Effect of System Configuration and Ramp up Time on Manufacturing System Acquisition under Uncertain Demand

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Abstract

The increasing frequency of new product introductions force today's companies to continuously upgrade their production capacities and system configuration. 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 paper aims to explore how a firm should optimally allocate its capacity investments among Dedicated Manufacturing Systems (DMS) and Reconfigurable Manufacturing Systems (RMS), considering the capacity evolution in ramp up period. We propose a mixed integer programming model that grasps various ramp up time patterns and takes into account RMS and DMS scalability lead time. We aim to see how capacity is allocated to RMS and DMS based on system cost, system responsiveness, and reconfiguration speed.

Keywords
Capacity management, Ramp up, system responsiveness, reconfiguration speed

1. Introduction

Manufacturing paradigm has shown rapid changes in the past decades due to an aggressive market competition on a global scale. From Dedicated Manufacturing Systems (DMS) to Flexible Manufacturing Systems (FMS), each paradigm provides economic benefits by exploiting product variety or production volume characteristics of a market. Dedicated systems are capable of producing one product type with a higher rate of production. Higher rate of production provides the advantage of economies of scale and helps the firms to reduce their production cost. On the other hand, FMS gives firms the ability to produce multiple product types albeit with a slower rate of production. When the market is competitive, requiring a variety of products, FMS gives firms the advantage of economies of scope. However, high initial investment and lack of hardware changeability of FMS cause manufacturers to look for a system that could accommodate an incremental increase in the capacity of their existing production system rather than the extra functionality delivered by FMS and avoid the underutilization of purchased capability. To cope with this limitation, Reconfigurable Manufacturing System (RMS) proposes acceptable lead time for launching and integrating new technologies while having the capability to upgrade to new functionality. The modular software and hardware structure of RMS allows for the ease of reconfiguration as a strategy to adapt to market demands. Thus, RMS incorporates the advantages of both DMS and FMS and occupies a middle ground between dedicated transfer lines and FMS in terms of production quantity and variety.

The focused flexibility and agility are the premises of RMS in responding to unexpected market changes quickly. In achieving the benefits of agility, 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. Therefore, while selecting the manufacturing system alternatives, one should consider the impact of reconfiguration and the relevant RMS cost structure. As well, reconfiguration period is affected by RMS layout characteristics. Selecting different RMS configurations may affect capacity and service level. Thus, the evolution of capacity during ramp up depends on both RMS layout configuration and RMS reconfiguration speed.

In this paper, we develop a decision model based on Dedicated and Reconfigurable manufacturing system characteristics to address how various RMS reconfigurations affect responsiveness (i.e. customer service level). The ramp up time and reconfiguration period of RMS are incorporated in the model as a function of the amount of added
or removed capacity. Finally, through an analysis of product shortage cost and capacity excess cost, we examine
how capacity portfolio of manufacturing systems change.

The paper outline is as follows: Section 2 reviews the relevant literature. The problem description is presented along
with the assumptions and parameters in section 3. In section 4, we explain the proposed methodology. Numerical
results are discussed in section 5. Conclusion is presented in section 6.

2. Literature Review

Capacity planning and management usually consists of determining the type of production systems as well as
capacity expansion/contraction times. Luss (1982) categorizes the major factors affecting the capacity management
as size, time, location, cost, demand, differing expansion, decision maker constraints, and capacity modification.
With the increasing volatility of demand and more frequent product introductions, capacity planning becomes even
more important for capital intensive industries. This problem can be analyzed at the strategic, tactical, and
operational levels (Wu et al. (2005)). While the strategic level approach focuses on capacity investment decisions
from the supply chain perspective and strategic interactions between two or more players, the operational level
focuses on product and firm-specific operational environment.

Dedicated and Reconfigurable systems represent different characteristics in terms of scalability, especially from the
perspective of lead time during capacity changes. 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, we focus on the tactical level analysis of capacity planning
from a firm’s perspective by differentiating capacity types such as Dedicated and Reconfigurable Systems. In this
section, we review the literature on capacity planning models that incorporate the lead time behavior and capacity
scalability at strategic, tactical, and operational levels.

At the strategic level, 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 the relative costs of each, considering the frequency of new products to market and the
stochastic nature of demand level. They argue that ISD 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 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 works 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 Dedicated and Flexible Manufacturing Systems which have different scalabilities.
Authors analyze multiple products’ demand for three consecutive periods using stochastic programming 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.

