Improving the Stability of Supply Chain Operations Planning Considering the Effects of Congestion

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ABSTRACT

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Reacting to customer demand changes by frequently re-planning and re-scheduling the production plans is one of the managerial perspectives to improve customer satisfaction enabled through new information technologies such as Radio Frequency Identification (RFID). However, this may cause nervousness in supply chain operations, resulting in unexpected operational costs, and increased lead time due to congestion in the nodes of the supply chain. The objective of this thesis is to develop a decision support system to identify the lot sizing and batching decisions by considering the congestion effects resulting from uncertainties in a supply chain environment. A Mixed Integer Linear Programming (MILP) model is developed to determine lot sizing decisions for a supply chain. The developed MILP model considers the effect of congestion at the supplier nodes using queuing models. In addition, instability metrics are proposed to measure the stability of supply chain lot sizing decisions. The output of the lot sizing decisions is tested with the proposed metrics in a simulation environment by considering various uncertainty levels. A sensitivity analysis is conducted in order to demonstrate the impact of batching and supplier capacity decisions under high, medium, and low demand variability. The results show that increasing the supplier capacity by a small increment has a significant improvement on the total cost. Moreover, considering the congestion effect into their MRP schedule increases

the overall service level. The benefits of incorporating the congestion effects have also been demonstrated by the proposed stability metric.

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Rayan Saleem M Omar

DEDICATION

I dedicate this work to my parents, wife, daughter and parents-in-law.

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LIST OF ABBREVIATIONS

AOC	Advance order commitment
BOM	Bill of material
CF	Clearing function
CRP	Capacity requirements planning
EOQ	Economic order quantity
F	Frozen period
HV	High demand variability
HVE	High demand variability with extra capacity
IC	Initial capacity
LDLT	Load dependent lead time
LV	Low demand variability
LVE	Low demand variability with extra capacity
MILP	Mixed integer linear programming
MINLP	Mixed integer non-linear programming

MPS	Master production schedule
MRP	Material requirements plan
MV	Medium demand variability
MVE	Medium demand variability with extra capacity
PC	Proposed capacity
R	Re-planning period
RCCP	Rough cut capacity planning
RFID	Radio frequency identification
SCV	Squared coefficient of variation
WIP	Work in process
WW	Wagner within

Chapter 1

1 Introduction

Reacting to customer demand changes by frequently re-planning and re-scheduling the production plans is one of the managerial perspectives in investing new information technologies such as radio frequency identification (RFID). However, this may cause nervousness in supply chain operations and result in unexpected operational costs, and increased lead time due to congestion in the nodes of the supply chain.

Production plans are the tools that link a company's objectives with a customer's needs by offsetting the demand's due date with the raw material and production lead-time. While the stability of the production plan is one of the production manager's most important considerations, this stability is affected due to the supply chain disruptions, such as suppliers' failure to meet delivery due dates, and the pressure to meet the changing customer demand.

There is also a missing link between tactical and operational level decision-making regarding production plans. At the tactical level, when constructing the master production schedule (MPS), all of the available facility capacity is considered in the plan to meet the customers demand without considering the variations. However, the internal or external disruption to their plan is usually not considered. Operational level managers are, therefore, struggling to implement the material production plan (MRP) into the shop floor. This is because the MRP is constructed according to the MPS, and the MPS is vulnerable to frequent re-scheduling and re-planning with any disruptions occurrence. The operational managers usually avoid frequently re-planning production plans whereas the tactical level managers and supply chain practitioners support it in order to meet customer requirements (Hozak & Hill (2009); Pujawan & Smart (2012)).

Technologies that allow real time tracking of supply chain flow such as RFID, a small programmable chip with memory, will provide companies with accurate and timely information regarding material movement, and inventory status. In fact, frequently receiving real time information's technology information may trigger the need to accordingly re-plan and re-schedule production plans, which may cause schedule instability.

The MRP is a popular tool for scheduling production plans, but it has some disadvantages. First, it fails to capture the facility capacity constraint and the effects of system congestion. Second, MRP is designed to work in a stable environment, (Roberts and Barrar (1992); Koh et al. (2000)).

Studies by Roberts and Barrar (1992), and Koh et al. (2000) emphasize the following point: companies will benefit from the MRP by ensuring the accuracy of the demand forecast. Otherwise, the system's instability will increase, since there is a need to re-plan the MRP. In other words, MRPs are established according to the forecast of the customer's demand, meaning that uncertainty is inherent to the plans. As the executed plan gets closer to the due date, the demand may change, thus making the MRP infeasible. For these reasons, maintaining high service levels requires keeping track of demand changes and updating the MRP accordingly. This will, however, cause system nervousness, and increase the cost of production and inventory. Nervousness of the production plan occurs when the quantity or the timing of the released production plan is changed frequently. Even minor changes will significantly impact the upstream in a supply chain context. I Nyoman Pujawan (2004) mention three types of MRP instability or nervousness that are caused by quantity change, delivery time change, and change in the item itself. This creates additional operational costs and impacts the performance negatively. Therefore, managing uncertainty is an important goal for the production managers in the presence of demand uncertainty and supply chain disruptions.

All of the afore-mentioned circumstances make the customer satisfaction an extremely difficult task. Literature shows that practitioners and researchers focus on dampening the instability of frequent changes of current operating plans in response to demand uncertainty (Koh & Gunasekaran (2006); Yeung, Wong, & Ma (1998)), instead of finding proper approaches to measure and include the effect of the schedule nervousness into their plans (Hozak & Hill (2009); Pujawan & Smart (2012)).

1.1 Problem statement

In considering the production plans that are constructed based on the demand forecast, there may be a need to frequently re-plan and re-schedule the production plans as changes in demand occur. This results in nervousness in production plans. In addition to that, the effect of the loading a finite capacity is not included in the MRP, making it infeasible in the face of uncertainties.

In the supply chain context, frequently re-planning and re-scheduling the MRP may cause schedule nervousness, which will increase in a supply chain environment as the changes propagates upstream. Therefore, in a supply chain environment, there is a need to incorporate the demand variation and congestion effects in order to minimize the impact of these changes on supply chain operations.

1.2 Objective

The specific objectives of this thesis are:

To demonstrate that appropriately choosing the lot-size quantity and setting the supplier capacity impact the stability of the supply chain. There are many different ways to calculate the optimal order size quantity, such as the Economic Order Quantity (EOQ), and the Wagner-Whitin (WW) for a time varying deterministic demand. However, more importance should be given to considering the capacity load in constructing the MRP in order to incorporate the effect of the congestion. As a result, the supplier capacities and batch sizes will be set so that the lead-time, the operation, and the inventory cost are reduced. Furthermore, in the case of a disruption, the system will become heavily loaded, which will increase the congestion accordingly. That will also lead to an increase in the instability of the entire supply chain.

