youssef, A.M.A., Elmaraghy, H.A. 2006. Modeling and optimization of multiple-aspect RMS configurations. *International Journal of Production Research* 44 (22), 4929-4958.

Appendix A: Complement constraints and ramp down modeling in Chapter 3

A complementary set of constraints for different systems are discussed as follows: First, it is assumed that capacity could be either purchased or removed at each period. Therefore, in the period that DMS capacity is removed, no more DMS capacity purchase is allowed (3-47, 3-48).

$$SU_{i,p}^{d} + \sum_{t=1}^{i-1} SD_{i,t,p}^{d} \leq 1 \qquad \forall\, i \in T, \forall\, p \in P \qquad \text{(3-47)}$$

$$PC_{i,p}^{d} \leq \boldsymbol{M} * (SU_{i,p}^{d}) \qquad \forall\, i \in T, \forall\, p \in P \qquad \text{(3-48)}$$

A set of similar constraints for FMS regarding removed capacity is considered during reconfiguration period. Constraints (3-49,..,3-54) explanation is the same as constraints (3-14,.., 3-18) in chapter 3.

$$RC_{i,t}^{f} \leq PC_{t}^{f} + \boldsymbol{M} * (1 - SD_{i,t}^{f}) \qquad \forall\, i \in \{2,..T\}, \forall\, t \in \{1,..,i-1\} \qquad \text{(3-49)}$$

$$RC_{i,t}^{f} \geq PC_{t}^{f} - \boldsymbol{M} * (1 - SD_{i,t}^{f}) \qquad \forall\, i \in \{2,..T\}, \forall\, t \in \{1,..,i-1\} \qquad \text{(3-50)}$$

$$\sum_{t=1}^{i-1} RC_{i,t}^{f} \leq PC_{t}^{f} \qquad \forall\, i \in T \qquad \text{(3-51)}$$

$$RC_{i,t}^{f} \leq \boldsymbol{M} * (SD_{i,t}^{f}) \qquad \forall\, i \in \{2,..T\}, \forall\, t \in \{1,..,i-1\} \qquad \text{(3-52)}$$

$$PC_{i}^{f} \leq \boldsymbol{M} * (SU_{i}^{f}) \qquad \forall\, i \in T \qquad \text{(3-53)}$$

$$SU_{i}^{f} + \sum_{t=1}^{i-1} SD_{i,t}^{f} \leq 1 \qquad \forall\, i \in T \qquad \text{(3-54)}$$

It is assumed that the actual and the nominal capacities in RMS are equal at RMS purchase time (3-55). Also, no module is allowed to be installed on RMS when RMS has been removed (3-56) and during Reconfiguration period either ramp up or ramp down is considered (3-57, 3-58). Total remaining amount of module installation on each RMS base is updated by constraint (3-59) and the amount of removed RMS bases during ramp down (3-62) must be equal to the amount of purchase (3-60,3-61). Furthermore, each base of RMS could be removed once during the planning horizon (3-63) and constraint (3-64) allows for capacity to be either scaled up or scaled down in the same time period.

$$IRMC_{i,i,p} = ARMC_{i,i,p} \qquad \forall\, i \in T, \forall\, p \in P \tag{3-55}$$

$$RMDMLE_{i,t,p} \le IRMC_{i-1,t,p} \qquad \forall\, t \in T \quad , \forall\, i \in \{t+1, .., T\}, \forall\, p \in P \tag{3-56}$$

$$\textstyle\sum_{t=1}^{i-1} RMDMLE_{i,t,p} \le \boldsymbol{M} * (1 - RC_{i,p}) \qquad \forall\, i \in \{2, .., T\}, \forall\, p \in P \tag{3-57}$$

$$ARMC_{i,i,p} + \textstyle\sum_{t=1}^{i-1} ADDMLE_{i,t,p} \le \boldsymbol{M} * (RC_{i,p}) \qquad \forall\, i \in \{2, .., T\}, \forall\, p \in P \tag{3-58}$$

$$MRC_t - \textstyle\sum_{l=t+1}^{i} RC_{l,t}^{r} \ge \sum_{p=1}^{P} ARMC_{i,t,p} \qquad \forall\, i \in T, \forall\, t \in T \tag{3-59}$$

$$RC_{i,t}^{r} \le MRC_t + M * (1 - SDB_{i,t}^{r}) \qquad \forall\, i \in \{2, .., T\}, \forall\, t \in \{1, .., i-1\} \tag{3-60}$$

$$RC_{i,t}^{r} \ge MRC_t - M * (1 - SDB_{i,t}^{r}) \qquad \forall\, i \in \{2, .., T\}, \forall\, t \in \{1, .., i-1\} \tag{3-61}$$

$$RC_{i,t}^{r} \le M * (SDB_{i,t}^{r}) \qquad \forall\, i \in \{2, .., T\}, \forall\, t \in \{1, .., i\} \tag{3-62}$$

$$\textstyle\sum_{t=1}^{i-1} \mathrm{RC}_{i,t}^{r} \le \mathrm{MRC}_{t} \qquad \forall\, i \in T \tag{3-63}$$

$$\mathrm{SDB}_{i,t}^{r} + \mathrm{SUB}_{i}^{r} \le 1 \qquad \forall\, i \in T, \forall\, t \in \{1, .., i-1\} \tag{3-64}$$

The following sets of constraints represent ramp down capacity during reconfiguration period, similar to Ramp up period. The only difference in this set is that a lower bound is identified instead of an upper bound to compute the amount of actual capacity during reconfiguration period (3-65,..,3-75).

Reconfiguration (Scaling Down) Constraints:

$$\textstyle\sum_{t=1}^{i-1} ARMC_{i,t,p} \ge \sum_{t=1}^{i-1} IRMC_{i-1,t,p} - .5(\sum_{t=1}^{i-1} RMDMLE_{i,t,p}) - SD_{i,p}^{r} \qquad \forall\, i \in T, \forall\, p \in P \tag{3-65}$$

$$SD_{i,p}^{r} \le .1 * \textstyle\sum_{t=1}^{i-1} RMDMLE_{i,t,p} - \boldsymbol{M} * RL1_{i,p} + \boldsymbol{M} \qquad \forall\, i \in T, \forall\, p \in P \tag{3-66}$$

$$SD_{i,p}^{r} \ge .1 * \textstyle\sum_{t=1}^{i-1} RMDMLE_{i,t,p} - \boldsymbol{M} * RL1_{i,p} \qquad \forall\, i \in T, \forall\, p \in P \tag{3-67}$$

$$SD_{i,p}^{r} \le .2 * \textstyle\sum_{t=1}^{i-1} RMDMLE_{i,t,p} - \boldsymbol{M} * RL2_{i,p} + \boldsymbol{M} \qquad \forall\, i \in T, \forall\, p \in P \tag{3-68}$$

$$SD_{i,p}^{r} \ge .2 * \textstyle\sum_{t=1}^{i-1} RMDMLE_{i,t,p} - \boldsymbol{M} * RL2_{i,p} \qquad \forall\, i \in T, \forall\, p \in P \tag{3-69}$$

$$SD_{i,p}^{r} \le .3 * \textstyle\sum_{t=1}^{i-1} RMDMLE_{i,t,p} - \boldsymbol{M} * RL3_{i,p} + \boldsymbol{M} \qquad \forall\, i \in T, \forall\, p \in P \tag{3-70}$$

$$SD^r_{i,p} \geq .3 * \sum_{t=1}^{i-1} RMDMLE_{i,t,p} - \boldsymbol{M} * RL3_{i,p} \qquad \forall\, i \in T, \forall\, p \in P \qquad (3\text{-}71)$$

$$SD^r_{i,p} \leq .4 * \sum_{t=1}^{i-1} RMDMLE_{i,t,p} - \boldsymbol{M} * RL4_{i,p} + \boldsymbol{M} \qquad \forall\, i \in T, \forall\, p \in P \qquad (3\text{-}72)$$

$$SD^r_{i,p} \geq .4 * \sum_{t=1}^{i-1} RMDMLE_{i,t,p} - \boldsymbol{M} * RL4_{i,p} \qquad \forall\, i \in T, \forall\, p \in P \qquad (3\text{-}73)$$

$$SD^r_{i,p} \leq .49 * \sum_{t=1}^{i-1} RMDMLE_{i,t,p} - \boldsymbol{M} * RL5_{i,p} + \boldsymbol{M} \qquad \forall\, i \in T, \forall\, p \in P \qquad (3\text{-}74)$$

$$SD^r_{i,p} \leq \sum_{t=1}^{i-1} RMDMLE_{i,t,p} \qquad \forall\, i \in T, \forall\, p \in P \qquad (3\text{-}75)$$

In order to tighten the search space, the following constraints are added (3-76... 3-82) to the model. For instance, constraint (3-77) shows that no module can be purchased for RMS before any RMS base purchase.

Speed up Constraints :

$$RMDMLE_{i,t,p} = 0 \qquad \forall\, t \in T\,, \forall\, i \in \{1,..,t\}, \forall\, p \in P \qquad (3\text{-}76)$$

$$ADDMLE_{i,t,p} = 0 \qquad \forall\, t \in T\,, \forall\, i \in \{1,..,t\}, \forall\, p \in P \qquad (3\text{-}77)$$

$$ARMC_{i,t,p} = 0 \qquad \forall\, t \in T\,, \forall\, i \in \{1,..,t-1\}, \forall\, p \in P \qquad (3\text{-}78)$$

$$IRMC_{i,t,p} = 0 \qquad \forall\, t \in T\,, \forall\, i \in \{1,..,t-1\}, \forall\, p \in P \qquad (3\text{-}79)$$

$$RC^r_{i,t} = 0 \qquad \forall\, t \in T, \forall\, i \in \{1,..,t\} \qquad (3\text{-}80)$$

$$RC^d_{i,t,p} = 0 \qquad \forall\, t \in T, \forall\, i \in \{1,..,t\}, \forall\, p \in P \qquad (3\text{-}81)$$

$$RC^f_{i,t} = 0 \qquad \forall\, t \in T, \forall\, i \in \{1,..,t\} \qquad (3\text{-}82)$$

Finally, constraints (3-83...3-85) show binary variables and real variables of the proposed model.

Binary Variables :

$$SU^d_{i,p}, SD^d_{i,t,p}, SU^f_i\,, SD^f_{i,t}, SUB^r_i\,, SDB^r_{i,t} \epsilon \{1,0\} \qquad \forall\, i \in T, \forall\, t \in T, \forall\, p \in P \qquad (3\text{-}83)$$

$$RL1_{i,p}, RL2_{i,p}, RL3_{i,p}, RL4_{i,p}, RL5_{i,p}, RC_{i,p} \epsilon \{1,0\} \qquad \forall\, i \in T, \forall\, t \in T, \forall\, p \in P \qquad (3\text{-}84)$$

Real Variables :

$$\{Z_{i,p}, Q_{i,p}, RMDMLE_{i,t,p}, ADDMLE_{i,t,p}, ARMC_{i,t,p}, IRMC_{i,t,p}, X_{i,p}, SU^r_{i,p}, SD^r_{i,p}, MRC_t, RC^r_{i,t}, RC^d_{l,t}, RC^f_{l,t}, PC^f_t\,, PC^d_t\,, EC^r_{i,p}, EC^d_{i,p}, EC^d_{i,p}, SA_{i,p}\} \in \mathbb{R}^+ \qquad \forall\, i \in T, \forall\, t \in T, \forall\, p \in P \qquad (3\text{-}85)$$

Appendix B: Input and output of MIP model for impact of reconfiguration characteristics in manufacturing systems

Table B 1 Reconfiguration input parameters

	Short Reconfiguration					Medium Reconfiguration					Long Reconfiguration				
Reconfiguration Time %	RL5	RL4	RL3	RL2	RL1	RL5	RL4	RL3	RL2	RL1	RL5	RL4	RL3	RL2	RL1
Reconfiguration cost $	20	50	100	200	400	40	80	160	320	640	80	160	320	640	1280
Capacity can be added (Unit)	50	75	112.5	168.8	253.1	25	37.5	56.25	84.38	126.6	12.5	18.75	28.13	42.19	63.28
Capacity can be removed (Unit)	100	150	225	337.5	506.3	50	75	112.5	168.8	253.1	25	37.5	56.25	84.38	126.6
RL5= 1/5th of Period ; RL4=1/4th of Period; RL3=1/3rd of Period; RL2=1/2nd of Period; RL1= 1 Period															

Table B 2 Growth-plateau demand, RMS medium reconfiguration, M/B=0.25, and excess/shortage ratio=1

Terms	**Decision Variables**	**Time Periods (i)**								
		1	2	3	4	5	6	7	8	9
Demand	$D_{i,p=A}$	50	180	280	300	275	225	200	190	190
	$D_{i,p=B}$	0	0	50	180	280	300	300	275	225
	$D_{i,p=C}$	0	0	0	0	50	180	280	300	300
Actual RMS Capacity	$ARMC_{i,1,p=A}$	175	180	224	225	225	225	200	190	190
Nominal RMS Capacity	$IRMC_{i,1,p=A}$	175	200	225	225	225	225	190	190	190
Added RMS module	$ADDMLE_{i,1,p=A}$	0	25	25	0	0	0	0	0	0
Removed RMS module	$RMDMLE_{i,1,p=A}$	0	0	0	0	0	0	35	0	0
Purchasing RMS Base with modules	MRC_1	225	0	0	0	0	0	0	0	0
Reconfiguration is 1/5th of Total Period	RL_5	0	1	1	0	0	0	1	0	0
Purchasing FMS	PC_i^f	0	0	100	0	0	0	0	0	0
Removing FMS	$RC_{i,t=3}^f$	0	0	0	0	0	100	0	0	0
Purchasing DMS	$PC_{i,p=B}^d$	0	0	0	300	0	0	0	0	0
	$PC_{i,p=C}^d$	0	0	0	0	0	300	0	0	0
Production by DMS	$X_{i,p=B}$	0	0	0	180	280	300	300	275	225
	$X_{i,p=C}$	0	0	0	0	0	180	280	300	300
Production by RMS	$Q_{i,p=A}$	50	180	224	225	225	225	200	190	190
Production by FMS	$Z_{i,p=A}$	0	0	50	75	50	0	0	0	0
	$Z_{i,p=B}$	0	0	50	0	0	0	0	0	0
	$Z_{i,p=C}$	0	0	0	0	50	0	0	0	0
Excess Capacity	EC_i^f	0	0	0	25	0	0	0	0	0
	$EC_{i,p=B}^D$	0	0	0	120	20	0	0	25	75
	$EC_{i,p=C}^D$	0	0	0	0	0	120	20	0	0
	$EC_{i,p=A}^R$	125	0	0	0	0	0	0	0	0

Appendix C: Linearization of clearing function

This section introduces linearization method which is employed in section 5.2.2 to solve the problem of the concavity of the clearing function. The concave clearing function in the MIP model can be replaced by a set of line within the following steps:

Step1: A set of points would be generated through the clearing function (5-34). These points are within the limits of the WIP and/or Capacity which are determined by the MIP model.