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.
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. Therefore, the selection of a good and reliable configuration is a must for manufacturer
which affects the life cycle cost of the manufacturing system. Abdi (2009) investigates the criteria which influence
the selection of an 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 1). The solution of the model, which is sensitive to firm priority, could reveal the best layout re-configurability.

![Diagram of RMS layout configuration](image)

Figure 1: RMS layout configuration

The initial configuration of the system has a major effect on the system adjustment step size and its cost. Therefore, the ramp up time depends on system responsiveness and its configuration. In order to incorporate the impact of configuration characteristics on the capacity selection at the tactical level, we take different ramp up patterns into account and analyze how initial configuration of a system could affect service level and capacity evolution. The proposed work sets itself apart from the earlier works by integrating the ramp up and configuration effect into the tactical level planning of capacity selection. For example, in a pure parallel RMS configuration, system capacity could follow market trend closely by a small increments. On the other hand, in serial configuration, capacity update lasts longer, which causes low service levels (Abdi 2009). Therefore, the system will reach to the new capacity level asymptotically depending on the configuration.

In order to analyze this impact, we develop a Mixed Integer Programming (MIP) model that grasps the configuration of RMS and DMS. The proposed MIP model considers reconfiguration of both RMS and DMS, ramp up period evolution, availability of new capacity, and the effect of reconfiguration speed and response range on serviceability in multi-period planning horizon. As a result, we analyze how reconfiguration pattern, ramp up speed, and RMS range of response could improve service level.

3. Capacity portfolio selection problem

In the context of this paper we assume that a company produces one product called (A), and the company anticipates that a new product (B) will emerge some time in future. Within the planned time horizon of T, 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, we assume the DMS scalability is low and DMS is configured in series. It can efficiently produce only one product at a time and it requires a longer reconfiguration time. RMS is able to produce multiple product family with higher scalability. However, depending on RMS layout, the scalability level varies. When RMS is designed towards a parallel configuration, the scalability of RMS increases but the system becomes more expensive (Abdi 2009).

Figure 2 represents the capacity evolution of different configurations during a reconfiguration period. The first plot represents the series configuration that costs less but it takes a longer time for the 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 system capacity which is a parallel-series configuration with an increased number of parallel stages. A pure parallel configuration is represented with the fourth plot. A higher share of capacity is available during reconfiguration period, however; the system configuration is more expensive (Koren et al 1998).

By modeling this reconfiguration pattern behavior, we aim to see how system configuration could benefit the decision maker to provide highest service level with optimal level of capacity. In the proposed model, the cost of product shortage, excess capacity cost, technology acquisition cost, and reconfiguration cost are considered as the main concerns of the decision maker.
3.1 Problem assumption and parameters

The capacity characteristic of Dedicated Technology is assumed to provide a large scale capacity just for one product family. The unit purchasing cost of DMS is less than RMS as a result of economies of scale. We assume DMS reconfiguration lasts a fixed period of time and added capacity is not available during reconfiguration period. Based on the layout of RMS, capacity update could follow a non-linear trend (Figure 2). A linearization approach is proposed as an approximate way of modeling the capacity expansion and contraction during this period. This approach is explained in detail in 4.2.

In addition to the above assumptions, we assume a discount factor of 2% in each period. The unmet demand is considered as lost. Either capacity expansion or contraction is allowed at each period. The reconfiguration cost and time of adding new RMS modules are a function of the amount of capacity change as explained in 4.1 and 4.2.

Parameters:

- $T$: Time horizon
- $P$: Products
- $\varsigma_t$: Discount factor at time $t$
- $\mu_{tp}$: Mean demand of product $p$ at time $t$
- $\sigma_{tp}$: Standard Deviation of the demand for product $p$ at time $t$
- $C_{dp}$: Unit cost of Dedicated System capacity for product $p$
- $C^r$: Unit cost of Reconfigurable System capacity
- $CP_{dp}$: Production cost of Dedicated system for product $p$
- $CP^r_{dp}$: Production cost of Reconfigurable system for product $p$
- $SC$: Shortage cost
- $EC$: Excess capacity cost
- $C^k_{dp}$, $C^k_{dp}$: Cost per unit capacity purchase for types II and III Reconfigurable System
- $C^1_{dp}$, $C^3_{dp}$: Reconfiguration cost parameter based on reconfiguration time
- $M$: Sufficiently large number
- $Z$: $Z$ value based on Serviceability