In order to accomplish this objective, we develop a decision support system to identify the lot sizing and batching decisions by considering the congestion effects due to uncertainties in a supply chain environment. A Mixed Integer Linear Programming Model (MILP) is developed to determine lot sizing decisions for a supply chain. The developed MILP model considers the effect of congestion at the supplier nodes using queuing models. In addition, instability metrics are proposed to measure the stability of supply chain lot sizing decisions. The output of the lot sizing decisions is tested with the proposed metric in a simulation environment by considering various uncertainty levels. sensitivity analysis is conducted in order to demonstrate the impact of batching and supplier capacity decisions under high, medium and low demand variability.

Therefore, this study seeks to find answers to the following specific questions:

1. What is the impact of the supplier capacity level on the stability of the supply chain operations in the case of demand uncertainty?
2. What is the optimal batch size, which will give more stability to the whole supply chain parties in the case of demand uncertainty?
3. What are the advantages of considering the congestion effects in constructing the MRP for the whole supply chain parties?
4. What is the added value of integrating the congestion effects on the instability measure metrics?

1.3 Thesis framework

This thesis is organized as follows:

- Chapter 1 includes the thesis introduction, the objective of the thesis.
- Chapter 2 provides a review of the relevant literature.
- In Chapter 3, the proposed methodology is explained. For the purpose of studying the effect of the forecast accuracy, the demand is generated with high, medium, and low variability. Second, the simulation model logic and description are elaborated. Third, the proposed metrics are discussed for the supply chain, to measure different lot-size quantities, and the suppliers' flexibility effect.
- Chapter 4 presents the numerical results.
- Chapter 5 concludes the thesis, and provides future work suggestions.
- Appendices include the clearing function (CF) calculation result, MILP model developed in Excel Microsoft 2010 and solved by OpenSolver (www.opensolver.org),

and the simulation model snapshot and results report based on Arena (www.arenasimulation.com).

Chapter 2

2 Literature review

The literature review regarding the production planning approaches is divided into three parts: the impact of demand uncertainty in supply chain, uncertainty on the operational level, and approaches to measure stability. First, the literature review of the demand uncertainty in supply chain is discussed in Section 2.1. Second, the works that relate to the operational level are presented in Section 2.2. Finally, the review of measuring stability literature is exhibited in Section 2.3.

2.1 Impact of demand uncertainty in supply chain

One of the most important decisions after the strategic decisions from the top management level is the allocation of the factory resources in order to meet the company objectives. This entails satisfying the customer's demand in the appropriate time and with the correct quantity. The MPS helps companies effectively assign the available capacity to meet their customers' demand. Usually, MPS can be generated for a long period of time, and the companies construct their MPS based on the forecast of their customer's demand. As a result, the efficiency of the MPS depends on the accuracy of the customer's demand forecast. Since the forecast error is an integral part of the MPS, the need to re-plan MPS will increase as the forecast error increases.

In recent years, the competition between the manufacturing companies has increased dramatically. As a result, companies are required to respond to demand changes quickly in order to be successful. Companies depend on having access to real time information tracking technology, especially in the supply chain context. This technology will greatly enhance companies’ responses to the market changes. The increased pressure to respond to every customer change as a result of this information technology demonstrates the importance of dealing with the uncertainties at the planning stage. The following section will introduce the insight of the MPS deficiency.

2.1.1 MPS deficiency

There is a gap between planning MPS at the higher managerial level decision making and operational level execution of MPS. The managers at the tactical level, when generating the aggregate plan, MPS, are trying to match the available capacity with the customer’s demand. Usually, the uncertainty at the operational level is not considered. Koh, Saad, & Jones (2002) did a comprehensive literature review on the MRP uncertainty, and they infer that the aggregate plan can only be executed in a particular setting. In other words, MRP is designed to be implanted into a stable environment without any disruptions. Otherwise, either re-planning or subcontracting the unscheduled quantity will be necessary to remedy the disruptions.

For that reason, supply chain parties support the idea of sharing the demand, the production plan information, and the forethought re-planning approach between parties in order to reduce the uncertainty in the supply chain. Griffiths & Margetts (2000) conclude that the communication between the supply chain parties should be faster in order to increase the visibility of the customer demand across the entire chain.

2.1.2 Real time information technology

Today, companies tend to use real time information systems technology in order to increase the customer satisfaction, as well as toward making sure that their production-plan are feasible. Technologies that allow real time tracking of supply chain flow such as RFID.

The literature reveals that companies use this technology in their facilities, and share its information with their suppliers (McFarlane & Sheffi (2003); S. Wang, Liu, & Wang (2008)). Timely information helps companies to reduce the safety stock level. In addition, the ordering cost for future orders will decrease according to reduction in the operational and inventory cost. A real time tracking system will maintain a high level of customer satisfaction by observing the inventory status, and by predicting the pattern, or the trend of future orders. McFarlane & Sheffi (2003) present comprehensive insight into the advantages of using the RFID for the company and supply chain by tracing the status of the inventory more frequently, giving the operation managers a sense of the demand variation in the current plan. Y. M. Lee, Cheng, & Leung (2004) construct a simulation model in order to study the impact of RFID across the supply chain. At the end of their study, they conclude that the RFID significantly improves not only the inventory level, but also the service level. S. Wang, Liu, & Wang (2008) constructed a simulation model to ascertain the impact of RFID on the inventory cost. They observe that the inventory level decreases and the inventory turnover increases by using the RFID. In other words, there is a direct link between the inventory level and the implementation of the RFID system in a company.

On the other hand, from the operational level manager’s point of view, frequently re-planning the production plans may cause distortion for the MRP. Hozak & Hill (2009) conclude that the supply chain parties did not model the cost of continually changing the production plans. Thus, re-planning the production plans should be done in order to cope with the uncertainty, but with the awareness to avoid the high cost from frequently doing so.

2.2 Uncertainty in operational level

The uncertainty in the operational level is divided into two categories, internal and external. The internal uncertainty is related more to the production process, such as machine failure, defective raw material and worker absence. On the other hand, the external category is about the system inputs, i.e. customer demands, raw material arrival, and the interrelationship between them, as illustrated in Figure 2.1 (from Koh, Saad, & Jones (2002)).