Step 2: Using the SUBCLUST function in Matlab, the points which are obtained in step 1 would be divided into clusters with a certain clusters centers. In the case where the clearing function has two dimensions, the cluster centers are $(\omega'_{t-1} + rm'_t, E(X'_t))$. It would be $(\omega'_{t-1} + rm'_t, R\xi'_t, E(X'_t))$ when the clearing function has three dimensions. The explanation of the subtractive clustering algorithm is available in Chiu (1994).

Step 3: Each point in clearing function would be estimated through the line/plane which is tangent to the clearing function at the center of the cluster which the point belongs.

Step 4: Once the clearing function has two dimensions, it is estimated by a set of lines (η) such as

$$f(\omega_{t-1} + rm_t) = \psi * (\omega_{t-1} + rm_t) + \lambda \qquad \text{(C-1)}$$

Where

$$\psi = \frac{\partial E(X_t)}{\partial(\omega_{t-1} + rm_t)}(\omega'_{t-1} + rm'_t) \qquad \text{(C-2)}$$

$$\lambda = E(X_t^{'}) - \psi \; *(\omega_{t-1}^{'} + rm_t^{'}) \qquad \text{C-3)}$$

Once the clearing function has three dimensions, it is estimated by a set of planes (ν) such as

$$f\,(\omega_{t-1} + rm_t\,, R\xi_t) = \psi \; *(\omega_{t-1} + rm_t\,) + \lambda \; *(R\xi_t) - \Upsilon \qquad \text{(C-4)}$$

Where

$$\psi = \frac{\partial E(X_t)}{\partial(\omega_{t-1} + rm_t)}(\omega_{t-1}^{'} + rm_t^{'}) \qquad \text{(C-5)}$$

$$\lambda = \frac{\partial E(X_t)}{\partial(R\xi_t)}(R\xi_t^{'}) \qquad \text{(C-6)}$$

$$\Upsilon = E(\omega_{t-1}^{'} + rm_t^{'}, R\xi_t^{'}) - \psi\,(\omega_{t-1}^{'} + rm_t^{'}) - \lambda\,(R\xi_t^{'}) \qquad \text{(C-7)}$$

Step 5: As it is shown in Figure c.13, the throughput for a given work load $(\omega_{t-1} + rm_t)$ in a two dimensional case is:

$$f(\omega_{t-1} + rm_t\,) = \min_{\eta}(\psi_{\eta} * (\omega_{t-1} + rm_t\,) + \lambda_{\eta}) \qquad \text{(C-8)}$$

The parameter η is the number of lines which estimate the clearing function.

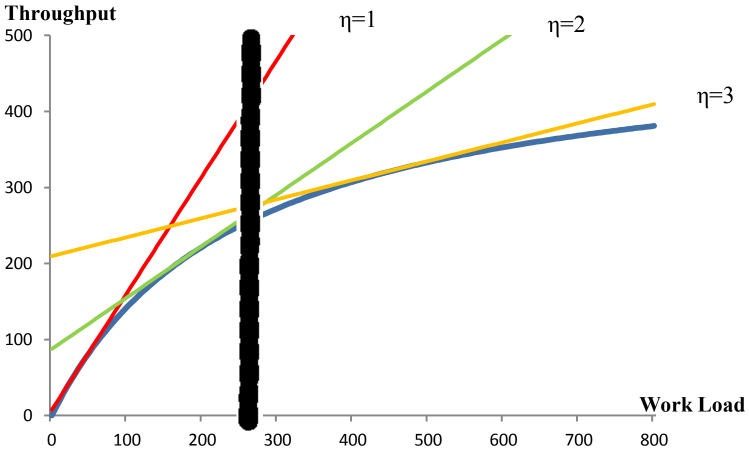


Figure C.0-1 The linearization method

The throughput for a given work load and capacity $(\omega_{t-1} + rm_t, R\xi_t)$ in three dimensional case is:

$$f(\omega_{t-1} + rm_t, R\xi_t) = \min_\upsilon(\psi_\upsilon * (\omega^r_{t-1} + rm^r_t) + \lambda_\upsilon * (R\xi_t) - \Upsilon_\upsilon) \tag{C-9}$$

The parameter ν is the number of planes which estimate the clearing function. In this method, the estimation error is controlled by changing the cluster radius. As the cluster radius decreases, the estimation error improves as a result of the increase in the number of clusters. On the other hand, this leads to an increase in the number of approximation lines. The *subclust* function in MATLAB is employed to find the cluster centers. The parameters of this function are cluster radius, quash factor, accept ratio and reject ratio which are set to 0.5, 1.25, 0.5 and 0.15 accordingly. As a result of these settings, the average of the maximum error for all the clearing functions used in the numerical study is equal to 3.86.

Appendix D: Disruption probability at time t with the length of ℓ

In chapter 5, the disruptions scenarios are generated based on this assumption that there could be maximum one disruption within the planning horizon (T). This represents the low frequency of the major disruption although the time of occurrence and the length of disruption are unlimited to show different scenarios.

The probability of each disruption scenario is computed through the Markov discrete time distribution. Based on the Markov chain principles, the DMS supplier has two states called: failure and operational. The probabilities of transition from one state to another one are as follow.

$$P(\text{Operational} \rightarrow \text{Failure}) = \alpha \tag{D-1}$$

$$P(\text{Operational} \rightarrow \text{Operational}) = 1 - \alpha \tag{D-2}$$

$$P(\text{Failure} \rightarrow \text{Operational}) = \beta \tag{D-3}$$

$$P(\text{Failure} \rightarrow \text{Failure}) = 1 - \beta \tag{D-4}$$

The parameter α is the probability of a failure state follows an operational state and the parameter β represents the probability of an operational state follows a failure state.

As it is illustrated in Figure D.1, the scenario with no disruption occurrence is created as result of transition from one operational state to another one consecutively.

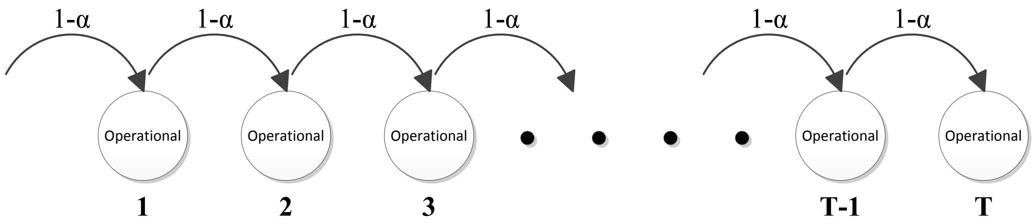


Figure D.0-1 The no disruption scenario

Therefore, the probability of the scenario with no disruption is:

$$P(\text{No Disruption}) = \underbrace{\qquad\qquad\qquad\qquad}_{T\ \text{times}} - \alpha)^{T} \tag{D-5}$$

The scenario of a disruption which occurs at time t , has length of l periods and finishes before the last period is presented in Figure 15.

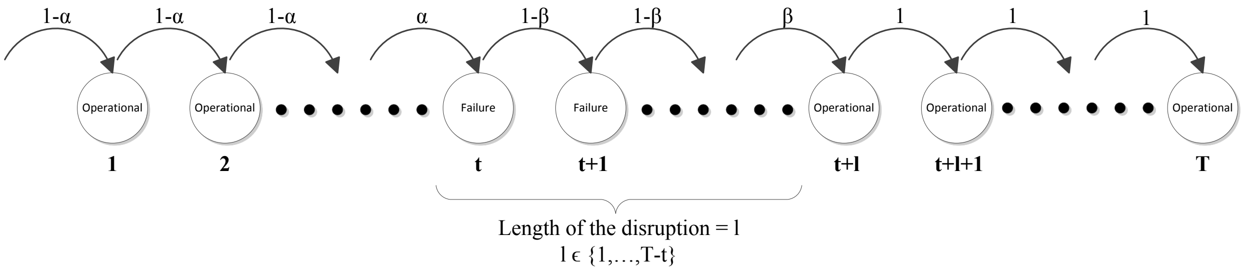


Figure D.0-2 Disruption scenario with time of occurrence = t, length = l, finishes before T

This scenario is generated through the following transitions:

I. $t-1$ time(s) transition among operational states.

II. A transition from the last operational state to failure state.

III. $l-1$ time(s) transition among the failure states.

IV. A transition from the last failure state to operational state.

Hence, the probability of the scenario with a disruption at time m with length of $l \in \{1,\ldots,T-t\}$ is:

$$P_{Disruption}(t\ ,\mathrm{l}) = \underbrace{\qquad\qquad\qquad}_{\text{t-1 times}}\ \underbrace{\qquad\qquad\qquad}_{\text{l-1 times}}\ (1-\alpha)^{t-1}\alpha(1-\beta)^{l-1}\beta \qquad \text{(D-6)}$$

Since it is assumed that disruption frequency within the planning horizon is equal to one, the transition probabilities after the end of disruption are equal to 1 to show that the system will stay only in operational condition until the end of the planning horizon.

Regarding the scenarios where the DMS transits in to the period T in failure state (Figure D.3), its transition to the next period could be either failure or operational, however the objective is determination of the disruption scenarios within the planning horizon (T).

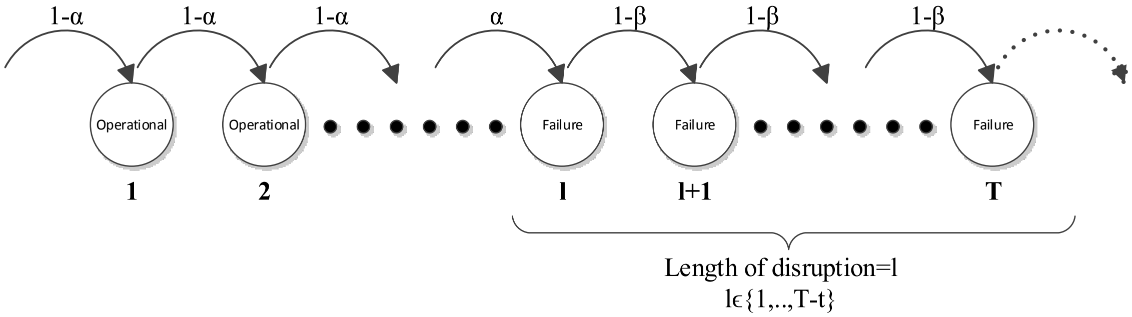


Figure D.0-3 Disruption scenario with time of occurrence = t, length = l, might finish at T or not

Therefore, in computing the probability of such scenarios, the consideration would be up to the transition in to period T in failure state and the result is called the probability of the scenario with disruption at time t and the length of $T-t+1$ periods or more.

$$P_{Disruption}(t\ ,\mathrm{l}) = \underbrace{\qquad\qquad\qquad}_{\text{t-1 times}}\ \underbrace{\qquad\qquad\qquad}_{\text{l-1 times}}\ -\alpha)^{t-1}\alpha(1-\beta)^{l-1} \qquad \text{(D-7)}$$