Variables:

- $\Delta_{dp}$: Dedicated system capacity at time $t$ for product $p$
- $\Delta_{dp}$: Dedicated system production at time $t$ for product $p$
- $\Delta_{dp}$: Dedicated capacity added at time $t$ for product $p$
- $\Delta_{dp}$: Dedicated capacity removed at time $t$ for product $p$
- $\Delta_{dp}$: Excess capacity of Dedicated system at time $t$ for product $p$
- $R_{dp}$: Actual capacity of Reconfigurable system at time $t$
- $R_{dp}$: Reconfigurable system production at time $t$ for product $p$
- $R_{dp}$: Nominal capacity of Reconfigurable system at time $t$
4 Proposed Methodology and Model Description

Market demand and capital investment have the highest impact on the system selection from the manufacturer’s perspective. For instance, by transferring from monopoly to oligopoly and perfect competition market, the manufacturing system selection might change from DMS to RMS or FMS. Nevertheless, the manufacturer could always benefit by a system that provides the highest serviceability with minimum capacity investment and reconfiguration cost. Therefore, the proposed model should include each system characteristic, including the responsiveness of the system and the integration of new capacity to the system. The following represents the MIP model and configuration pattern. In MIP model, we evaluate each configuration based on the capacity cost, service level, and excess capacity cost. Moreover, we observe how the capacity of RMS and DMS evolves from one period to another based on the assigned reconfiguration pattern.

4.1 MIP Model

The objective function of the MIP model minimizes the capacity investment cost by selecting the optimal DMS and RMS capacity levels. This model minimizes all cost issues toward purchasing and updating of capacity during the selected planning horizon.

In developing such a model, we minimize the production cost (01), capacity investment cost (02), system reconfiguration cost (03), capacity excess cost, and cost of lost demand (04). We assume that each unit of reconfigurable system capacity is greater than the dedicated system counterpart (Van Mieghem (1998), Ceryan and Koren (2009)).

\[
\begin{align*}
\sum_{t \in T} \sum_{p \in P} (C_{p} + D_{t,p} + C_{p} \cdot R_{t,p}) \\
+ (C_{t} + C_{t} \cdot K_{t}^{2} + C_{t} \cdot K_{t}^{3}) \cdot R_{t} + \sum_{t \in T} (C_{t} + C_{t} \cdot K_{t}^{2} + C_{t} \cdot K_{t}^{3}) \cdot R_{t} \cdot \Delta t_{t} + \sum_{p \in P} C_{p} \cdot D_{t,p} + \sum_{t \in T} \sum_{p \in P} (C_{p} \cdot \Delta t_{t})
\end{align*}
\]

Product demand is released by a specific mean (μ) and variance (σ) at each period. In order to meet the uncertain demand, we consider the allocation of a safety capacity, as expressed in (20), in each period by following the critical fractile ratio, Z, based on following formula.

\[
Z = N^{-1} \left( \frac{SC}{SC + EC} \right)
\]

Based on this safety factor we provide a safety capacity for satisfying the random demand. After the demand is realized for a period, it is satisfied by a mix of RMS and DMS production, or it is lost (05). We formulate each system specification by a set of constraints. For instance, a DMS is dedicated to one product. Therefore, available dedicated capacity is allocated to one product’s demand at each period (06). Moreover, according to DMS specifications, we assume that increasing the capacity of DMS takes one period and no amount of added capacity is available during ramp up period, which means that there is a step increase after one period (07).

In a reconfigurable system, the unutilized capacity is determined as an excess capacity at each period (06). For the reconfigurable system, we assume that some of the added capacity is available during reconfiguration. Therefore, during the reconfiguration period we deal with two characteristics of reconfigurable capacity: nominal capacity and actual capacity. The nominal capacity determines the amount of capacity that the system should reach at the end of reconfiguration period (15). 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, in the case of ramp down it is considered as excess capacity (16) based on the fact that system is not able to reach to desired capacity instantly.

Another aspect that we take into account in our model is the reconfiguration cost. The reconfiguration activity entails a reconfiguration cost for the manufacturing system. This cost includes labor cost, re-arrangement cost, and setup cost. We measure the reconfiguration cost based on the time of reconfiguration. For DMS, constraints (08-09) forces binary variable \( Y_{D}^{\text{p}} \) to get the value one during ramp up and ramp down period. In RMS, the appropriate amount of reconfiguration time that is based on the amount of added or removed capacity is presented by the binary variable, \( Y_{I}^{\text{p}} \) (19). We assume that the scale of DMS capacity that could be added or removed at each period should be more than maximum amount of capacity that could be added or removed by RMS (08). We justify this assumption based on the economies of scale principle of DMS. Therefore, the amount of capacity that can be added or removed from a system by DMS is in larger steps. Also, the amount of DMS capacity that is removed from the system must be less than current DMS capacity (10).