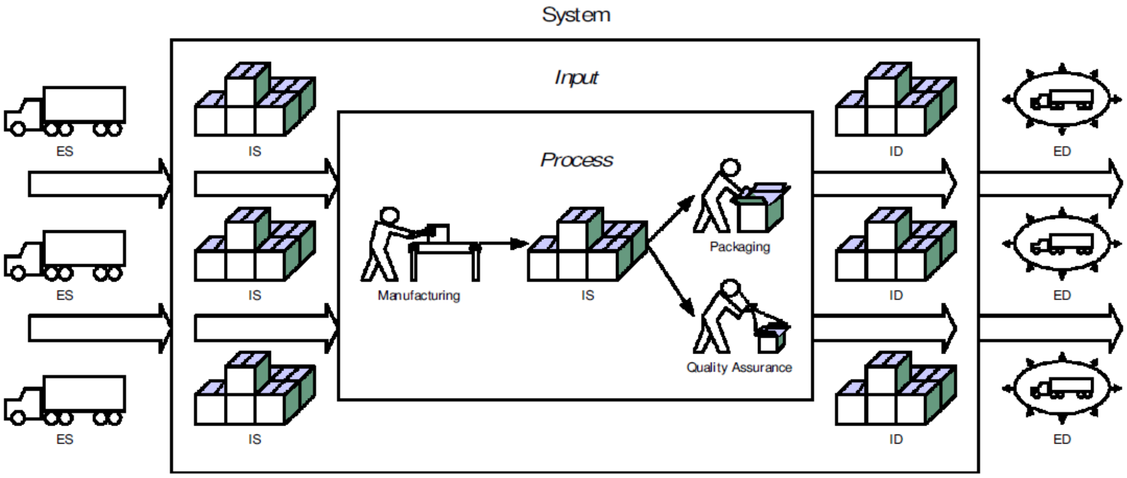

Figure 2.1: The interrelationship between the external and internal uncertainty factors, in the supply chain environments (from Koh, Saad, & Jones (2002)) .

The external factors are affecting the stability of the production plan more than the internal ones, which are also affected by the real time information technology. Pujawan & Smart (2012) studied the schedule instability in the manufacturing companies. They focus their study on the communication between suppliers and customers as external factors, as well as the manufacturer internal process. They conclude that the external factors are affecting the schedule stability more than the internal processes.

The literature regarding dealing with the uncertainty addressed to the MRP plan is abundant. The classification of MRP disruption literature is according to the different viewpoints for tackling the external uncertainty events, and the review of the works related to each is presented as follows: source of uncertainty in Section 2.2.1, strategies to reduce MRP instability in Section 2.2.2, and measuring schedule stability in Section 2.2.3.

2.2.1 Sources of uncertainty

There is a great deal of research on the sources that affect the schedule stability. Yeung, Wong, & Ma (1998) did a comprehensive review of the factors affecting the performance of the MRP. The MRP is constructed based on the MPS, and the factors affecting the MPS will affect the MRP as well. They classify these factors into seven groups. Two of them are considered as external sources, and the rest are the parameters that can be modified to create strategies for reducing the instability. The external sources are:

- Product structure (bill of material),
- Forecast accuracy.

2.2.1.1 The effect of the product structure on MRP stability

Product structure (bill of material (BOM)) complexities increased the stability of the production plan in the presence of high demand variability.

T. S. Lee & Adam (1986) did a simulation model to study the impact of forecast accuracy on four different product structures. They conclude that complex product structure with present forecast error will increase the operational cost. In their work, they focused on the forecast error magnitude, which can be mitigated by re-scheduling the current plan. However, the frequency of change, which greatly affects the stability of the schedule, is ignored. Meixell (2005) studied the impact of demand variability on the MRP schedule stability with different factors, such as capacity, product flexibility, and setup cost. Based on the simulation outcomes, they conclude that product flexibility provides more stability to the entire supply chain.

2.2.1.2 The effect of the forecast error on MRP stability

Forecast accuracy is a significant factor that affects the stability of both the MPS and MRP because it is built according to the MPS. Since production plans are constructed based on a customer demand forecast, there might be a need to change the plan more frequently. This is why the plan is vulnerable to nervousness. Unstable plans will cause an increase into the production and inventory cost. Bodt & Wassenhove (1983) conducted a simulation model to study the effect of the forecast error on the lot-size method. They concluded that a minor error in the forecast has a significant impact on the cost efficiency of the lot-size methods. There will be no difference in the cost of using the different lot-size methods with the presence of the forecast error. However, they focus their study on a single level, un-capacitated system. Wemmerlov (1986) studied the effect of the forecast error on the inventory and order cost. He concludes that the forecast error will increase the inventory level, and as a result, not only will it increase the inventory cost, but it will also increase the cost of future orders. Moreover, the difference between the forecast and the actual demand will decrease the service level dramatically. Krupp (1997) put together a statistical model to monitor the impact of the safety stock on the forecast error. He concludes that tracking the demand change does not help decrease the quantity of the inventory, but it will change the time of placing safety stock.

Sridharan & LaForge (1989) examine the effect of introducing safety stock into the MPS level as buffer in order to reduce the effect of the forecast error, and limit the need to frequently change the production plans. Their simulation results show that small quantities of safety stock will give stability to the MPS and MRP. Nevertheless, keeping large amounts of safety stock will cause schedule instability, in the case of uncertain demand. They emphasize the importance of the location of the safety stock in multi-echelon system. Unfortunately, they consider the demand uncertainty on their work in a single item, single level. Their conclusion matches (Fildes & Kingsman (2011)) as they support the idea of accurate forecast is the way to reduce the inventory cost, and increase the stability of the production plans.

2.2.2 Strategies to reduce MRP instability

Some research is intended to mitigate schedule instability through different methods. According to Yeung's (1998) factors that affect the stability of the MRP, the following are directly linked to the strategies of reducing MRP instability:

- The frequency of re-planning and re-scheduling the production plan,
- Length of the frozen period,
- Length of the planning horizon of the MPS,
- Safety stock,
- Lot-size rules.

2.2.2.1 The effect of frequently re-planning and re-scheduling on the production plan

Most of the studies conducted in this area ascertain that production costs will increase dramatically as a result of frequent re-planning and re-scheduling the plan. Lin et al. (1994) studied the impact of the lot-sizing rule, the product structure, and the forecast accuracy on the length of the re-planning period (R) and the length of the frozen period (F). They conclude that the lot-sizing rule and the product structure have a significant impact on the selection of R and F. However, the forecast accuracy has a minor effect on the length of the R and F. Unfortunately, they did not address in their work the issue of schedule integration and operational flexibility throughout the supply chain parties. Sahin, Powell Robinson, & Gao (2008) investigated the MPS and the advance order commitment (AOC) in different environments and MPS designs. The following environmental factors are considered: flexibility of the vendors, demand lumpiness, demand variability, and manufacturers reorder period length. These factors are tested on three independent MPS designs; frequency of re-planning, the planning horizon, and the frozen schedule length. The simulation results show that the most essential factors in the environment of two echelon supply chains is the flexibility of the vendor. Omar & Bennell (2009) examined the effects of re-planning periodicity, demand pattern, unit production costs, and setup cost on the production performance of batch procedure industries on MPS stability. Their simulation proves that the re-planning frequency has the most significant influence on the stability of the production schedule. Unfortunately, they considered in their study the short-term horizon only.