Appendix E: Mixed integer programming model of chapter 4

```
/*********************************************
 * OPL 12.2.0.2 Model
 * Author: Iman
 * Creation Date: Jul 3, 2011 at 7:58:07 PM
 *********************************************/
/* Parameters*/
int NbCurrentTime=...;
int NbProduct=...;
range Product=1..NbProduct;
range CurrentTime=1..NbCurrentTime;
float PD[CurrentTime][Product]=...; // Product Demand
float sigma[CurrentTime][Product]=...; //Demand Variance
float DFC[Product]=...; // Dedicated Capacity Investment Cost
float DFPC[Product]=...; // Dedicated Facility Production Cost
float SPC[Product]=...; //Shortage Penalty Cost
float RFC=...; //Reconfigurable Capacity Cost
float RFPC[Product]=...; //Reconfigurable Production Cost
float ECC[Product]=...; //Excess Capacity Cost
float RECC=...;

/* Variables*/
dvar float+ MXAC; //Maximum Capacity that could be added in one period
dvar int+ DFCapacity[CurrentTime][Product]; //Dedicated Capacity
dvar int+ DFP[CurrentTime][Product]; //Dedicated Facility Production
dvar int+ RFP[CurrentTime][Product]; //Reconfigurable Production
dvar int+ IRFC[CurrentTime]; // Ideal Reconfigurable Capacity
```

```
dvar int+ CRFC[CurrentTime]; //Current Reconfigurable Capacity

dvar int+ ADC[CurrentTime]; //Added Capacity

dvar int+ RDC[CurrentTime]; //Removed Capacity

dvar int+ URC[CurrentTime]; //upper bound Capacity

dvar int+ LRC[CurrentTime]; //lower bound Capacity

dvar int+ REC[CurrentTime]; //Reconfigurable Excess Capacity

dvar int+ DEC[CurrentTime][Product]; //Dedicated Excess Capacity

dvar int+ DAC[CurrentTime][Product]; //Dedicated Added Capacity

dvar int+ DRC[CurrentTime][Product]; //Dedicated Removed Capacity

dvar int+ Y1[CurrentTime] in 0..1; //Period sub interval 1

dvar int+ Y2[CurrentTime] in 0..1; //Period sub interval 2

dvar int+ Y3[CurrentTime] in 0..1; //Period sub interval 3

dvar int+ Y4[CurrentTime] in 0..1; //Period sub interval 1

dvar int+ Y5[CurrentTime] in 0..1; //Period sub interval 2

dvar int+ Y6[CurrentTime] in 0..1; //Period sub interval 3

dvar int+ Y7[CurrentTime] in 0..1; //Period sub interval 1

dvar int+ Y8[CurrentTime] in 0..1; //Period sub interval 2

dvar int+ Y9[CurrentTime] in 0..1; //Period sub interval 3

dvar int+ Y10[CurrentTime] in 0..1; //Ramp up or Ramp down

dvar int+ Y11[CurrentTime][Product] in 0..1; //Dedicated Added...Removed

dvar int+ YD[CurrentTime][Product] in 0..1; //Dedicated Added...Removed

dvar int+ K1 in 0..1; //Period sub interval 1

dvar int+ K2 in 0..1; //Period sub interval 2

dvar int+ K3 in 0..1; //Period sub interval 3

dvar int+ K4 in 0..1; //Period sub interval 3

dvar int+ DL[CurrentTime][Product]; //Demand Lost

dexpr float ProductionCost=sum(t in CurrentTime, p in Product)
(DFPC[p]*DFP[t][p]+RFPC[p]*RFP[t][p]);
```

```
dexpr float CapacityCost=RFC*CRFC[1]+sum(t in CurrentTime)(RFC*ADC[t])+ sum(p
in Product)DFC[p]*DFCapacity[1][p]+sum(t in CurrentTime,p in Product)
DFC[p]*(DAC[t][p]) ;

dexpr float DemandLost= sum(t in CurrentTime, p in Product)SPC[p]*DL[t][p];

dexpr float ReconfigExcessCost= sum(t in CurrentTime) REC[t]*RECC;

dexpr float DedicatedExcessCost=sum(t in CurrentTime,p in Product)
DEC[t][p]*ECC[p];

dexpr float ReconfigurationCost=sum(t in CurrentTime)
(100*Y1[t]+200*Y2[t]+300*Y3[t]+200*Y4[t]+400*Y5[t]+600*Y6[t]+300*Y7[t]+600*
Y8[t]+900*Y9[t]);

dexpr float SeriesReconfigurationCost=sum(t in CurrentTime,p in Product) 50*YD[t][p];


dexpr float TotalCapacityCost=

        +ProductionCost
        +CapacityCost
        +DemandLost
        +ReconfigExcessCost
        +DedicatedExcessCost
        +ReconfigurationCost
        +SeriesReconfigurationCost;

minimize TotalCapacityCost;

constraints {

        forall( t in CurrentTime)

          forall(p in Product)

                PD[t][p]+sigma[t][p]==DFP[t][p]+RFP[t][p]+DL[t][p];

        forall (t in CurrentTime)

          forall (p in Product)

                DFP[t][p]+DEC[t][p]==DFCapacity[t][p];


/*******New Dedicated Capacity Constraints (Series Reconfiguration)********/
```

```
    forall (t in CurrentTime:t>=2)
        forall (p in Product)
        DFCapacity[t][p]==DFCapacity[t-1][p]+DAC[t-1][p]-DRC[t][p];

    forall (t in CurrentTime)
        forall(p in Product)
            DAC[t][p]+DRC[t][p]>=700+5000*YD[t][p]-5000;

    forall (t in CurrentTime)
        forall(p in Product)
            DAC[t][p]+DRC[t][p]<=5000*YD[t][p];

    forall (t in CurrentTime)
        forall(p in Product)
            DRC[t][p]<=DFCapacity[t][p];

    forall (t in CurrentTime)
        forall(p in Product)
            DAC[t][p]<=5000*(Y11[t][p]);

     forall (t in CurrentTime)
        forall(p in Product)
            DRC[t][p]<=5000*(1-Y11[t][p]);

    forall (t in CurrentTime)
        forall (p in Product)
        YD[t][p]<=K4;

************************************************************************/

    forall(t in CurrentTime)
        sum(p in Product) RFP[t][p]+REC[t]==CRFC[t];

    forall (t in CurrentTime:t>=2)
            IRFC[t]==IRFC[t-1]+ADC[t]-RDC[t];

    forall (t in CurrentTime:t>=2)
            CRFC[t]==IRFC[t-1]+URC[t]-LRC[t];

/**Reconfiguration Type 1: In this configuration available capacity during
reconfiguration is between[30%-85%] of Ideal Capacity. This percentage is depend on
amount of capacity which is added or removed.**/

    forall (t in 2..NbCurrentTime)
            URC[t]+LRC[t]<=.85*(ADC[t]+RDC[t])+5000*(1-Y1[t]);
    forall (t in 2..NbCurrentTime)
```

```
                URC[t]+LRC[t]>=.65*(ADC[t]+RDC[t])- 5000*(1-Y1[t]);
        forall (t in 2..NbCurrentTime)
                        URC[t]+LRC[t]<=.65*(ADC[t]+RDC[t])+ 5000*(1-Y2[t]);
        forall (t in 2..NbCurrentTime)
                        URC[t]+LRC[t]>=.5*(ADC[t]+RDC[t])- 5000*(1-Y2[t]);
        forall (t in 2..NbCurrentTime)
                        URC[t]+LRC[t]<=.5*(ADC[t]+RDC[t])+ 5000*(1-Y3[t]);
        forall (t in 2..NbCurrentTime)
                        URC[t]+LRC[t]>=.3*(ADC[t]+RDC[t])- 5000*(1-Y3[t]);

/**Reconfiguration   Type   2:In   this   configuration   available   capacity   during
reconfiguration is between[50%-95%] of Ideal Capacity depend on amount of capacity
which is added or removed  **/
        forall (t in 2..NbCurrentTime)
                        URC[t]+LRC[t]<=.95*(ADC[t]+RDC[t])+5000*(1-Y4[t]);
        forall (t in 2..NbCurrentTime)
                URC[t]+LRC[t]>=.84*(ADC[t]+RDC[t])- 5000*(1-Y4[t]);
        forall (t in 2..NbCurrentTime)
                        URC[t]+LRC[t]<=.84*(ADC[t]+RDC[t])+ 5000*(1-Y5[t]);
        forall (t in 2..NbCurrentTime)
                        URC[t]+LRC[t]>=.67*(ADC[t]+RDC[t])- 5000*(1-Y5[t]);
        forall (t in 2..NbCurrentTime)
                        URC[t]+LRC[t]<=.67*(ADC[t]+RDC[t])+ 5000*(1-Y6[t]);
        forall (t in 2..NbCurrentTime)
                        URC[t]+LRC[t]>=.5*(ADC[t]+RDC[t])- 5000*(1-Y6[t]);

/**Reconfiguration Type 3:In this configuration available capacity during reconfiguration
is between[70%-100%] of Ideal Capacity depend on amount of capacity which is added
or removed**/

        forall (t in 2..NbCurrentTime)
                        URC[t]+LRC[t]<=ADC[t]+RDC[t]+5000*(1-Y7[t]);
        forall (t in 2..NbCurrentTime)
                URC[t]+LRC[t]>=.94*(ADC[t]+RDC[t])- 5000*(1-Y7[t]);
        forall (t in 2..NbCurrentTime)
                        URC[t]+LRC[t]<=.94*(ADC[t]+RDC[t])+ 5000*(1-Y8[t]);
        forall (t in 2..NbCurrentTime)
                        URC[t]+LRC[t]>=.85*(ADC[t]+RDC[t])- 5000*(1-Y8[t]);
        forall (t in 2..NbCurrentTime)
                        URC[t]+LRC[t]<=.85*(ADC[t]+RDC[t])+ 5000*(1-Y9[t]);
        forall (t in 2..NbCurrentTime)
                        URC[t]+LRC[t]>=.7*(ADC[t]+RDC[t])- 5000*(1-Y9[t]);

        /* Configuration 1 Speed */

        forall (t in 2..NbCurrentTime)
```

```
                        ADC[t]+RDC[t]<=.05*MXAC+5000-5000*Y1[t];
        forall (t in 2..NbCurrentTime)
                        ADC[t]+RDC[t]>=.05*MXAC-5000+5000*Y2[t];
        forall (t in 2..NbCurrentTime)
                        ADC[t]+RDC[t]<=.25*MXAC+5000-5000*Y2[t];
        forall (t in 2..NbCurrentTime)
                        ADC[t]+RDC[t]>=.25*MXAC-5000+5000*Y3[t];
        forall (t in 2..NbCurrentTime)
                        ADC[t]+RDC[t]<=MXAC+5000-5000*Y3[t];


/* Configuration 2 Speed */

forall (t in 2..NbCurrentTime)
                        ADC[t]+RDC[t]<=.33*MXAC+5000-5000*Y4[t];
        forall (t in 2..NbCurrentTime)
                        ADC[t]+RDC[t]>=.33*MXAC-5000+5000*Y5[t];
        forall (t in 2..NbCurrentTime)
                        ADC[t]+RDC[t]<=.66*MXAC+5000-5000*Y5[t];
        forall (t in 2..NbCurrentTime)
                        ADC[t]+RDC[t]>=.66*MXAC-5000+5000*Y6[t];
        forall (t in 2..NbCurrentTime)
                        ADC[t]+RDC[t]<=MXAC+5000-5000*Y6[t];

 /* Configuration 3 Speed */

forall (t in 2..NbCurrentTime)
                        ADC[t]+RDC[t]<=.8*MXAC+5000-5000*Y7[t];
        forall (t in 2..NbCurrentTime)
                        ADC[t]+RDC[t]>=.8*MXAC-5000+5000*Y8[t];
        forall (t in 2..NbCurrentTime)
                        ADC[t]+RDC[t]<=.9*MXAC+5000-5000*Y8[t];
        forall (t in 2..NbCurrentTime)
                        ADC[t]+RDC[t]>=.9*MXAC-5000+5000*Y9[t];
        forall (t in 2..NbCurrentTime)
                        ADC[t]+RDC[t]<=MXAC+5000-5000*Y9[t];

/* Selection of Reconfiguration Type*/

 forall (t in CurrentTime)
                Y1[t]+Y2[t]+Y3[t]<=K1;

 forall (t in CurrentTime)
                Y4[t]+Y5[t]+Y6[t]<=K2;

 forall (t in CurrentTime)
```

```
                Y7[t]+Y8[t]+Y9[t]<=K3;


   /* Ramp up or Ramp down Selection during Reconfiguration*/

  forall (t in 1..NbCurrentTime)
         URC[t]+ADC[t]<=5000*(Y10[t]);

  forall(t in 1..NbCurrentTime)
          LRC[t]+RDC[t]<=5000*(1-Y10[t]);


   forall (t in CurrentTime)

         ADC[t]+URC[t]<=5000*(Y1[t]+Y2[t]+Y3[t]+Y4[t]+Y5[t]+Y6[t]+Y7[t]+Y8[t]+
Y9[t]);
   forall (t in CurrentTime)

         RDC[t]+LRC[t]<=5000*(Y1[t]+Y2[t]+Y3[t]+Y4[t]+Y5[t]+Y6[t]+Y7[t]+Y8[t]+Y
9[t]);

 }

 /* one Reconfiguration is selected */

 subject to {
                K1+K2+K3+K4==1;}

 subject to {
                ct1: RDC[1]==0;
                ct2: ADC[1]==0;
                ct3: URC[1]==0;
                ct4: LRC[1]==0;
                ct5: IRFC[1]==CRFC[1];
                ct6: MXAC<=700*K1+700*K2+700*K3;
                ct7: DRC[1][1]+DRC[1][2]==0;
                //ct8: K2==1;
 }
```