At each period we assume that we have either capacity increase (11, 17) or decrease (12, 18) for both DMS and RMS.

<table>
<thead>
<tr>
<th>Constraints:</th>
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<tbody>
<tr>
<td><strong>Demand Satisfaction:</strong></td>
</tr>
<tr>
<td>( \mu_{t,p} = D \lambda_{t,p} + R \xi_{t,p} + D_{t,p} ) ( \forall t \in T, p \in P ) (05)</td>
</tr>
<tr>
<td><strong>Dedicated System:</strong></td>
</tr>
<tr>
<td>( D \lambda_{t,p} + E \xi_{t,p} = D \xi_{t,p} ) ( \forall t \in T, p \in P ) (06)</td>
</tr>
<tr>
<td>( D \xi_{t,p} = D \xi_{t-1,p} + D \Delta \xi_{t-1,p} - D \Delta \xi_{t,p} ) ( \forall t \in {2..T}, p \in P ) (07)</td>
</tr>
<tr>
<td>( D \Delta \xi_{t-1,p} + D \Delta \xi_{t,p} \geq \delta + M \cdot Y_{D,0}^{\text{p}} - M ) ( \forall t \in T, p \in P ) (08)</td>
</tr>
<tr>
<td>( D \Delta \xi_{t-1,p} + D \Delta \xi_{t,p} \leq M \cdot Y_{D,0}^{\text{p}} ) ( \forall t \in T, p \in P ) (09)</td>
</tr>
<tr>
<td>( D \Delta \xi_{t,p} \leq D \xi_{t,p} ) ( \forall t \in T, p \in P ) (10)</td>
</tr>
<tr>
<td>( D \Delta \xi_{t,p} \leq M \cdot (Y_{I,0}^{\text{p}}) ) ( \forall t \in T, p \in P ) (11)</td>
</tr>
<tr>
<td>( D \Delta \xi_{t,p} \leq M \cdot (1-Y_{I,0}^{\text{p}}) ) ( \forall t \in T, p \in P ) (12)</td>
</tr>
<tr>
<td>( Y_{D,0}^{\text{p}} \leq K^{4} ) ( \forall t \in T, p \in P ) (13)</td>
</tr>
<tr>
<td><strong>Reconfigurable System:</strong></td>
</tr>
<tr>
<td>( R \lambda_{t,p} + E \xi_{t}^{\text{r}} = R \xi_{t} ) ( \forall t \in T ) (14)</td>
</tr>
<tr>
<td>( IR \xi_{t} = IR \xi_{t-1} + R \Delta \xi_{t}^{+} - R \Delta \xi_{t}^{-} ) ( \forall t \in {2..T} ) (15)</td>
</tr>
<tr>
<td>( R \xi_{t} = IR \xi_{t-1} + U \xi_{t}^{\text{r}} - L \xi_{t}^{\text{r}} ) ( \forall t \in {2..T} ) (16)</td>
</tr>
<tr>
<td>( R \Delta \xi_{t}^{+} + U \xi_{t}^{\text{r}} \leq M \cdot Y_{I,0}^{10} ) ( \forall t \in T ) (17)</td>
</tr>
<tr>
<td>( R \Delta \xi_{t}^{-} + L \xi_{t}^{\text{r}} \leq M \cdot (1-Y_{I,0}^{10}) ) ( \forall t \in T ) (18)</td>
</tr>
<tr>
<td>( R \Delta \xi_{t}^{+} + U \xi_{t}^{\text{r}} + R \Delta \xi_{t}^{-} + L \xi_{t}^{\text{r}} \leq M \cdot \sum_{i=1}^{9} Y_{I}^{i} ) ( \forall t \in T ) (19)</td>
</tr>
<tr>
<td><strong>Safety Capacity:</strong></td>
</tr>
<tr>
<td>( \sum_{p \in P} (Z \cdot \sigma_{t,p}^{\text{D}} + D \lambda_{t,p} + R \lambda_{t,p}) \leq \sum_{p \in P} D \xi_{t,p} + R \xi_{t} ) ( \forall t \in T ) (20)</td>
</tr>
<tr>
<td><strong>Auxiliary constraints:</strong></td>
</tr>
<tr>
<td>( R \Delta \xi_{t}^{+} = 0, R \Delta \xi_{t}^{-} = 0, U \xi_{t}^{\text{r}} = 0, L \xi_{t}^{\text{r}} = 0 ) (21)</td>
</tr>
<tr>
<td>( IR \xi_{t} = R \xi_{t}^{1} ) ( \forall t \in T ) (22)</td>
</tr>
<tr>
<td>( \sum_{p=1}^{P} D \Delta \xi_{t,p} = 0 ) ( \forall t ) (23)</td>
</tr>
</tbody>
</table>