2.2.2.2 The effect of the length of the frozen period and the planning horizon on MRP

Freezing part of the production plan will lead to decreases in the service level. This gives more stability to the MPS and MRP because freezing the MPS will decrease number of setups as well as the inventory level. Sridharan, Berry & Udayabhanu (1987) conducted a simulation model to study the effects of the planning horizon length, the length of the frozen period, as well as the freezing method into the stability of the MPS. The simulation results show that freezing less than 50% of the MPS will not have a significant impact in decreasing the operational costs. On the other hand, freezing more than 50% will have a considerable effect on the operational cost. Unfortunately, the result of their study cannot be generalized to multilevel, as they focus on studying the single level MPS system. Zhao & Lee (1993) studied the effect of different MPS parameters, namely, the re-planning periodicity, the length of the frozen zone, the length of the planning horizon on the service level, the schedule instability, and the total cost. The analysis of their simulation results assert that, first, the frequent re-planning of the production plan worsens the performance of the system. Second, the longer frozen zone improves the schedule stability and reduces the total cost. Third, the forecast accuracy influences the total cost and the instability of the production plan.

2.2.2.3 The effect of safety stock on MRP stability

Safety stock is one way of dampening the demand variability, and increasing the stability of the production plan. However, the quantity of the safety stock should be carefully calculated to avoid getting an inverse feedback of the safety stock (Sridharan & LaForge (1989)).

Tang & Grubbström (2002) derived a model for planning the MPS under stochastic demand, in which the safety stock in the model is a dynamic function of the time. In other words, as the time is moving forward the safety stock level should increase, that is because of the service level depends on the cumulative forecast error. Pujawan (2008) investigates schedule instability in a simple supply chain of one buyer and one supplier. He conducted a simulation study for different supply chain strategies and different operating conditions, which are demand uncertainty, product cost structure (time between orders) for the buyer and the supplier, and the safety stock level. He concludes that in order to cope with the demand uncertainty and forecast error, the companies should invest in safety stock.

The relationship between the buyer and the supplier will determine who should hold the safety stock and how they should share the inventory expenses, as the supplier should realize that it is not only the responsibility of the buyer to get an accurate forecast. The supplier must support their client with demand forecast for the lower level in order to have a stable supply chain environment. Unfortunately, Pujawan (2008) focused his research on one planning period horizon only. Furthermore, they consider the schedule instability from the time change perspective only and ignore the quantity change. van Kampen, van Donk, & van der Zee (2010) investigate the advantage of using safety stock or safety lead time carrying with the presence of supply variability and demand unreliability. The authors run a simulation model tackling this problem with three sources of unreliability caused by changing the order size, the order type changes, and changes in order sequence. They use transportation performance and inventory status as a performance measure. At the end of the study, the results show that the safety stock gives more responsiveness and safety lead-time, providing more flexibility. In other words, safety lead-time is the best buffer to hedge against supplier variability, and safety stock for demand uncertainty. Their study did not consider order cancellation and ignored the service level.

2.2.2.4 The effect of the lot-size methods into MRP stability

Lot-size rules are deeply investigated by the researchers for the proper selection of the lot-size methods that should be used. Nevertheless, the effect of the lot-size rules on the production plan stability is not significant (Bodt & Wassenhove (1983)).

Wemmerlov & Whybark (1984) did a simulation study to evaluate 14 different lot-size procedures for a single stage with respect to the forecast error of the demand. They infer from their statistical analysis, that with the presence of forecast error, there will be no difference between the different lot-size procedures.

However, assuming a fixed lead time regardless of the lot size quantity will decrease the MRP stability. Indeed, this assumption will lead to an infeasible plan. This is because the effects of the congestion are ignored.

2.2.2.5 Clearing function (CF)

Implementing the MRP plan in the shop floor is very a difficult task in the presence of demand uncertainty and capacity constraints. Due to the fact that the facility capacity is not considered in the MRP plan, and since there is a variation in the demand, the workload release rate to the facility may be higher than the facility capacity. It will thus violate the assumption of a fixed lead time, and increase the lead time exponentially as the system is loaded close to its maximum capacity, as it shown in Figure 2.2 (from Asmundsson, Uzsoy & Rardin (2002)).

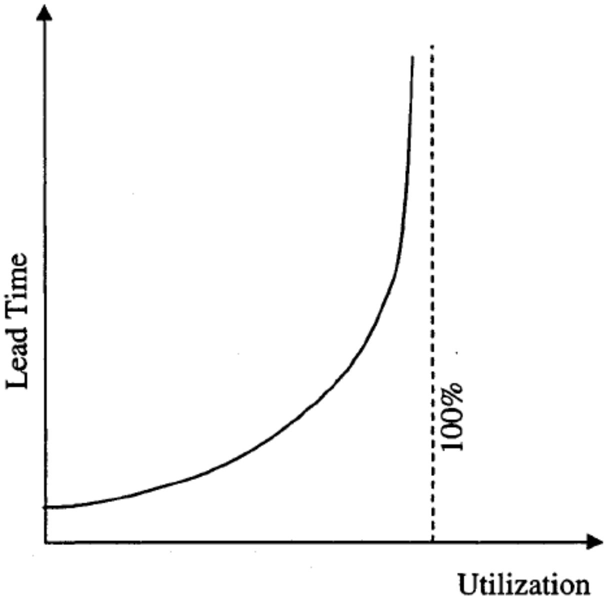

Figure 2.2: The relation between the lead time and the utilization (from Asmundsson, Uzsoy & Rardin (2002)).

The literature shows that there were some attempts to recap MRP disabilities by Rough Cut Capacity Planning (RCCP), Capacity Requirements Planning (CRP) (Hopp et al. (2000)), and CF. RCCP is a quick check of the available resource capacity. In essence, RCCP calculates the required total processing time to produce the planned quantity, and match it with the available resource capacity time in each period. Unfortunately, the method did not consider the lead time of the items. In other words, if the process time for an item requires more than one period, it would not be accounted for in the RCCP. While CRP considered this by calculating the required capacity time based on the MPR, neither RCCP nor CRP takes into account the congestion effect in their calculation of the capacity and the impact it has on MRP.

There are a few works that have been done in the area of relating the workload and the work in process (WIP) with the lead-time. Overall, as the workload increases, the lead-time increases too, and this causes system congestion (Karmarkar (1989); Asmundsson, Uzsoy & Rardin (2002)). Furthermore, the queuing theory is proposed to address the WIP and lead-time to study the system usage.