Appendix F: Mixed integer programming input data chapter 4

```
/*********************************************

 * OPL 12.2.0.2 Data

 * Author: Iman

 * Creation Date: Jul 3, 2011 at 7:58:07 PM

 *********************************************/

NbCurrentTime=10;
NbProduct=2;

////// product demand

PD=[[400,0],[600,0],[900,400],[1200,600],[1200,900],[1200,1200],[1000,1200],[800,120
0],[400,1000],[200,800]];


////safety capacity adjustment based on the service level

//Z=-2;
/*
sigma=[[-356  0],[-464       0],[-568       -356],[-536    -464],[-536    -568],[-536
        -536],[-564    -536],[-530    -536],[-288    -564],[-154    -530]];
//*/
//Z=-1.5;
/*
sigma=[[-267  0],[-348       0],[-426       -267],[-402    -348],[-402    -426],[-402
        -402],[-423    -402],[-397    -402],[-216    -423],[-115    -397]];
//*/

//Z=-1;
/*
sigma=[[-178  0],[-232       0],[-284       -178],[-268    -232],[-268    -284],[-268
        -268],[-282    -268],[-265    -268],[-144    -282],[-77     -265]];
//*/

//Z=-.5;
/*
sigma=[[-89   0],[-116       0],[-142       -89],[-134     -116],[-134    -142],[-134
        -134],[-141    -134],[-132    -134],[-72     -141],[-38     -132]];
//*/
```

```
//Z=0;
/*
sigma=[[0      0],[0    0],[0    0],[0    0],[0    0],[0    0],[0    0],[0    0],[0    0],[0    0]];
//*/

//Z=.5;
//*
sigma=[[89    0],[116 0],[142 89],[134        116],[134       142],[134       134],[141
        134],[132       134],[72        141],[38        132]];
//*/

//Z=1;
/*
sigma=[
        [178    0],[232 0],[284 178],[268       232],[268       284],[268       268],[282
        268],[265       268],[144       282],[77        265]];
//*/

//Z=1.5
/*
sigma=[[267   0],[348 0],[426 267],[402       348],[402       426],[402       402],[423
        402],[397       402],[216       423],[115       397]];
//*/

//Z=2;
/*
sigma=[
        [356    0],[464 0],[568 356],[536       464],[536       568],[536       536],[564
        536],[530       536],[288       564],[154       530]];
//*/

DFC= [9,9]; //dedicated capacity cost

RFC= 15 ; //reconfiguratble capacity cost

DFPC= [.8,.8] ;    // dedicated capacity production cost

RFPC=[1.5,1.5]; // reocnfiugrable capacity production cost

SPC=[50,50]; // shortage cost

ECC=[30,30]; //  dedicated excess capacity cost

RECC=30; // reconfigurable excess capacity cost
```

Appendix G: Simulation output of chapter 4

Table G 1 Simulation output sample for service level of 70% and excess cost of S

Identifier	Average	Half-width	Minimum	Maximum	Replications
Product A produced	7685.5	205.96	6641	9084	30
Total Unit Demand Lost	1044.7	190.59	242	2343	30
PercentageDemandLost4allPeriods	0.07536	0.01249	0.01952	0.15453	30
Product B produced	4881	212.68	3448	6172	30
PercentageofExcessCapacity4allPeriods	0.18062	0.01454	0.10972	0.25185	30
Total Unit Excess Capacity	2847.1	229.18	1730.3	3972.5	30
RMS.NumberSeized	6209.1	183.82	5280	7080	30
RMS.ScheduledUtilization	0.68873	0.02973	0.50998	0.86454	30
DM1.NumberSeized	5114.6	125.31	4102	5694	30
DM1.ScheduledUtilization	0.8038	0.0197	0.64458	0.89493	30
DM2.NumberSeized	1248.7	16.876	1055	1266	30
DM2.ScheduledUtilization	0.5702	0.00771	0.48173	0.57807	30

Table G 2 Simulation utilization output sample for service level of 70% and excess cost of S

Average DC A Utilization	Average DC B Utilization	Average RC Utilization	% of Demand Lost	% of Excess Capacity	Total Unit Demand Lost	Total Unit Excess Capacity	Total Production	Shortage Cost	Excess Cost	Production Cost	Total Cost
0.73753	0.56587	0.58811	0.06329	0.23664	887.86	4076.9	12786.3	10352.45	20384.5	12786.3	77220.2476
0.72124	0.56752	0.58231	0.0698	0.23672	973.2	4042	12642.5	11347.51	20210	12642.5	75200.492
0.8038	0.5702	0.68873	0.07536	0.18062	1044.7	2847.1	12566.5	12181.2	14235.5	12566.5	72398.202
0.67883	0.44849	0.4266	0.06231	0.22225	856.06	4889.4	12586	9981.66	24447	12586	72474.6596