**4.2 Reconfiguration pattern**

We determine the system configuration pattern by using binary variables, \( K^{1} \) to \( K^{4} \). Binary variable \( K^{4} \) represents DMS reconfiguration. In this scenario, we assume that a capacity change is allowed only for DMS, whereas RMS capacity is fixed. One can consider this scenario as RMS designed as FMS. It is able to produce multiple products at the same time but has fixed capacity during time horizon.

In type I reconfiguration pattern as shown in Figure 3, a predetermined percentage of capacity is available during reconfiguration time based on the maximum amount of capacity that could be added to system at each period. We assume \( 0 \leq \Delta C \leq \%5 \) C, could be installed in \( \Delta t_{1} \), 5% C \( \leq \Delta C \leq \%25 \) C, could be installed in \( \Delta t_{2} \), and 25% C \( \leq \Delta C \leq \% C \), could be installed in \( \Delta t_{3} \) (1-7 to 1-12). In type I reconfiguration, available capacity of added/removed capacity falls in 25% to 60% of added or removed capacity (1-1 to 1-6).
In type II reconfiguration pattern (Figure 4), we assume $0 \leq \Delta C \leq %33 \% C$, could be installed in $\Delta t_1$, $33\% C \leq \Delta C \leq %66 \% C$, could be installed in $\Delta t_2$, and $66\% C \leq \Delta C \leq C$, could be installed in $\Delta t_3$ (2-7 to 2-12) based on the maximum amount of capacity that could be added to system at each period. In type II reconfiguration, the available capacity of added or removed capacity falls between 40% and 80% of the added/removed capacity (2-1 to 2-6).

In type III reconfiguration pattern (Figure 5), we assume $0 \leq \Delta C \leq %62.5 \% C$, could be installed in $\Delta t_1$, $62.5\% C \leq \Delta C \leq %87.5 \% C$, could be installed in $\Delta t_2$, and $87.5\% C \leq \Delta C \leq C$, could be installed in $\Delta t_3$ (3-7 to 3-12).
In type III reconfiguration, the available capacity of added or removed capacity falls in 80% to 100% of desired nominal capacity (3-1 to 3-6).

![Figure 5: Reconfiguration type III more capacity is available during reconfiguration](image)

5 Numerical Results

We considered a firm that produces product (A and B) but product B is introduced to market later than product A. The mean demand ($\mu$) for products A and B for ten consecutive periods is shown in Figure 6. We assume demand follows normal distribution and demand variance ($\sigma$) changes by the change in product lifecycle. For example, we assume that a product demand has higher variation during the introduction and the decline phase and less variation during the maturity phase.

We select four factors to analyze capacity evolution for a given time horizon. First, the binary variables associated with the reconfiguration type are fixed in order to determine the ramp up curve. Afterward, we set the service level
to predetermined values of 70%, 80%, and 90%. According to the service level, safety capacity is determined in the MIP model as shown in constraint (20). Moreover, we increase the excess cost from 33% to 100% of purchase capacity cost to analyze how excess capacity cost affects capacity selection at different reconfiguration patterns. We show this ratio by $S$, $2S$, and $3S$. We refer to a combination of each service level and excess capacity cost as one scenario.

Finally, we test the responsiveness of RMS system at two different levels. At the first level, we assume the RMS system is able to respond to a range of the demand variation equivalent to $\sigma$, and at the second level, we assume the RMS is able to respond to $3\sigma$ range of the demand variation. By doing so, we try to see how RMS range of response leads to consideration of RMS Type I, II and III reconfiguration by manufacturer. The experiments are solved to optimality within MIPGAP set to 1E-04 using CPLEX 11.0.