Bertrand (1981) studied the impact of the capacity and order release rate on the behavior of the lead-time. In the final analysis, he asserts that the workload has a direct relationship with the lead-time. Karmarkar (1989) proposed the use of the clearing function to compose the MRP, which will not only reflect the available capacity into the plan, but also the lead-time variation caused by congestion.

Asmundsson, Uzsoy & Rardin (2002) studied the nonlinear relationship between the service time, which is the output from a system, and the WIP level by the queuing theory, and derived the clearing function model. This clearing function is derived from the queuing model based on G/G/1, where the WIP is $queue\ length = \frac{c_a^2+c_s^2}{2} * \frac{\rho^2}{1-\rho} + \rho$ and c_a^2, c_s^2 are the Squared coefficient of variation (SCV) of the arrival and service time respectively, and ρ is the utilization. Since this expression is composed of utilization, it could be a surrogate for throughput. Eventually solving this expression for the utilization leads to an equation, which gives the system throughput as a function of WIP. This expression is to present for the relationship between the WIP level and utilization of a system.

The clearing function will track the increasing rate of production by increasing the WIP level, as it’s illustrated in Figure 2.3.

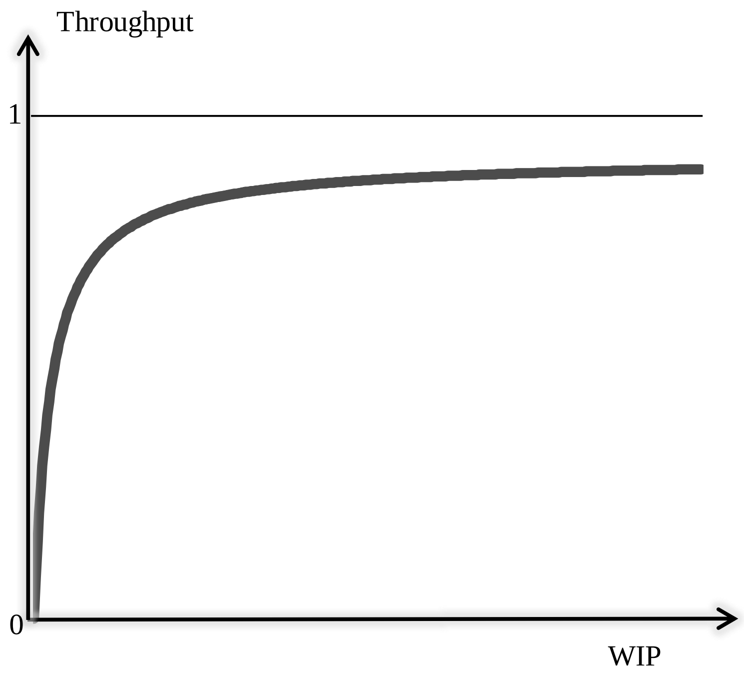

Figure 2.3: Clearing function

Using the clearing function will give an accurate representation of the system behavior in constructing the MRP. This allows better feasibility to the MRP plan, as the release rate is linked to the facility capacity to avoid the congestion. The relationship between the WIP level and lead-time is very important to be addressed in the production plan. A good way to increase the feasibility of the MRP in the supply chain context is to determine the lot sizing decisions by introducing the clearing function in constructing the MRP for the entire supply chain parties.

2.3 Measuring schedule instability

A few studies focus on measuring the cost of the MRP schedule change and the instability. Blackburn, Kropp, & Millen (1986) investigate the effects of the lot-sizing methods, the length of the planning horizon, the number of setups, the holding cost, and the product structure of the schedule instability and system cost. In order to achieve this, they propose a metric to capture the unplanned orders on the imminent period for a single level single item. Unfortunately, this metric, BKM, fails to capture the changes in the planning horizon, except for the imminent period. Furthermore, they could not assess the value of the changes in the order in process, due to the assumption of the zero lead-time.

Sridharan, Berry, & Udayabhanu (1988) focus their research on measuring MPS stability, assessing the impact of freezing the MPS schedule, the length of the portion of the MPS that is frozen, and the length of the MPS planning horizon on the schedule instability. They describe the instability of the production schedule as the weighted average of order quantity changes in timing divided by the number of orders. Their proposed metric, SBU, is for a single item single level. However, this metric fails to measure the changes in the batch size and ordering periods, and the product configuration.

Kadipasaoglu & Sridharan (1997) created a metric to assess schedule nervousness in multilevel MRP system and multi products. They made some modification to the SBU metric, by considering multi-end items and multi-levels product configurations. They infer that dividing the order quantity change by the order number is biased, as there is no link between changing the order quantity and the number of setups. They eliminate the bias in SBU metric by taking-off the division of the order quantity from the metric. However, they did not include the effect the multi-levels have on the product structure, and they studied the effect of instability in short-terms only.

Kabak & Ornek (2009) claim that measuring the nervousness of the schedule instability is the way to control it and to find the best remedy strategy. For that reason, they created new metrics for measuring the schedule nervousness in a multi-item and multi-level in a rolling horizon framework for the timing (setup) and quantity changes.

Nevertheless, they did not include the effect of the congestion caused by high capacity loading as a result of quantity change.

In this thesis, the effects of congestion are measured, in addition to the quantity change and the number of setups required, as the order is canceled.

2.4 Conclusion

There are wide ranges of factors that affect the performance of the MRP. However, there are two major factors most damaging MRP feasibility. The first is the effect of the disruption in the lower level which has been ignored at the MPS plan. The second is the fact that MRP ignores the strong relationship between WIP level and the throughput of the system.

The managers at the higher level are assigning the company resources to meet the customer's demand, without considering the disruption effect at the lower level into their plan at all. Moreover, the companies try to maintain a high customer's satisfaction by using real time information technology, which will send accurate inventory information to the shop floor frequently. Thus, that may require updating the current production plans, though frequently re-planning the production plan will increase the nervousness of the MRP. The nervousness will lead to infeasible MRP plan.

Neglecting the relationship between WIP level and throughput of the system will result in overestimating the actual capacity. In fact, MRP not only discards this relationship, but also assumes an infinite system's capacity. All of those circumstances will lead to an infeasible MPS.

In order to improve the stability of supply chains, MRP should be constructed with respect to the congestion effect and the capacity of the resources. In addition, the stability of the plan with regard to the congestion effect, and factors affecting the stability such as lot-size rules and supplier capacity, can be measured.

The literature review shows that the effect of the congestion caused by demand uncertainty has not been studied yet. In addition to that, the congestion effect has been ignored in the instability measure area too. Therefore, the objective of this thesis is to develop a decision support system to identify the lot sizing and batching decisions by considering the congestion effects resulting from uncertainties in a supply chain environment. In addition to, studying the effect of the supplier capacity buffer to improve the stability of the supply chain.