Appendix H: Mixed integer programming model of chapter 5

```
/*********************************************
 * OPL 12.4 Model
 * Creation Date: 2012-08-22 at 4:10:06 PM
 *********************************************/
int NbCurrentTime=...;
int NbProduct=...;
range Product=1..NbProduct;//we assume the NbProduct is one
range CurrentTime=0..NbCurrentTime;
float PD[CurrentTime][Product]=...; // Product Demand
float DFC[Product]=...; // Dedicated Capacity Investment Cost
float DFPC[Product]=...; // Dedicated Facility Production Cost
float SPC[CurrentTime]=...; //Shortage Penalty Cost
float RFC=...; //Reconfigurable Capacity Cost
float RFPC[Product]=...; //Reconfigurable Production Cost
float ECC[CurrentTime]=...; //Dedicated Excess Capacity Cost
float RECC[CurrentTime]=...;//Reconfigurable Excess Capacity Cost
float HC[Product]=...; //Holding Cost
float DWIPC[CurrentTime]=...;//Dedicated WIP Cost
float RWIPC[CurrentTime]=...;//Reconfigurable WIP Cost
float RRMC[Product]=...;// Reconfigurable Release Material Cost
float DRMC[Product]=...;// Dedicated Releasae Material Cost
float MDC=...;//Maximum Dedicated Capacity
float MRC=...;//Maximum Reconfigurable Capacity
float MlCa=...;//Module Capacity
float DS[CurrentTime]=...; //DMS availability (not disrupted)
/* Variables*/
//dvar float+ MXRC; //Maximum Capacity that could be removed in one
period
dvar int+ DFP[CurrentTime][Product]; //Dedicated Facility Production
dvar int+ RFP[CurrentTime][Product]; //Reconfigurable Production
dvar int+ IRFC[CurrentTime]; // Ideal Reconfigurable Capacity
dvar int+ CRFC[CurrentTime]; //Current Reconfigurable Capacity
dvar int+ ADC[CurrentTime]; //Added Capacity
dvar int+ RDC[CurrentTime]; //Removed Capacity
dvar int+ URC[CurrentTime]; //upper bound Capacity
dvar int+ LRC[CurrentTime]; //lower bound Capacity
dvar int+ REC[CurrentTime]; //Reconfigurable Excess Capacity
dvar int+ DEC[CurrentTime][Product]; //Dedicated Excess Capacity
dvar int+ Inv[CurrentTime][Product]; //Inventory Cost
dvar int+ RWIP[CurrentTime]; //Reconfigurable WIP at period t
dvar int+ DWIP[CurrentTime]; //Dedicated WIP at period t
dvar int+ RRM[CurrentTime][Product];//Reconfigurable Release Material
dvar int+ DRM[CurrentTime][Product];//Dedicated Release Material
dvar int+ SD[CurrentTime][Product];//Satisfied Demand
dvar int+ Y1[CurrentTime] in 0..1; //Period sub interval 1
dvar int+ Y2[CurrentTime] in 0..1; //Period sub interval 2
dvar int+ Y3[CurrentTime] in 0..1; //Period sub interval 3
dvar int+ Y4[CurrentTime] in 0..1; //Period sub interval 1
dvar int+ Y5[CurrentTime] in 0..1; //Period sub interval 2
dvar int+ Y0[CurrentTime] in 0..1; //Reconfiguration is occured
dvar int+ DL[CurrentTime][Product]; //Demand Lost
dvar int+ Y6[CurrentTime] in 0..1; //100 capacity
dvar int+ Y7[CurrentTime] in 0..1; //200 capacity
```

```
dvar int+ Y8[CurrentTime] in 0..1; //300 capacity
dvar int+ Y9[CurrentTime] in 0..1; //400 capacity


dexpr float ProductionCost=sum(t in CurrentTime, p in Product)
(DFPC[p]*DFP[t][p]+RFPC[p]*RFP[t][p]);
dexpr float CapacityCost=sum(t in CurrentTime)(RFC*(ADC[t]+RDC[t])) ;
dexpr float Inventory= sum(t in CurrentTime, p in
Product)(HC[p]*Inv[t][p]);
dexpr float DemandLost= sum(t in CurrentTime, p in
Product)(SPC[t]*DL[t][p]);
dexpr float ReconfigExcessCost= sum(t in CurrentTime) REC[t]*RECC[t];
dexpr float DedicatedExcessCost=sum(t in CurrentTime,p in Product)
DEC[t][p]*ECC[t];
dexpr float WIPCost=sum(t in CurrentTime)
(DWIPC[t]*DWIP[t]+RWIPC[t]*RWIP[t]);
dexpr float ReleaseMaterialCost=sum(t in CurrentTime,p in Product)
(RRMC[p]*RRM[t][p]+DRMC[p]*DRM[t][p]);
dexpr float TotalCapacityCost=
ProductionCost+CapacityCost+Inventory+DemandLost+ReconfigExcessCost+Ded
icatedExcessCost+WIPCost+ReleaseMaterialCost;

minimize TotalCapacityCost;


 constraints {
      forall( t in CurrentTime:t>=2)//Inventory balance constraint
        forall(p in Product)
            Inv[t][p]==Inv[t-1][p]+(DS[t]*DFP[t][p])+RFP[t][p]-
SD[t][p];



      forall(p in Product) // Inventory at First Period
            Inv[1][p]==(DS[1]*DFP[1][p])+RFP[1][p]-SD[1][p];


      forall (t in CurrentTime) // Demand Balance Constraint
        forall (p in Product)
            SD[t][p]+DL[t][p]==PD[t][p];

      forall(t in CurrentTime) // The product is lost when the
Inventory is zero
        forall(p in Product)
          DL[t][p]<=5000*(1-Y5[t]);

      forall(t in CurrentTime)
        forall(p in Product)
         Inv[t][p]<=5000*(Y5[t]);


      forall (t in CurrentTime) //Dedicated Capacity balance
        forall (p in Product)
            DFP[t][p]+DEC[t][p]==MDC*DS[t];


       forall(t in CurrentTime) //Reconfigurable Capacity balance
```

```
            sum(p in Product) RFP[t][p]+REC[t]==CRFC[t];

       forall (t in CurrentTime:t>=1) // Nominal Capacity at each
period
                  IRFC[t]==IRFC[t-1]+ADC[t]-RDC[t];

       forall (t in CurrentTime:t>=1) // Actual Capacity at each period
                  CRFC[t]==IRFC[t-1]+URC[t]-LRC[t];

       forall (t in CurrentTime)
                  IRFC[t]<=MRC;


      /* Reconfiguration : available capacity during reconfiguration is
between[30%-85%] of nominal Capacity. This
            percentage is depend on amount of capacity which is added
or removed.*/

       forall (t in 1..NbCurrentTime)
                  URC[t]+LRC[t]<=.95*(ADC[t]+RDC[t])+5000*(1-Y1[t]);
       forall (t in 1..NbCurrentTime)
            URC[t]+LRC[t]>=.85*(ADC[t]+RDC[t])- 5000*(1-Y1[t]);
       forall (t in 1..NbCurrentTime)
                  URC[t]+LRC[t]<=.85*(ADC[t]+RDC[t])+ 5000*(1-Y2[t]);
       forall (t in 1..NbCurrentTime)
                  URC[t]+LRC[t]>=.7*(ADC[t]+RDC[t])- 5000*(1-Y2[t]);
       forall (t in 1..NbCurrentTime)
                  URC[t]+LRC[t]<=.7*(ADC[t]+RDC[t])+ 5000*(1-Y3[t]);
       forall (t in 1..NbCurrentTime)
                  URC[t]+LRC[t]>=.55*(ADC[t]+RDC[t])- 5000*(1-Y3[t]);


      /* Number of Modules that can be added*/

      forall (t in 1..NbCurrentTime)
                  ADC[t]+RDC[t]==MlCa*Y1[t]+2*MlCa*Y2[t]+3*MlCa*Y3[t];


    /* Either Capacity could be added or removed*/

   forall (t in 1..NbCurrentTime)
       URC[t]+ADC[t]<=5000*(Y4[t]);

   forall(t in 1..NbCurrentTime)
         LRC[t]+RDC[t]<=5000*(1-Y4[t]);


  /* No capacity addition or deletion is allowed without
reconfiguration*/
   forall (t in CurrentTime)
                  Y0[t]+Y1[t]+Y2[t]+Y3[t]==1;
   forall (t in CurrentTime)
                  RDC[t]+LRC[t]<=5000*(Y1[t]+Y2[t]+Y3[t]);

forall (t in CurrentTime)
                  ADC[t]+URC[t]<=5000*(Y1[t]+Y2[t]+Y3[t]);
```

```
  /* WIP Balance Equation DMS*/

  forall (t in CurrentTime:t>=2)
    DWIP[t]==DWIP[t-1]+sum(p in Product)(DS[t]*(DRM[t][p]-DFP[t][p]));

  /*WIP at First Period DMS*/

  DWIP[1]==sum(p in Product)DS[1]*(DRM[1][p]-DFP[1][p]);

//No release in DMS if it is disrupted//
forall (t in CurrentTime:t>=1)
  sum(p in Product)DRM[t][p]<=5000*DS[t];

  /* WIP Balance Equation RMS*/

  forall (t in CurrentTime:t>=2)
    RWIP[t]==RWIP[t-1]+sum(p in Product)(RRM[t][p]-RFP[t][p]);

  /*WIP at First Period RMS*/

  RWIP[1]==sum(p in Product)(RRM[1][p]-RFP[1][p]);


  //nominal capacity with respect to modules capacity
  forall (t in CurrentTime)
    IRFC[t]==MlCa*Y6[t]+2*MlCa*Y7[t]+3*MlCa*Y8[t]+4*MlCa*Y9[t];

   forall (t in CurrentTime)
    Y6[t]+Y7[t]+Y8[t]+Y9[t]==1;

//DMS WIP less than available capacity

forall(t in CurrentTime:t>=2)
    forall(p in Product)
DWIP[t-1]+DRM[t][p]<=500;

forall(t in CurrentTime:t==1)
    forall(p in Product)
DRM[t][p]<=500;

//RMS WIP less than available capacity

forall(t in CurrentTime:t>=1)
    forall(p in Product)
RWIP[t-1]+RRM[t][p]<= CRFC[t];

 /* Boundry of DMS production restricted by WIP*/

  forall(t in CurrentTime:t>=2)
    forall(p in Product)
            DFP[t][p]<=(0.98*(DWIP[t-1]+DRM[t][p]))*DS[t];

  forall(t in CurrentTime:t>=2)
    forall(p in Product)
            DFP[t][p]<=(0.79*(DWIP[t-1]+DRM[t][p])+ 52.91)*DS[t];

forall(t in CurrentTime:t>=2)
```

```
    forall(p in Product)
            DFP[t][p]<=(0.95*(DWIP[t-1]+DRM[t][p])+ 2.2)*DS[t];

forall(t in CurrentTime:t>=2)
    forall(p in Product)
            DFP[t][p]<=(0.97*(DWIP[t-1]+DRM[t][p])-0.56)*DS[t];

forall(t in CurrentTime:t>=2)
    forall(p in Product)
            DFP[t][p]<=(0.91*(DWIP[t-1]+DRM[t][p])+ 12.02)*DS[t];

forall(t in CurrentTime:t>=2)
    forall(p in Product)
            DFP[t][p]<=(0.48*(DWIP[t-1]+DRM[t][p])+ 191.18)*DS[t];

  forall(t in CurrentTime:t==1)
    forall(p in Product)
            DFP[t][p]<=(0.98*(DRM[t][p]))*DS[t];

  forall(t in CurrentTime:t==1)
    forall(p in Product)
            DFP[t][p]<=(0.79*(DRM[t][p])+ 52.91)*DS[t];

forall(t in CurrentTime:t==1)
    forall(p in Product)
            DFP[t][p]<=(0.95*(DRM[t][p])+ 2.2)*DS[t];

forall(t in CurrentTime:t==1)
    forall(p in Product)
            DFP[t][p]<=(0.97*(DRM[t][p])- 0.56)*DS[t];

forall(t in CurrentTime:t==1)
    forall(p in Product)
            DFP[t][p]<=(0.91*(DRM[t][p])+ 12.01)*DS[t];

forall(t in CurrentTime:t==1)
    forall(p in Product)
            DFP[t][p]<=(0.48*(DRM[t][p])+ 191.18)*DS[t];



/* Boundry of RMS production restricted by WIP when there is no
reconfiguration stay in 100*/

     forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.42*(RRM[t][p])+ 7.52 + 5000*(2-Y0[t]-Y6[t]);

     forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.57*(RRM[t][p])+ 0.67 + 5000*(2-Y0[t]-Y6[t]);

forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.34*(RRM[t][p])+ 14.42 + 5000*(2-Y0[t]-Y6[t]);
```

```
forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.65*(RRM[t][p])+ 5000*(2-Y0[t]-Y6[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.42*(RWIP[t-1]+RRM[t][p])+   7.52   +   5000*(2-
Y0[t]-Y6[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.57*(RWIP[t-1]+RRM[t][p])+   0.67   +   5000*(2-
Y0[t]-Y6[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.34*(RWIP[t-1]+RRM[t][p])+   14.42   +   5000*(2-
Y0[t]-Y6[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.65*(RWIP[t-1]+RRM[t][p])+        5000*(2-Y0[t]-
Y6[t]);


    /* Boundry of RMS production restricted by WIP when there is no
reconfiguration stay in 200*/

     forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.56*(RRM[t][p])+ 29.85 + 5000*(2-Y0[t]-Y7[t]);

     forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.78*(RRM[t][p])+ 3.56 + 5000*(2-Y0[t]-Y7[t]);

forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.86*(RRM[t][p])- 0.41 + 5000*(2-Y0[t]-Y7[t]);

forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.69*(RRM[t][p])+ 13.17 + 5000*(2-Y0[t]-Y7[t]);

forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.88*(RRM[t][p])+ 5000*(2-Y0[t]-Y7[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.56*(RWIP[t-1]+RRM[t][p])+   29.85   +   5000*(2-
Y0[t]-Y7[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.78*(RWIP[t-1]+RRM[t][p])+   3.56   +   5000*(2-
Y0[t]-Y7[t]);
```

```
     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.86*(RWIP[t-1]+RRM[t][p])-   0.41   +   5000*(2-
Y0[t]-Y7[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.69*(RWIP[t-1]+RRM[t][p])+   13.17   +   5000*(2-
Y0[t]-Y7[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.88*(RWIP[t-1]+RRM[t][p])+        5000*(2-Y0[t]-
Y7[t]);


    /* Boundry of RMS production restricted by WIP when there is no
reconfiguration stay in 300*/

     forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.64*(RRM[t][p])+ 48.67 + 5000*(2-Y0[t]-Y8[t]);

     forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.85*(RRM[t][p])+ 6.58 + 5000*(2-Y0[t]-Y8[t]);

     forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.92*(RRM[t][p])- 0.16 + 5000*(2-Y0[t]-Y8[t]);

     forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.78*(RRM[t][p])+ 19.24 + 5000*(2-Y0[t]-Y8[t]);

     forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.94*(RRM[t][p])+ 5000*(2-Y0[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.64*(RWIP[t-1]+RRM[t][p])+   48.67   +   5000*(2-
Y0[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.85*(RWIP[t-1]+RRM[t][p])+   6.58   +   5000*(2-
Y0[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.92*(RWIP[t-1]+RRM[t][p])-   0.16   +   5000*(2-
Y0[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
```

```