5.1 Capacity Investment

RMS capacity investment results for reconfiguration Type I, Type II and Type III are shown in Table 1. In all reconfiguration types, the allocation to RMS increases as we increase the excess cost from 33% to 100% of capacity purchase cost at the same service level. For example, RMS investment is increased from 46% to 77% at small response range and 90% service level. This indicates that, the benefit of scalability outweighs the added investment cost against a dedicated system. Also, the increment of response range has a positive correlation with RMS investment. At $\sigma$ response range and 90% service level, when response range increases, RMS investment increases from 74% to 84%. At this response level, the investment on RMS decreases as we increase the service level. For example, investment on RMS decreases from 58% to 46% at low excess cost in Table 1. However, at the high range of response, the rate of reduction in RMS investment is less than low range of response as service level increases. RMS range of response has a positive effect on serviceability since RMS system could provide higher serviceability during reconfiguration period. The result of series reconfiguration is shown in Table 2. In series reconfiguration, the RMS investment portion is low since no capacity could be added or removed to/from RMS. Also, we see that by increasing the service level, more investment is done on DMS.

<table>
<thead>
<tr>
<th>Reconfiguration Type</th>
<th>Service Level</th>
<th>Type I 70%</th>
<th>80%</th>
<th>90%</th>
<th>Type II 70%</th>
<th>80%</th>
<th>90%</th>
<th>Type III 70%</th>
<th>80%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Response range</td>
<td>Excess Cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\theta^r = \sigma$</td>
<td>S</td>
<td>60%</td>
<td>46%</td>
<td>38%</td>
<td>58%</td>
<td>46%</td>
<td>46%</td>
<td>70%</td>
<td>67%</td>
<td>56%</td>
</tr>
<tr>
<td></td>
<td>2S</td>
<td>68%</td>
<td>68%</td>
<td>65%</td>
<td>78%</td>
<td>75%</td>
<td>71%</td>
<td>83%</td>
<td>71%</td>
<td>68%</td>
</tr>
<tr>
<td></td>
<td>3S</td>
<td>80%</td>
<td>80%</td>
<td>78%</td>
<td>82%</td>
<td>81%</td>
<td>77%</td>
<td>83%</td>
<td>82%</td>
<td>79%</td>
</tr>
<tr>
<td>$\theta^r = 3\sigma$</td>
<td>S</td>
<td>63%</td>
<td>63%</td>
<td>63%</td>
<td>76%</td>
<td>76%</td>
<td>74%</td>
<td>76%</td>
<td>76%</td>
<td>75%</td>
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<tr>
<td></td>
<td>2S</td>
<td>84%</td>
<td>82%</td>
<td>82%</td>
<td>86%</td>
<td>85%</td>
<td>84%</td>
<td>84%</td>
<td>84%</td>
<td>75%</td>
</tr>
<tr>
<td></td>
<td>3S</td>
<td>84%</td>
<td>83%</td>
<td>82%</td>
<td>86%</td>
<td>85%</td>
<td>84%</td>
<td>85%</td>
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<td>83%</td>
</tr>
</tbody>
</table>

Figure 6: Demand of Product A and B
Table 2. RMS investment in Series Reconfiguration

<table>
<thead>
<tr>
<th>Serviceability</th>
<th>70%</th>
<th>80%</th>
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6. Conclusions

In this paper, we modeled ramp up time based on different system configurations. System configuration could vary by system layout, scalability of systems, and the ability of allocating more capacity during the planning horizon. We propose a novel mixed integer programming model that grasps various ramp up time patterns of RMS and takes into account RMS and DMS scalability lead time. Ramp up shape of each configuration is modeled in the linear and nonlinear fashion of updating capacity according to system configuration. We considered four types of reconfiguration patterns. Each pattern represent capacity evolution during ramp up period based on specific configuration such as parallel machining layout, hybrid layout and series layout. We assume that capacity is updated with faster rate when we move from series layout to parallel machining. The results show that improving the response range of RMS increases the percentage of RMS capacity investment. We see this increase in both increasing service level and increasing excess cost. Among reconfigurations Type I to Type III, Type III reconfiguration (parallel reconfiguration) provides better responsiveness and enables RMS to reach the desired level of capacity faster. In low range of response, better responsiveness is an advantage for RMS since the capacity evolution of RMS during planning horizon is able to follow the mean of demand closely. Therefore, more investment is done on RMS at Type III reconfiguration in spite of the higher investment cost.

References