Table 2.1: Summary of the literature review on strategies to reduce MRP instability

	Literature	Lin 94	Omar 09	Sridharan 87	Zhao 93	Pujawan 08	Van 10	Omar 12
Methodology	MILP	X	X					X
	Simulation		X	X	X	X	X	X
	Instability metrics							X
Studied Parameters	Lot-size	X	X					X
	Product/SC structure	X				X		X
	Forecast error	X	X			X	X	X
	Re-plan period	X	X		X			X
	Planning horizon			X	X			
Strategies	Safety Stock					X	X	
	Frozen length	X	X	X	X			
	Congestion							X
	Capacity buffer							X

Table 2.2: Summary of the literature review of the instability measure

	Literature	Blackburn 86	Sridharan 88	Kadipasaoglu 97	Kabak 09	Omar 12
Studied Conditions	Single Level	X	X			
	Single Item	X	X			
	Multi levels			X	X	X
	Multi items			X	X	X
	Rolling horizon				X	
	WIP level					X

Chapter 3

3 Proposed methodology

Observing the difference between the initial production plan and current inventory status will enhance the feasibility of the plan. However, real time inventory tracking systems may trigger re-planning the production plans more frequently by expediting or postponing the order due date, canceling the order, or adding quantity to the current plan period (Kabak & Ornek (2009)). Doing so will disrupt the current production plan. For that reason, we propose to introduce not only the disruption effect on the MRP, but also the congestion effect, in order to have a feasible plan. An MILP model is used to generate the MRP with respect to these circumstances for the entire supply chain parties. Then, a simulation study is conducted to validate the MRP plans generated from the MILP. The four disruption cases are molded in the simulation model. Finally, an instability metric is proposed to help in the decision of the lot size and the supplier capacity buffer, in order to have a stable supply chain environment.

The following steps are followed in developing the methodology to address this problem:

1. Developing a mixed integer linear programming model to determine the supply chain lot sizing decisions by considering the congestion effects. This requires analyzing the relationship between the batch size and the production congestion with respect to load dependent lead time (LDLT).
2. Incorporating the disruption characteristics to the resources.

3. Performing sensitivity analysis to determine the relationship of the supplier capacity and the production congestion with respect to disruptions.
4. Validating the batch size decisions through the simulations and testing by computing the stability level.

In this chapter, we first introduce an MILP model for constructing the MRP plan covering the entire supply chain parties by considering the congestion effect. Second, we look at the propagation of the disruption effects on the upstream level of the supply chain by modeling it in a simulation environment. Finally, the MRP stability for the supply chain parties with respect to WIP level is measured by a proposed stability metric.

3.1 Problem context

The supply chain deliberated in this research consists of two main tiers: the downstream, which receives the demand from the customer, is the manufacturer of product A. The components of product A are supplied from the upstream level or the suppliers of product A, which are manufacturers B and C. The required components are one unit of part B and two units of part C to assemble one product A as illustrated in Figure 3.1.

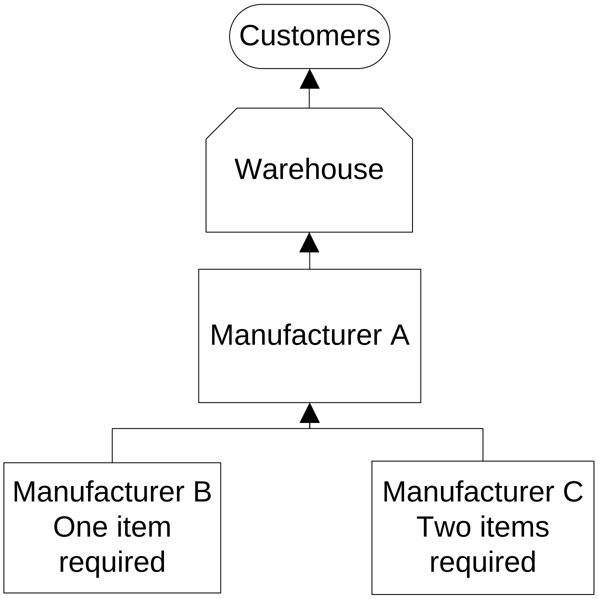

Figure 3.1: Supply chain configuration

We assume that the real time information system is installed in manufacturer A; manufacturer A often receives information about the product stocks and movements, and it has to react accordingly. Thus, manufacturer A should update its production plans as soon as any real time information is available. However, frequently changing the release plan will impact the upstream production activities and their supplier. The operational and material flow's assumptions are as follows:

1. The customer demand follows normal distribution.
2. The assembly line at manufacturer A requires a set-up time to produce a batch of product A.
3. The batch size for manufacturer A is calculated using the EOQ,

$$EOQ = \sqrt{\frac{2*Setup\_Cost*Demand}{Holding\_Cost}}. \qquad (3\text{-}1)$$

4. Suppliers B and C are responsible to provide the required items, in batches, to A in order to be assembled to produce the final product. It is then sent to the warehouse where a real time information system is installed in order to keep track of the changes.

The primary production plans for the entire supply chain for 12 periods are generated from the optimization model by considering congestion effects. The queuing theory, based on G/G/1 is applied to incorporate the congestion effect. Due to the fact that the queuing models are highly nonlinear, a linearization method is used to linearize the problem and solve it in MILP. The main reason for choosing G/G/1 is that the status of system will change in the case of any disruption occurs. In other words, the markovian arrival and processing characteristics will be affected by the disruptions, making a general type distribution more suitable for this case.

3.2 Methodology

The optimization model is formulated by MILP in order to find the optimal production rate and inventory level for each period with respect to the cost of production, inventory, raw material release, WIP, and setup in a supply chain environment (Askin & Goldberg (2002)). On the other hand, validation of the system and the four types of disruption are modeled using simulation. The result of the simulation model is the input of the stability metrics in order to assess the performance of the batching and capacity level selection. In the following section, the optimization model is demonstrated and afterwards, the simulation and stability measuring metrics will be discussed.

3.3 Optimization model

The first step in developing the MILP model is to incorporate the disruption and congestion effects into the product flow.

3.3.1 The effect of disruption to the capacity of supply chain nodes

Disruptions in a process affect the effective production rate by stopping the processing activities. The effect of these disruptions is derived from the following equations (Hopp & Spearman (2000)):

$$AT = \frac{E[T_d]}{E[T_d]+E[T_r]} \quad (3\text{-}2)$$

$$E[T_e] = \frac{E[T_s]}{AT} \quad (3\text{-}3)$$

$$C_e^2 = C_s^2 + (1 + C_r^2)AT(1 - AT)\frac{E[T_r]}{E[T_s]} \quad (3\text{-}4)$$

The availability AT of the resource in a disruption is calculated from the expected disruption occurrence time $E[T_d]$, and the expected disruption length $E[T_r]$, as shown in equation (3-2). $E[T_e]$ is the expected effective process time, where $E[T_s]$ is the expected natural process time. Finally, the SCV $C_e^2, C_s^2, and\ C_r^2$ are for effective process time, service time, and disruption time, respectively.