            RFP[t][p]<=0.78*(RWIP[t-1]+RRM[t][p])+   19.24   +   5000*(2-
Y0[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.94*(RWIP[t-1]+RRM[t][p])+        5000*(2-Y0[t]-
Y8[t]);

    /* Boundry of RMS production restricted by WIP when there is no
reconfiguration stay in 400*/

     forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.68*(RRM[t][p])+ 68.32 + 5000*(2-Y0[t]-Y9[t]);

forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.89*(RRM[t][p])+ 9.62 + 5000*(2-Y0[t]-Y9[t]);

forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.95*(RRM[t][p])+ 0.25 + 5000*(2-Y0[t]-Y9[t]);

forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.96*(RRM[t][p])- 0.29 + 5000*(2-Y0[t]-Y9[t]);

forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.93*(RRM[t][p])+ 2.45 + 5000*(2-Y0[t]-Y9[t]);

forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.82*(RRM[t][p])+ 26.69 + 5000*(2-Y0[t]-Y9[t]);

forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.45*(RRM[t][p])+ 151.18 + 5000*(2-Y0[t]-Y9[t]);

forall(t in CurrentTime:t==1)
      forall(p in Product)
            RFP[t][p]<=0.97*(RRM[t][p])+ 5000*(2-Y0[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.68*(RWIP[t-1]+RRM[t][p])+   68.32   +   5000*(2-
Y0[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.89*(RWIP[t-1]+RRM[t][p])+   9.62   +   5000*(2-
Y0[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.95*(RWIP[t-1]+RRM[t][p])+   0.25   +   5000*(2-
Y0[t]-Y9[t]);
```

```
     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.96*(RWIP[t-1]+RRM[t][p])-   0.29   +   5000*(2-
Y0[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.93*(RWIP[t-1]+RRM[t][p])+   2.45   +   5000*(2-
Y0[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.82*(RWIP[t-1]+RRM[t][p])+  26.69   +   5000*(2-
Y0[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.45*(RWIP[t-1]+RRM[t][p])+  151.18  +   5000*(2-
Y0[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
            RFP[t][p]<=0.97*(RWIP[t-1]+RRM[t][p])+       5000*(2-Y0[t]-
Y9[t]);
/*  Boundry  of  RMS  production  restricted  by  WIP  when  there  is
reconfiguration (one period) 100 to 200*/


     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.59*(RWIP[t-1]+RRM[t][p])+0.22*(CRFC[t])-19.61       +
5000*(2-Y1[t]-Y7[t]);

    forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.8*(RWIP[t-1]+RRM[t][p])+0.04*(CRFC[t])-7.41         +
5000*(2-Y1[t]-Y7[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.75*(RWIP[t-1]+RRM[t][p])+0.08*(CRFC[t])-11.47       +
5000*(2-Y1[t]-Y7[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.54*(RWIP[t-1]+RRM[t][p])+0.26*(CRFC[t])-21.39       +
5000*(2-Y1[t]-Y7[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.52*(RWIP[t-1]+RRM[t][p])+0.29*(CRFC[t])-22.77       +
5000*(2-Y1[t]-Y7[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
```

```
      RFP[t][p]<=0.85*(RWIP[t-1]+RRM[t][p])+0.01*(CRFC[t])-2.6         +
5000*(2-Y1[t]-Y7[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.73*(RWIP[t-1]+RRM[t][p])+0.09*(CRFC[t])-11.93       +
5000*(2-Y1[t]-Y7[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.85*(RWIP[t-1]+RRM[t][p])+0.01*(CRFC[t])-2.68        +
5000*(2-Y1[t]-Y7[t]);


     /*  Boundry  of  RMS  production  restricted  by  WIP  when  there  is
reconfiguration (first period) (one period) 100 to 200*/

      forall(p in Product)
      RFP[1][p]<=0.59*(RRM[1][p])+0.22*(CRFC[1])-19.61+5000*(2-Y1[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.8*(RRM[1][p])+0.04*(CRFC[1])-7.41+5000*(2-Y1[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.75*(RRM[1][p])+0.08*(CRFC[1])-11.47+5000*(2-Y1[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.54*(RRM[1][p])+0.26*(CRFC[1])-21.39+5000*(2-Y1[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.52*(RRM[1][p])+0.29*(CRFC[1])-22.77+5000*(2-Y1[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.85*(RRM[1][p])+0.01*(CRFC[1])-2.6+5000*(2-Y1[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.73*(RRM[1][p])+0.09*(CRFC[1])-11.93+5000*(2-Y1[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.85*(RRM[1][p])+0.01*(CRFC[1])-2.68+5000*(2-Y1[1]-
Y7[1]);

     /*  Boundry  of  RMS  production  restricted  by  WIP  when  there  is
reconfiguration (two period) 100 to 300*/


     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.63*(RWIP[t-1]+RRM[t][p])+0.23*(CRFC[t])-22.97       +
5000*(2-Y2[t]-Y8[t]);
```

```
     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.84*(RWIP[t-1]+RRM[t][p])+0.05*(CRFC[t])-9.27        +
5000*(2-Y2[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.82*(RWIP[t-1]+RRM[t][p])+0.07*(CRFC[t])-11.59       +
5000*(2-Y2[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.9*(RWIP[t-1]+RRM[t][p])+0.01*(CRFC[t])-3.68         +
5000*(2-Y2[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.57*(RWIP[t-1]+RRM[t][p])+0.3*(CRFC[t])-25.12        +
5000*(2-Y2[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.64*(RWIP[t-1]+RRM[t][p])+0.22*(CRFC[t])-22.05       +
5000*(2-Y2[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.9*(RWIP[t-1]+RRM[t][p])+0.01*(CRFC[t])-2.73         +
5000*(2-Y2[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.81*(RWIP[t-1]+RRM[t][p])+0.07*(CRFC[t])-11.44       +
5000*(2-Y2[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.45*(RWIP[t-1]+RRM[t][p])+0.41*(CRFC[t])-27.02       +
5000*(2-Y2[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.89*(RWIP[t-1]+RRM[t][p])+0.02*(CRFC[t])-5.39        +
5000*(2-Y2[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.74*(RWIP[t-1]+RRM[t][p])+0.14*(CRFC[t])-17.92       +
5000*(2-Y2[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.93*(RWIP[t-1]+RRM[t][p])-0.98    +    5000*(2-Y2[t]-
Y8[t]);
```

```
     /* Boundry of RMS production restricted by WIP when there is
reconfiguration (first period) (two period) 100 to 300*/

      forall(p in Product)
      RFP[1][p]<=0.63*(RRM[1][p])+0.23*(CRFC[1])-22.97+5000*(2-Y2[1]-
Y8[1]);

      forall(p in Product)
      RFP[1][p]<=0.84*(RRM[1][p])+0.05*(CRFC[1])-9.27+5000*(2-Y2[1]-
Y8[1]);

      forall(p in Product)
      RFP[1][p]<=0.82*(RRM[1][p])+0.07*(CRFC[1])-11.59+5000*(2-Y2[1]-
Y8[1]);

      forall(p in Product)
      RFP[1][p]<=0.9*(RRM[1][p])+0.01*(CRFC[1])-3.68+5000*(2-Y2[1]-
Y8[1]);

      forall(p in Product)
      RFP[1][p]<=0.57*(RRM[1][p])+0.3*(CRFC[1])-25.12+5000*(2-Y2[1]-
Y8[1]);

      forall(p in Product)
      RFP[1][p]<=0.64*(RRM[1][p])+0.22*(CRFC[1])-22.05+5000*(2-Y2[1]-
Y8[1]);

      forall(p in Product)
      RFP[1][p]<=0.9*(RRM[1][p])+0.01*(CRFC[1])-2.73+5000*(2-Y2[1]-
Y8[1]);

      forall(p in Product)
      RFP[1][p]<=0.81*(RRM[1][p])+0.07*(CRFC[1])-11.44+5000*(2-Y2[1]-
Y8[1]);

      forall(p in Product)
      RFP[1][p]<=0.45*(RRM[1][p])+0.41*(CRFC[1])-27.02+5000*(2-Y2[1]-
Y8[1]);

      forall(p in Product)
      RFP[1][p]<=0.89*(RRM[1][p])+0.02*(CRFC[1])-5.39+5000*(2-Y2[1]-
Y8[1]);

      forall(p in Product)
      RFP[1][p]<=0.74*(RRM[1][p])+0.14*(CRFC[1])-17.92+5000*(2-Y2[1]-
Y8[1]);

      forall(p in Product)
      RFP[1][p]<=0.93*(RRM[1][p])-0.98+5000*(2-Y2[1]-Y8[1]);

     /* Boundry of RMS production restricted by WIP when there is
reconfiguration (three period) 100 to 400*/

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.61*(RWIP[t-1]+RRM[t][p])+0.26*(CRFC[t])-24.91       +
5000*(2-Y3[t]-Y9[t]);
```

```
forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.62*(RWIP[t-1]+RRM[t][p])+0.26*(CRFC[t])-24.33        +
5000*(2-Y3[t]-Y9[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.81*(RWIP[t-1]+RRM[t][p])+0.09*(CRFC[t])-13.77        +
5000*(2-Y3[t]-Y9[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.83*(RWIP[t-1]+RRM[t][p])+0.08*(CRFC[t])-12.47        +
5000*(2-Y3[t]-Y9[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.91*(RWIP[t-1]+RRM[t][p])+0.02*(CRFC[t])-4.55         +
5000*(2-Y3[t]-Y9[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.9*(RWIP[t-1]+RRM[t][p])+0.02*(CRFC[t])-4.57          +
5000*(2-Y3[t]-Y9[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.6*(RWIP[t-1]+RRM[t][p])+0.27*(CRFC[t])-24.18         +
5000*(2-Y3[t]-Y9[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.92*(RWIP[t-1]+RRM[t][p])+0.01*(CRFC[t])-3.76         +
5000*(2-Y3[t]-Y9[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.89*(RWIP[t-1]+RRM[t][p])+0.04*(CRFC[t])-8.09         +
5000*(2-Y3[t]-Y9[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.78*(RWIP[t-1]+RRM[t][p])+0.12*(CRFC[t])-17.29        +
5000*(2-Y3[t]-Y9[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.86*(RWIP[t-1]+RRM[t][p])+0.05*(CRFC[t])-10.37        +
5000*(2-Y3[t]-Y9[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.84*(RWIP[t-1]+RRM[t][p])+0.06*(CRFC[t])-10.22        +
5000*(2-Y3[t]-Y9[t]);

forall(t in CurrentTime:t>=2)
```

```
      forall(p in Product)
      RFP[t][p]<=0.49*(RWIP[t-1]+RRM[t][p])+0.39*(CRFC[t])-28.17       +
5000*(2-Y3[t]-Y9[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.5*(RWIP[t-1]+RRM[t][p])+0.38*(CRFC[t])-28.01        +
5000*(2-Y3[t]-Y9[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.75*(RWIP[t-1]+RRM[t][p])+0.14*(CRFC[t])-18.21       +
5000*(2-Y3[t]-Y9[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.43*(RWIP[t-1]+RRM[t][p])+0.44*(CRFC[t])-28.27       +
5000*(2-Y3[t]-Y9[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.74*(RWIP[t-1]+RRM[t][p])+0.14*(CRFC[t])-17.19       +
5000*(2-Y3[t]-Y9[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.93*(RWIP[t-1]+RRM[t][p])-   0.93   +   5000*(2-Y3[t]-
Y9[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.94*(RWIP[t-1]+RRM[t][p])-   0.96   +   5000*(2-Y3[t]-
Y9[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.93*(RWIP[t-1]+RRM[t][p])-   0.95   +   5000*(2-Y3[t]-
Y9[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.94*(RWIP[t-1]+RRM[t][p])-   0.97   +   5000*(2-Y3[t]-
Y9[t]);

     /* Boundry of RMS production restricted by WIP when there is
reconfiguration (first period) (three period) 100 to 400*/

      forall(p in Product)
      RFP[1][p]<=0.61*(RRM[1][p])+0.26*(CRFC[1])-24.91+5000*(2-Y3[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.62*(RRM[1][p])+0.26*(CRFC[1])-24.33+5000*(2-Y3[1]-
Y9[1]);

forall(p in Product)
```

```
      RFP[1][p]<=0.81*(RRM[1][p])+0.09*(CRFC[1])-13.77+5000*(2-Y3[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.83*(RRM[1][p])+0.08*(CRFC[1])-12.47+5000*(2-Y3[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.91*(RRM[1][p])+0.02*(CRFC[1])-4.55+5000*(2-Y3[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.9*(RRM[1][p])+0.02*(CRFC[1])-4.57+5000*(2-Y3[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.6*(RRM[1][p])+0.27*(CRFC[1])-24.18+5000*(2-Y3[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.92*(RRM[1][p])+0.01*(CRFC[1])-3.76+5000*(2-Y3[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.89*(RRM[1][p])+0.04*(CRFC[1])-8.09+5000*(2-Y3[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.78*(RRM[1][p])+0.12*(CRFC[1])-17.29+5000*(2-Y3[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.86*(RRM[1][p])+0.05*(CRFC[1])-10.37+5000*(2-Y3[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.84*(RRM[1][p])+0.06*(CRFC[1])-10.22+5000*(2-Y3[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.49*(RRM[1][p])+0.39*(CRFC[1])-28.17+5000*(2-Y3[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.5*(RRM[1][p])+0.38*(CRFC[1])-28.01+5000*(2-Y3[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.75*(RRM[1][p])+0.14*(CRFC[1])-18.21+5000*(2-Y3[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.43*(RRM[1][p])+0.44*(CRFC[1])-28.27+5000*(2-Y3[1]-
Y9[1]);

forall(p in Product)
```

```
      RFP[1][p]<=0.74*(RRM[1][p])+0.14*(CRFC[1])-17.19+5000*(2-Y3[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.93*(RRM[1][p])-0.93+5000*(2-Y3[1]-Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.94*(RRM[1][p])-0.96+5000*(2-Y3[1]-Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.93*(RRM[1][p])-0.95+5000*(2-Y3[1]-Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.94*(RRM[1][p])-0.97+5000*(2-Y3[1]-Y9[1]);

     /* Boundry of RMS production restricted by WIP when there is
reconfiguration (one period) 200 to 300*/

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.69*(RWIP[t-1]+RRM[t][p])+0.19*(CRFC[t])-21.81 +
5000*(2-Y1[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.9*(RWIP[t-1]+RRM[t][p])+0.03*(CRFC[t])-6.36 +