3.3.2 Computation for items arrival rate to A

The mean arrival rate and the SCV of the downstream A should be calculated, as it receives the raw material from the supplier in batches and then the product A is assembled. The arrival rate to producer A is the departure rate of items from the less frequent supplier, as the environment of the proposed supply chain is an assembly. The departure coefficient of the variation of B and C is derived from the following equation:

$$C_d^2(G/\mathrm{G}/1) \approx (1-u^2) * C_a^2 + u^2 C_s^2 \qquad (3\text{-}5)$$

where $u = E[T_a]/E[T_s]$, $E[T_a]$ is the expected time between arrivals, and C_d^2 is the SCV of the departure from the supplier (Curry & Feldman (2009)).

Next, the SCV of arrivals to manufacturer A will be derived from the following equation (Curry & Feldman (2009)):

$$C_a^2 = \sum_{i=1}^{n} \frac{\lambda_i}{\lambda_A} * C_{di}^2 \qquad (3\text{-}6)$$

3.3.3 The effect of batching

The batch size for components B and C are given by A using the EOQ formulation. The assumption of the batch size is given by manufacturer A, which can be calculated from the EOQ equation. Meanwhile, batching will affect the arrival rate and the coefficient of the variation of arrivals to A. The batching effect is derived from the following equation (Curry & Feldman (2009)):

$$\lambda(\mathrm{Batch}) = \frac{\lambda(\mathrm{A})}{k} \qquad (3\text{-}7)$$

$$C^2[T(Batch)] = \frac{C^2[T_d]}{k} \qquad (3\text{-}8)$$

Where, *k* is the batch size.

3.3.4 The (MILP) model

Once the coefficient of variation for arrivals to manufacturer A and the coefficient of variation for service times at the suppliers B and C are calculated, it can be inserted in the clearing function to accurately represent the capacity utilization at these nodes. The supply chain lot sizing model can then be formulated as follows:

Parameters:

S_i	Setup cost in stage i,
h_{it}	Holding cost in stage i at time t,
w_{it}	WIP cost in stage i at time t,
re_{it}	Raw material released job cost in stage i at time t,
D_t	Demand rate of final stage at time t,
c_i	Coefficients of variation of stage i,
c_a	Coefficients of variation of arrival rate,
c_s	Coefficients of variation of service time,
M	Large number,
k	Batch size,
Cap_i	Resource capacity of stage i,
$r_{i,b(i)}$	Number of items of the current stage required to assemble each item of the predecessors stage,
N	Number of lines for the clearing function of stage 1,
F	Number of lines for the clearing function of stage i,
ULU	Upper limit utilization,
Z	Number of lines, which should be active,

Decision variables:

X_{it}	production level in stage i at time t,
I_{it}	Inventory level in stage i at time t,
W_{it}	WIP level in stage i at time t,

R_{it} Number of released jobs in stage i at time t,

δ_{it} Binary number= $\begin{cases} 1, & \text{if a setup is required in stage I at time t.} \\ 0, & \text{otherwise.} \end{cases}$,

γ_{yt} Binary number for stage 1= $\begin{cases} 0, & \text{if the CF representing lines is matched} \\ & \text{with the desired ULU at time t.} \\ 1, & \text{otherwise.} \end{cases}$,

β_{yt} Binary number for stage i = $\begin{cases} 0, & \text{if the CF representing lines is matched} \\ & \text{with the desired ULU at time t.} \\ 1, & \text{otherwise.} \end{cases}$,

$$Min\ \sum_{t=1}^{T}(S_i * \delta_{it} + h_{it} * \ I_{it} + w_{it} * W_{it} + re_{it} * R_{it}) \qquad (3\text{-}9)$$

Subject to:

$$X_{it} \leq M * \delta_{it} \quad \forall_{it} \qquad (3\text{-}10)$$

$$I_{1t} = I_{1,t-1} + X_{1t} - D_t \quad \forall_{i,t} \qquad (3\text{-}11)$$

$$I_{it} = I_{i,t-1} + X_{it} - r_{i,b(i)} * X_{b(i),t} \quad \forall_{i,t} \qquad (3\text{-}12)$$

$$W_{it} = W_{i,t-1} + R_{it} - X_{it} \quad \forall_{i,t} \qquad (3\text{-}13)$$

$$X_{1t} \leq Cap_1 * \left(\frac{k*\mu_{1t}}{(k*\mu_{1t})+\delta_{1t}}\right) * \left(\frac{W_{1t}+1\sqrt{W_{1t}^2+(2*c_1^2*W_{1t})+1}}{1-c_1^2}\right) \quad \forall_{1t} \qquad (3\text{-}14)$$

$$X_{it} \leq Cap_i * \left(\frac{W_{it}+1\sqrt{W_{it}^2+(2*c_i^2*W_{it})+1}}{1-c_i^2}\right) \quad \forall_{it} \qquad (3\text{-}15)$$

$$\left(\frac{k*\mu_{1t}}{(k*\mu_{1t})+\delta_{1t}}\right) * \left(\frac{W_{1t}+1\sqrt{W_{1t}^2+(2*c_1^2*W_{1t})+1}}{1-c_1^2}\right) \leq ULU + M * \gamma_{yt} \quad (y = \ 1{,}2 \ldots, N)\ \forall_{1t,yt}$$

(3-16)

$$\left(\frac{W_{it}+1\sqrt{W_{it}^2+(2*c_i^2*W_{it})+1}}{1-c_i^2}\right) \leq ULU + M * \beta_{et} \quad (e = \ 1{,}2 \ldots, F)\ \forall_{it}$$

(3-17)

$$\sum_{y=1}^{N} \gamma_y = N - Z \qquad (3\text{-}18)$$

$$\sum_{e=1}^{F} \beta_e = F - Z \qquad (3\text{-}19)$$

The objective function minimizes the production cost, inventory cost, WIP holding cost, and raw material release cost (3-9). The setup cost will occur if there is a production (3-10). The inventory balance for the last stage, and the inventory balance for the upstream stages is shown in (3-11) and (3-12) respectively. WIP flow balance between released quantities and the production quantity is represented in (3-13). Clearing functions in (3-14) and (3-15) where $c_i = \frac{c_a^2 + c_s^2}{2}$, Pahl, Voss, & Woodruff (2007) represents the nonlinear relationship between the throughput and the WIP. Utilization is limited by constraints (3-16), and (3-17) in order to avoid excessive amount of congestion. Finally, constraints (3-18) and (3-19) ensure that the Z number of lines are only active, to set an upper bound on the utilization level.