5000*(2-Y1[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.81*(RWIP[t-1]+RRM[t][p])+0.09*(CRFC[t])-13.94 +
5000*(2-Y1[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.83*(RWIP[t-1]+RRM[t][p])+0.08*(CRFC[t])-13.34 +
5000*(2-Y1[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.57*(RWIP[t-1]+RRM[t][p])+0.31*(CRFC[t])-26.6 +
5000*(2-Y1[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.93*(RWIP[t-1]+RRM[t][p])+0.01*(CRFC[t])-2.8 +
5000*(2-Y1[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.92*(RWIP[t-1]+RRM[t][p])+0.01*(CRFC[t])-2.78 +
5000*(2-Y1[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.54*(RWIP[t-1]+RRM[t][p])+0.33*(CRFC[t])-26.81 +
5000*(2-Y1[t]-Y8[t]);
```

```
     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.94*(RWIP[t-1]+RRM[t][p])+ 5000*(2-Y1[t]-Y8[t]);

     /* Boundry of RMS production restricted by WIP when there is
reconfiguration (first period) (one period) 200 to 300*/

      forall(p in Product)
      RFP[1][p]<=0.69*(RRM[1][p])+0.19*(CRFC[1])-21.81+5000*(2-Y1[1]-
Y8[1]);

forall(p in Product)
      RFP[1][p]<=0.9*(RRM[1][p])+0.03*(CRFC[1])-6.36+5000*(2-Y1[1]-
Y8[1]);

forall(p in Product)
      RFP[1][p]<=0.81*(RRM[1][p])+0.09*(CRFC[1])-13.94+5000*(2-Y1[1]-
Y8[1]);

forall(p in Product)
      RFP[1][p]<=0.83*(RRM[1][p])+0.08*(CRFC[1])-13.34+5000*(2-Y1[1]-
Y8[1]);

forall(p in Product)
      RFP[1][p]<=0.57*(RRM[1][p])+0.31*(CRFC[1])-26.6+5000*(2-Y1[1]-
Y8[1]);

forall(p in Product)
      RFP[1][p]<=0.93*(RRM[1][p])+0.01*(CRFC[1])-2.8+5000*(2-Y1[1]-
Y8[1]);

forall(p in Product)
      RFP[1][p]<=0.92*(RRM[1][p])+0.01*(CRFC[1])-2.78+5000*(2-Y1[1]-
Y8[1]);

forall(p in Product)
      RFP[1][p]<=0.54*(RRM[1][p])+0.33*(CRFC[1])-26.81+5000*(2-Y1[1]-
Y8[1]);

forall(p in Product)
      RFP[1][p]<=0.94*(RRM[1][p])+5000*(2-Y1[1]-Y8[1]);

     /* Boundry of RMS production restricted by WIP when there is
reconfiguration (two period) 200 to 400*/

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.71*(RWIP[t-1]+RRM[t][p])+0.2*(CRFC[t])-23.55        +
5000*(2-Y2[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.91*(RWIP[t-1]+RRM[t][p])+0.03*(CRFC[t])-8.26        +
5000*(2-Y2[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
```

```
      forall(p in Product)
      RFP[t][p]<=0.94*(RWIP[t-1]+RRM[t][p])+0.01*(CRFC[t])-3.81         +
5000*(2-Y2[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.73*(RWIP[t-1]+RRM[t][p])+0.18*(CRFC[t])-22.02        +
5000*(2-Y2[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.87*(RWIP[t-1]+RRM[t][p])+0.06*(CRFC[t])-12.19        +
5000*(2-Y2[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.95*(RWIP[t-1]+RRM[t][p])+0.01*(CRFC[t])-2.88         +
5000*(2-Y2[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.62*(RWIP[t-1]+RRM[t][p])+0.28*(CRFC[t])-26.9         +
5000*(2-Y2[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.88*(RWIP[t-1]+RRM[t][p])+0.05*(CRFC[t])-10.54        +
5000*(2-Y2[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.49*(RWIP[t-1]+RRM[t][p])+0.41*(CRFC[t])-29.64        +
5000*(2-Y2[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.96*(RWIP[t-1]+RRM[t][p])-0.96    +    5000*(2-Y2[t]-
Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.92*(RWIP[t-1]+RRM[t][p])+0.02*(CRFC[t])-6.47         +
5000*(2-Y2[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.96*(RWIP[t-1]+RRM[t][p])-0.99    +    5000*(2-Y2[t]-
Y9[t]);

     /*  Boundry  of  RMS  production  restricted  by  WIP  when  there  is
reconfiguration (first period) (two period) 200 to 400*/

      forall(p in Product)
      RFP[1][p]<=0.71*(RRM[1][p])+0.2*(CRFC[1])-23.55+5000*(2-Y2[1]-
Y9[1]);

forall(p in Product)
```

```
      RFP[1][p]<=0.91*(RRM[1][p])+0.03*(CRFC[1])-8.26+5000*(2-Y2[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.94*(RRM[1][p])+0.01*(CRFC[1])-3.81+5000*(2-Y2[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.73*(RRM[1][p])+0.18*(CRFC[1])-22.02+5000*(2-Y2[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.87*(RRM[1][p])+0.06*(CRFC[1])-12.19+5000*(2-Y2[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.95*(RRM[1][p])+0.01*(CRFC[1])-2.88+5000*(2-Y2[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.62*(RRM[1][p])+0.28*(CRFC[1])-26.9+5000*(2-Y2[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.88*(RRM[1][p])+0.05*(CRFC[1])-10.54+5000*(2-Y2[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.49*(RRM[1][p])+0.41*(CRFC[1])-29.64+5000*(2-Y2[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.96*(RRM[1][p])-0.96+5000*(2-Y2[1]-Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.92*(RRM[1][p])+0.02*(CRFC[1])-6.47+5000*(2-Y2[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.96*(RRM[1][p])-0.99+5000*(2-Y2[1]-Y9[1]);

     /*  Boundry  of  RMS  production  restricted  by  WIP  when  there  is
reconfiguration (one period) 300 to 400*/

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.78*(RWIP[t-1]+RRM[t][p])+0.15*(CRFC[t])-20.24       +
5000*(2-Y1[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.94*(RWIP[t-1]+RRM[t][p])+0.02*(CRFC[t])-4.72        +
5000*(2-Y1[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
```

```
      RFP[t][p]<=0.88*(RWIP[t-1]+RRM[t][p])+0.06*(CRFC[t])-11.46        +
5000*(2-Y1[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.89*(RWIP[t-1]+RRM[t][p])+0.05*(CRFC[t])-10.74        +
5000*(2-Y1[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.63*(RWIP[t-1]+RRM[t][p])+0.28*(CRFC[t])-27.6         +
5000*(2-Y1[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.61*(RWIP[t-1]+RRM[t][p])+0.3*(CRFC[t])-27.39         +
5000*(2-Y1[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.95*(RWIP[t-1]+RRM[t][p])+0.01*(CRFC[t])-2.9          +
5000*(2-Y1[t]-Y9[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.96*(RWIP[t-1]+RRM[t][p])+0.01*(CRFC[t])-1.92         +
5000*(2-Y1[t]-Y9[t]);

     /*  Boundry  of  RMS  production  restricted  by  WIP  when  there  is
reconfiguration (first period) (one period) 300 to 400*/

      forall(p in Product)
      RFP[1][p]<=0.78*(RRM[1][p])+0.15*(CRFC[1])-20.24+5000*(2-Y1[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.94*(RRM[1][p])+0.02*(CRFC[1])-4.72+5000*(2-Y1[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.88*(RRM[1][p])+0.06*(CRFC[1])-11.46+5000*(2-Y1[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.89*(RRM[1][p])+0.05*(CRFC[1])-10.74+5000*(2-Y1[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.63*(RRM[1][p])+0.28*(CRFC[1])-27.6+5000*(2-Y1[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.61*(RRM[1][p])+0.3*(CRFC[1])-27.39+5000*(2-Y1[1]-
Y9[1]);

forall(p in Product)
```

```
      RFP[1][p]<=0.95*(RRM[1][p])+0.01*(CRFC[1])-2.9+5000*(2-Y1[1]-
Y9[1]);

forall(p in Product)
      RFP[1][p]<=0.96*(RRM[1][p])+0.01*(CRFC[1])-1.92+5000*(2-Y1[1]-
Y9[1]);

     /*  Boundry  of  RMS  production  restricted  by  WIP  when  there  is
reconfiguration (one period) 200 to 100*/


     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.44*(RWIP[t-1]+RRM[t][p])+0.23*(CRFC[t])-15.66       +
5000*(2-Y1[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.6*(RWIP[t-1]+RRM[t][p])+0.07*(CRFC[t])-6.77         +
5000*(2-Y1[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.57*(RWIP[t-1]+RRM[t][p])+0.11*(CRFC[t])-10.06       +
5000*(2-Y1[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.41*(RWIP[t-1]+RRM[t][p])+0.28*(CRFC[t])-17.41       +
5000*(2-Y1[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.45*(RWIP[t-1]+RRM[t][p])+0.21*(CRFC[t])-14.42       +
5000*(2-Y1[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.68*(RWIP[t-1]+RRM[t][p])+0.02*(CRFC[t])-3.01        +
5000*(2-Y1[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.65*(RWIP[t-1]+RRM[t][p])+0.02*(CRFC[t])-2.82        +
5000*(2-Y1[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.34*(RWIP[t-1]+RRM[t][p])+0.33*(CRFC[t])-17.61       +
5000*(2-Y1[t]-Y6[t]);

/*  Boundry  of  RMS  production  restricted  by  WIP  when  there  is
reconfiguration (first period) (one period) 200 to 100*/

      forall(p in Product)
      RFP[1][p]<=0.44*(RRM[1][p])+0.23*(CRFC[1])-15.66+5000*(2-Y1[1]-
Y6[1]);
```

```
forall(p in Product)
      RFP[1][p]<=0.6*(RRM[1][p])+0.07*(CRFC[1])-6.77+5000*(2-Y1[1]-
Y6[1]);

forall(p in Product)
      RFP[1][p]<=0.57*(RRM[1][p])+0.11*(CRFC[1])-10.06+5000*(2-Y1[1]-
Y6[1]);

forall(p in Product)
      RFP[1][p]<=0.41*(RRM[1][p])+0.28*(CRFC[1])-17.41+5000*(2-Y1[1]-
Y6[1]);

forall(p in Product)
      RFP[1][p]<=0.45*(RRM[1][p])+0.21*(CRFC[1])-14.42+5000*(2-Y1[1]-
Y6[1]);

forall(p in Product)
      RFP[1][p]<=0.68*(RRM[1][p])+0.02*(CRFC[1])-3.01+5000*(2-Y1[1]-
Y6[1]);

forall(p in Product)
      RFP[1][p]<=0.65*(RRM[1][p])+0.02*(CRFC[1])-2.82+5000*(2-Y1[1]-
Y6[1]);

forall(p in Product)
      RFP[1][p]<=0.34*(RRM[1][p])+0.33*(CRFC[1])-17.61+5000*(2-Y1[1]-
Y6[1]);

/* Boundry of RMS production restricted by WIP when there is
reconfiguration (two period) 300 to 100*/

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.5*(RWIP[t-1]+RRM[t][p])+0.24*(CRFC[t])-18.4 +
5000*(2-Y2[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.68*(RWIP[t-1]+RRM[t][p])+0.08*(CRFC[t])-8.23 +
5000*(2-Y2[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.48*(RWIP[t-1]+RRM[t][p])+0.28*(CRFC[t])-20.57 +
5000*(2-Y2[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.68*(RWIP[t-1]+RRM[t][p])+0.09*(CRFC[t])-10.38 +
5000*(2-Y2[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.78*(RWIP[t-1]+RRM[t][p])+0.02*(CRFC[t])-4.08 +
5000*(2-Y2[t]-Y6[t]);
```

```
forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.51*(RWIP[t-1]+RRM[t][p])+0.22*(CRFC[t])-16.57       +
5000*(2-Y2[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.74*(RWIP[t-1]+RRM[t][p])+0.02*(CRFC[t])-3.06        +
5000*(2-Y2[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.39*(RWIP[t-1]+RRM[t][p])+0.35*(CRFC[t])-20.54       +
5000*(2-Y2[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.61*(RWIP[t-1]+RRM[t][p])+0.16*(CRFC[t])-15.5        +
5000*(2-Y2[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.79*(RWIP[t-1]+RRM[t][p])+0.01*(CRFC[t])-1.78        +
5000*(2-Y2[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.38*(RWIP[t-1]+RRM[t][p])+0.38*(CRFC[t])-21.59       +
5000*(2-Y2[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.63*(RWIP[t-1]+RRM[t][p])+0.1*(CRFC[t])-10.41        +
5000*(2-Y2[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.39*(RWIP[t-1]+RRM[t][p])+0.39*(CRFC[t])-23.4        +
5000*(2-Y2[t]-Y6[t]);

/*  Boundry  of  RMS  production  restricted  by  WIP  when  there  is
reconfiguration (first period) (two period) 300 to 100*/

forall(p in Product)
      RFP[1][p]<=0.5*(RRM[1][p])+0.24*(CRFC[1])-18.4+5000*(2-Y2[1]-
Y6[1]);

forall(p in Product)
      RFP[1][p]<=0.68*(RRM[1][p])+0.08*(CRFC[1])-8.23+5000*(2-Y2[1]-
Y6[1]);

forall(p in Product)
      RFP[1][p]<=0.48*(RRM[1][p])+0.28*(CRFC[1])-20.57+5000*(2-Y2[1]-
Y6[1]);

forall(p in Product)
```

```
      RFP[1][p]<=0.68*(RRM[1][p])+0.09*(CRFC[1])-10.38+5000*(2-Y2[1]-
Y6[1]);

forall(p in Product)
      RFP[1][p]<=0.78*(RRM[1][p])+0.02*(CRFC[1])-4.08+5000*(2-Y2[1]-
Y6[1]);

forall(p in Product)
      RFP[1][p]<=0.51*(RRM[1][p])+0.22*(CRFC[1])-16.57+5000*(2-Y2[1]-
Y6[1]);

forall(p in Product)
      RFP[1][p]<=0.74*(RRM[1][p])+0.02*(CRFC[1])-3.06+5000*(2-Y2[1]-
Y6[1]);

forall(p in Product)
      RFP[1][p]<=0.39*(RRM[1][p])+0.35*(CRFC[1])-20.54+5000*(2-Y2[1]-
Y6[1]);

forall(p in Product)
      RFP[1][p]<=0.61*(RRM[1][p])+0.16*(CRFC[1])-15.5+5000*(2-Y2[1]-
Y6[1]);

forall(p in Product)
      RFP[1][p]<=0.79*(RRM[1][p])+0.01*(CRFC[1])-1.78+5000*(2-Y2[1]-
Y6[1]);

forall(p in Product)
      RFP[1][p]<=0.38*(RRM[1][p])+0.38*(CRFC[1])-21.59+5000*(2-Y2[1]-
Y6[1]);

forall(p in Product)
      RFP[1][p]<=0.63*(RRM[1][p])+0.1*(CRFC[1])-10.41+5000*(2-Y2[1]-
Y6[1]);

forall(p in Product)
      RFP[1][p]<=0.39*(RRM[1][p])+0.39*(CRFC[1])-23.4+5000*(2-Y2[1]-
Y6[1]);

/*  Boundry  of  RMS  production  restricted  by  WIP  when  there  is
reconfiguration (three period) 400 to 100*/

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.56*(RWIP[t-1]+RRM[t][p])+0.27*(CRFC[t])-22.7        +
5000*(2-Y3[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.56*(RWIP[t-1]+RRM[t][p])+0.28*(CRFC[t])-23.49       +
5000*(2-Y3[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.73*(RWIP[t-1]+RRM[t][p])+0.11*(CRFC[t])-14.03       +
5000*(2-Y3[t]-Y6[t]);
```

```
forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.76*(RWIP[t-1]+RRM[t][p])+0.1*(CRFC[t])-13.83        +
5000*(2-Y3[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.85*(RWIP[t-1]+RRM[t][p])+0.03*(CRFC[t])-5.15        +
5000*(2-Y3[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.53*(RWIP[t-1]+RRM[t][p])+0.29*(CRFC[t])-22.12       +
5000*(2-Y3[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.84*(RWIP[t-1]+RRM[t][p])+0.02*(CRFC[t])-4.23        +
5000*(2-Y3[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.86*(RWIP[t-1]+RRM[t][p])+0.03*(CRFC[t])-5.23        +
5000*(2-Y3[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.71*(RWIP[t-1]+RRM[t][p])+0.15*(CRFC[t])-17.08       +
5000*(2-Y3[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.89*(RWIP[t-1]+RRM[t][p])+0.01*(CRFC[t])-1.83        +
5000*(2-Y3[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.78*(RWIP[t-1]+RRM[t][p])+0.08*(CRFC[t])-11.86       +
5000*(2-Y3[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.46*(RWIP[t-1]+RRM[t][p])+0.37*(CRFC[t])-25.11       +
5000*(2-Y3[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.48*(RWIP[t-1]+RRM[t][p])+0.36*(CRFC[t])-26.37       +
5000*(2-Y3[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.88*(RWIP[t-1]+RRM[t][p])+0.01*(CRFC[t])-1.86        +
5000*(2-Y3[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
```

```
      RFP[t][p]<=0.76*(RWIP[t-1]+RRM[t][p])+0.08*(CRFC[t])-10.91       +
5000*(2-Y3[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.82*(RWIP[t-1]+RRM[t][p])+0.06*(CRFC[t])-9.84        +
5000*(2-Y3[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.65*(RWIP[t-1]+RRM[t][p])+0.19*(CRFC[t])-19.15       +
5000*(2-Y3[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.41*(RWIP[t-1]+RRM[t][p])+0.41*(CRFC[t])-25.08       +
5000*(2-Y3[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.64*(RWIP[t-1]+RRM[t][p])+0.17*(CRFC[t])-17.62       +
5000*(2-Y3[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.9*(RWIP[t-1]+RRM[t][p])-0.91 + 5000*(2-Y3[t]-Y6[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.87*(RWIP[t-1]+RRM[t][p])-0.92+ 5000*(2-Y3[t]-Y6[t]);

/*  Boundry  of  RMS  production  restricted  by  WIP  when  there  is
reconfiguration (first period) (three period) 400 to 100*/

      forall(p in Product)
      RFP[1][p]<=0.56*(RRM[1][p])+0.27*(CRFC[1])-22.7+5000*(2-Y3[1]-
Y6[1]);

      forall(p in Product)
      RFP[1][p]<=0.56*(RRM[1][p])+0.28*(CRFC[1])-23.49+5000*(2-Y3[1]-
Y6[1]);

      forall(p in Product)
      RFP[1][p]<=0.73*(RRM[1][p])+0.11*(CRFC[1])-14.03+5000*(2-Y3[1]-
Y6[1]);

      forall(p in Product)
      RFP[1][p]<=0.76*(RRM[1][p])+0.1*(CRFC[1])-13.83+5000*(2-Y3[1]-
Y6[1]);

      forall(p in Product)
      RFP[1][p]<=0.85*(RRM[1][p])+0.03*(CRFC[1])-5.15+5000*(2-Y3[1]-
Y6[1]);

      forall(p in Product)
      RFP[1][p]<=0.53*(RRM[1][p])+0.29*(CRFC[1])-22.12+5000*(2-Y3[1]-
Y6[1]);
```

```
      forall(p in Product)
      RFP[1][p]<=0.84*(RRM[1][p])+0.02*(CRFC[1])-4.23+5000*(2-Y3[1]-
Y6[1]);

      forall(p in Product)
      RFP[1][p]<=0.86*(RRM[1][p])+0.03*(CRFC[1])-5.23+5000*(2-Y3[1]-
Y6[1]);

      forall(p in Product)
      RFP[1][p]<=0.71*(RRM[1][p])+0.15*(CRFC[1])-17.08+5000*(2-Y3[1]-
Y6[1]);

      forall(p in Product)
      RFP[1][p]<=0.89*(RRM[1][p])+0.01*(CRFC[1])-1.83+5000*(2-Y3[1]-
Y6[1]);

      forall(p in Product)
      RFP[1][p]<=0.78*(RRM[1][p])+0.08*(CRFC[1])-11.86+5000*(2-Y3[1]-
Y6[1]);

      forall(p in Product)
      RFP[1][p]<=0.46*(RRM[1][p])+0.37*(CRFC[1])-25.11+5000*(2-Y3[1]-
Y6[1]);

      forall(p in Product)
      RFP[1][p]<=0.48*(RRM[1][p])+0.36*(CRFC[1])-26.37+5000*(2-Y3[1]-
Y6[1]);

      forall(p in Product)
      RFP[1][p]<=0.88*(RRM[1][p])+0.01*(CRFC[1])-1.86+5000*(2-Y3[1]-
Y6[1]);

      forall(p in Product)
      RFP[1][p]<=0.76*(RRM[1][p])+0.08*(CRFC[1])-10.91+5000*(2-Y3[1]-
Y6[1]);

      forall(p in Product)
      RFP[1][p]<=0.82*(RRM[1][p])+0.06*(CRFC[1])-9.84+5000*(2-Y3[1]-
Y6[1]);

      forall(p in Product)
      RFP[1][p]<=0.65*(RRM[1][p])+0.19*(CRFC[1])-19.15+5000*(2-Y3[1]-
Y6[1]);

      forall(p in Product)
      RFP[1][p]<=0.41*(RRM[1][p])+0.41*(CRFC[1])-25.08+5000*(2-Y3[1]-
Y6[1]);

      forall(p in Product)
      RFP[1][p]<=0.64*(RRM[1][p])+0.17*(CRFC[1])-17.62+5000*(2-Y3[1]-
Y6[1]);

      forall(p in Product)
      RFP[1][p]<=0.9*(RRM[1][p])-0.91+5000*(2-Y3[1]-Y6[1]);

      forall(p in Product)
```

```
      RFP[1][p]<=0.87*(RRM[1][p])-0.92+5000*(2-Y3[1]-Y6[1]);

/* Boundry of RMS production restricted by WIP when there is
reconfiguration (one period) 300 to 200*/

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.62*(RWIP[t-1]+RRM[t][p])+0.22*(CRFC[t])-20.55        +
5000*(2-Y1[t]-Y7[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.83*(RWIP[t-1]+RRM[t][p])+0.04*(CRFC[t])-6.75         +
5000*(2-Y1[t]-Y7[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.72*(RWIP[t-1]+RRM[t][p])+0.12*(CRFC[t])-15.31        +
5000*(2-Y1[t]-Y7[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.56*(RWIP[t-1]+RRM[t][p])+0.27*(CRFC[t])-22.94        +
5000*(2-Y1[t]-Y7[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.79*(RWIP[t-1]+RRM[t][p])+0.07*(CRFC[t])-10.33        +
5000*(2-Y1[t]-Y7[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.48*(RWIP[t-1]+RRM[t][p])+0.34*(CRFC[t])-24.36        +
5000*(2-Y1[t]-Y7[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.86*(RWIP[t-1]+RRM[t][p])+0.02*(CRFC[t])-3.47         +
5000*(2-Y1[t]-Y7[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.88*(RWIP[t-1]+RRM[t][p])+0.01*(CRFC[t])-1.8          +
5000*(2-Y1[t]-Y7[t]);

/* Boundry of RMS production restricted by WIP when there is
reconfiguration (first period) (three period) 300 to 200*/

forall(p in Product)
      RFP[1][p]<=0.62*(RRM[1][p])+0.22*(CRFC[1])-20.55+5000*(2-Y1[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.83*(RRM[1][p])+0.04*(CRFC[1])-6.75+5000*(2-Y1[1]-
Y7[1]);

forall(p in Product)
```

```
      RFP[1][p]<=0.72*(RRM[1][p])+0.12*(CRFC[1])-15.31+5000*(2-Y1[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.56*(RRM[1][p])+0.27*(CRFC[1])-22.94+5000*(2-Y1[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.79*(RRM[1][p])+0.07*(CRFC[1])-10.33+5000*(2-Y1[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.48*(RRM[1][p])+0.34*(CRFC[1])-24.36+5000*(2-Y1[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.86*(RRM[1][p])+0.02*(CRFC[1])-3.47+5000*(2-Y1[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.88*(RRM[1][p])+0.01*(CRFC[1])-1.8+5000*(2-Y1[1]-
Y7[1]);

/*  Boundry  of  RMS  production  restricted  by  WIP  when  there  is
reconfiguration (two period) 400 to 200*/

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.62*(RWIP[t-1]+RRM[t][p])+0.23*(CRFC[t])-22.6        +
5000*(2-Y2[t]-Y7[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.84*(RWIP[t-1]+RRM[t][p])+0.05*(CRFC[t])-8.41        +
5000*(2-Y2[t]-Y7[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.59*(RWIP[t-1]+RRM[t][p])+0.26*(CRFC[t])-24.03       +
5000*(2-Y2[t]-Y7[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.82*(RWIP[t-1]+RRM[t][p])+0.07*(CRFC[t])-10.69       +
5000*(2-Y2[t]-Y7[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.9*(RWIP[t-1]+RRM[t][p])+0.01*(CRFC[t])-3.7          +
5000*(2-Y2[t]-Y7[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.71*(RWIP[t-1]+RRM[t][p])+0.15*(CRFC[t])-17.87       +
5000*(2-Y2[t]-Y7[t]);

     forall(t in CurrentTime:t>=2)
```

```
      forall(p in Product)
      RFP[t][p]<=0.89*(RWIP[t-1]+RRM[t][p])+0.01*(CRFC[t])-2.68        +
5000*(2-Y2[t]-Y7[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.49*(RWIP[t-1]+RRM[t][p])+0.36*(CRFC[t])-26.25       +
5000*(2-Y2[t]-Y7[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.82*(RWIP[t-1]+RRM[t][p])+0.06*(CRFC[t])-9.09        +
5000*(2-Y2[t]-Y7[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.75*(RWIP[t-1]+RRM[t][p])+0.13*(CRFC[t])-16.61       +
5000*(2-Y2[t]-Y7[t]);

forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.41*(RWIP[t-1]+RRM[t][p])+0.44*(CRFC[t])-27.69       +
5000*(2-Y2[t]-Y7[t]);

      forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.92*(RWIP[t-1]+RRM[t][p])+ 5000*(2-Y2[t]-Y7[t]);

/*  Boundry  of  RMS  production  restricted  by  WIP  when  there  is
reconfiguration (first period) (two period) 400 to 200*/

forall(p in Product)
      RFP[1][p]<=0.62*(RRM[1][p])+0.23*(CRFC[1])-22.6+5000*(2-Y2[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.84*(RRM[1][p])+0.05*(CRFC[1])-8.41+5000*(2-Y2[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.59*(RRM[1][p])+0.26*(CRFC[1])-24.03+5000*(2-Y2[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.82*(RRM[1][p])+0.07*(CRFC[1])-10.69+5000*(2-Y2[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.9*(RRM[1][p])+0.01*(CRFC[1])-3.7+5000*(2-Y2[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.71*(RRM[1][p])+0.15*(CRFC[1])-17.87+5000*(2-Y2[1]-
Y7[1]);

forall(p in Product)
```

```
      RFP[1][p]<=0.89*(RRM[1][p])+0.01*(CRFC[1])-2.68+5000*(2-Y2[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.49*(RRM[1][p])+0.36*(CRFC[1])-26.25+5000*(2-Y2[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.82*(RRM[1][p])+0.06*(CRFC[1])-9.09+5000*(2-Y2[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.75*(RRM[1][p])+0.13*(CRFC[1])-16.61+5000*(2-Y2[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.41*(RRM[1][p])+0.44*(CRFC[1])-27.69+5000*(2-Y2[1]-
Y7[1]);

forall(p in Product)
      RFP[1][p]<=0.92*(RRM[1][p])+5000*(2-Y2[1]-Y7[1]);

/*  Boundry  of  RMS  production  restricted  by  WIP  when  there  is
reconfiguration (one period) 400 to 300*/

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.71*(RWIP[t-1]+RRM[t][p])+0.18*(CRFC[t])-21.49       +
5000*(2-Y1[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.91*(RWIP[t-1]+RRM[t][p])+0.02*(CRFC[t])-5.46        +
5000*(2-Y1[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.83*(RWIP[t-1]+RRM[t][p])+0.08*(CRFC[t])-13.36       +
5000*(2-Y1[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.84*(RWIP[t-1]+RRM[t][p])+0.07*(CRFC[t])-12.69       +
5000*(2-Y1[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.57*(RWIP[t-1]+RRM[t][p])+0.31*(CRFC[t])-26.49       +
5000*(2-Y1[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.93*(RWIP[t-1]+RRM[t][p])+0.01*(CRFC[t])-2.8         +
5000*(2-Y1[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
```

```
      RFP[t][p]<=0.93*(RWIP[t-1]+RRM[t][p])+0.01*(CRFC[t])-2.82        +
5000*(2-Y1[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.56*(RWIP[t-1]+RRM[t][p])+0.32*(CRFC[t])-26.51       +
5000*(2-Y1[t]-Y8[t]);

     forall(t in CurrentTime:t>=2)
      forall(p in Product)
      RFP[t][p]<=0.95*(RWIP[t-1]+RRM[t][p])+ 5000*(2-Y1[t]-Y8[t]);

/*  Boundry  of  RMS  production  restricted  by  WIP  when  there  is
reconfiguration (first period) (one period) 400 to 300*/

      forall(p in Product)
      RFP[1][p]<=0.71*(RRM[1][p])+0.18*(CRFC[1])-21.49+5000*(2-Y1[1]-
Y8[1]);

forall(p in Product)
      RFP[1][p]<=0.91*(RRM[1][p])+0.02*(CRFC[1])-5.46+5000*(2-Y1[1]-
Y8[1]);

forall(p in Product)
      RFP[1][p]<=0.83*(RRM[1][p])+0.08*(CRFC[1])-13.36+5000*(2-Y1[1]-
Y8[1]);

forall(p in Product)
      RFP[1][p]<=0.84*(RRM[1][p])+0.07*(CRFC[1])-12.69+5000*(2-Y1[1]-
Y8[1]);

forall(p in Product)
      RFP[1][p]<=0.57*(RRM[1][p])+0.31*(CRFC[1])-26.49+5000*(2-Y1[1]-
Y8[1]);

forall(p in Product)
      RFP[1][p]<=0.93*(RRM[1][p])+0.01*(CRFC[1])-2.8+5000*(2-Y1[1]-
Y8[1]);

forall(p in Product)
      RFP[1][p]<=0.93*(RRM[1][p])+0.01*(CRFC[1])-2.82+5000*(2-Y1[1]-
Y8[1]);

forall(p in Product)
      RFP[1][p]<=0.56*(RRM[1][p])+0.32*(CRFC[1])-26.51+5000*(2-Y1[1]-
Y8[1]);

forall(p in Product)
      RFP[1][p]<=0.95*(RRM[1][p])+5000*(2-Y1[1]-Y8[1]);


  }

  /* Extra Constraints */

  subject to {
             URC[0]==0;
```

```
           LRC[0]==0;
           IRFC[0]==100;
           CRFC[0]==100;
           forall (p in Product)
           DFP[0][p]==0;
           forall (p in Product)
           RFP[0][p]==0;
            forall (p in Product)
           RRM[0][p]==0;
           forall (p in Product)
           DRM[0][p]==0;

}
```