This model consists of (5 * i * t) decision variables and (3 * t) + (12 * i) constraints. Some heuristics should be use to solve the model if there is a need to enlarge the size of the supply chain members or number of the items.

Since the clearing functions are nonlinear, they should be linearized to solve the model in MILP. A fuzzy clustering method is used to linearize the clearing function (Nejad (2011), forthcoming). The next Section presents the essence of the fuzzy clustering method implemented for clearing functions.

3.3.4.1 Fuzzy clustering method

The linearization method consists of a fuzzy clustering method, which converts a concave clearing function into a set of linear constraints. This is done, first, by finding the cluster center for a set of points, and then, by finding the radius of the cluster to the selected center point in order to determine the members of the cluster. At the end, the line equation for each cluster center is derived.

The methodology is divided into two parts. The first part finds the segments, which divide the entire curve into small sections. In order to do that, the second derivative of the concave function should be derived in order to detect the change of the curve's decreasing slope rate. Afterward, the points with similar slope rates are grouped together in a segment. Furthermore, clusters that correspond to each segment are found.

The second part is the clustering method. Clustering is implemented by using one of the MATLAB functions, which is Subclust. The Subclust parameters are presented as follows (Chiu (1994)):

c	Clusters centers,
s	The influence of the cluster center in each of the data dimensions,
G	Consists of G_1 and G_2, where G_1 is the WIP level, and G_2 is the throughput corresponding to the WIP level.
r_a	Cluster center radius; with a range between 0.2 and 0.5,
γ	This factor is used to multiply the radii values that determine the neighborhood of a cluster center, so as to squash the potential for outlying points to be considered as part of that cluster,

α This factor sets the potential as a fraction of the potential of the first cluster center, above which another data point is accepted as a cluster center.

β This factor sets the potential, as a fraction of the potential of the first cluster center, below which a data point is rejected as a cluster center.

$$[c, s] = subclust(G, r_a, [\gamma, \alpha, \beta]) \qquad (3\text{-}20)$$

Subclust is a function that sets the cluster center for the G_1 and G_2 sets of points. The range of the cluster center radius is between 0.2 and 0.5, as the cluster center approaches to 0.5, the number of clusters decreases. Doing so will increase the gap between the successive lines and the accuracy will decrease as well.

Using the following equation forms the set of lines that represents the curve:

$$G_2 = slope * G_1 + b \qquad (3\text{-}21)$$

First, the concave function is derived in order to get the slope of the corresponding cluster center. Second, by solving the equation (3-21) to b, the line equations are formed. Finally, the curve will resemble the one shown in Figure 3.2. By incorporating the set of lines in place of the nonlinear clearing function, we can convert the proposed model into a MILP.

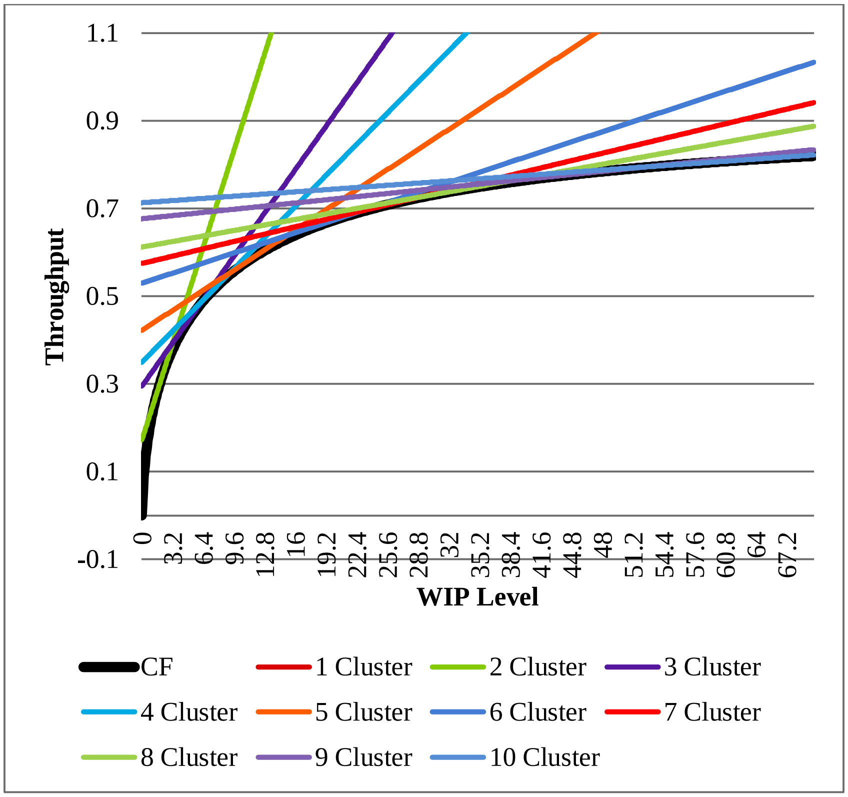

Figure 3.2: Concave curve linearization

3.4 Simulation model

The simulation model is built in order to validate the MILP model. The input of the simulation model is the result of the optimization model, which is the production level at each stage of the supply chain. The entire year is divided into 12 periods, and the supplier, manufacturers B and C, will begin their production according to the released plan. Meanwhile, the customer, manufacturer A, may request an update to the current period plan, which will be based on the real time information system by one of the four disruption factors: expediting, canceling, adding, and postponing an order.

If the update is to cancel the order, the supplier resource will be idle for the cancelled period, and that is considered as a loss. In the case of a postponement, the finished products will be stored in the inventory for the next period, and that will increase the inventory cost. In the case of an increase in quantity or if the order is expedited, the manufacturer should check the capacity and the production lead time in order to respond to these disruptions. In the following subsection, the simulation model logic is presented.

3.4.1 Simulation model architecture

The simulation model is based on the MRP schedule generated from the optimization model. Once the demand is generated for the current period, it first has to check if this demand was expedited in the previous period. If it is the case, the order will be cancelled. Otherwise, it will check if there is a request to cancel this order and if so, the order will be cancelled. If not, the model will check if there is a sufficient inventory to meet the demand and if not, it will send a request to produce the demand quantity. Before sending the order, check whether a postponement has to be done, and if not, then batch the demand into the required batched size and send it. Otherwise, send the postponement order to the inventory.

In case of expediting and adding order to the current MRP schedule. First, the model checks if there is a sufficient inventory to meet these changes, and if not, the utilization of the resource is verified. If it's less than 80%, the simulation model will send a request to produce the extra order quantity. If not, the order will be cancelled. These processes are illustrated in Figure 3.3.

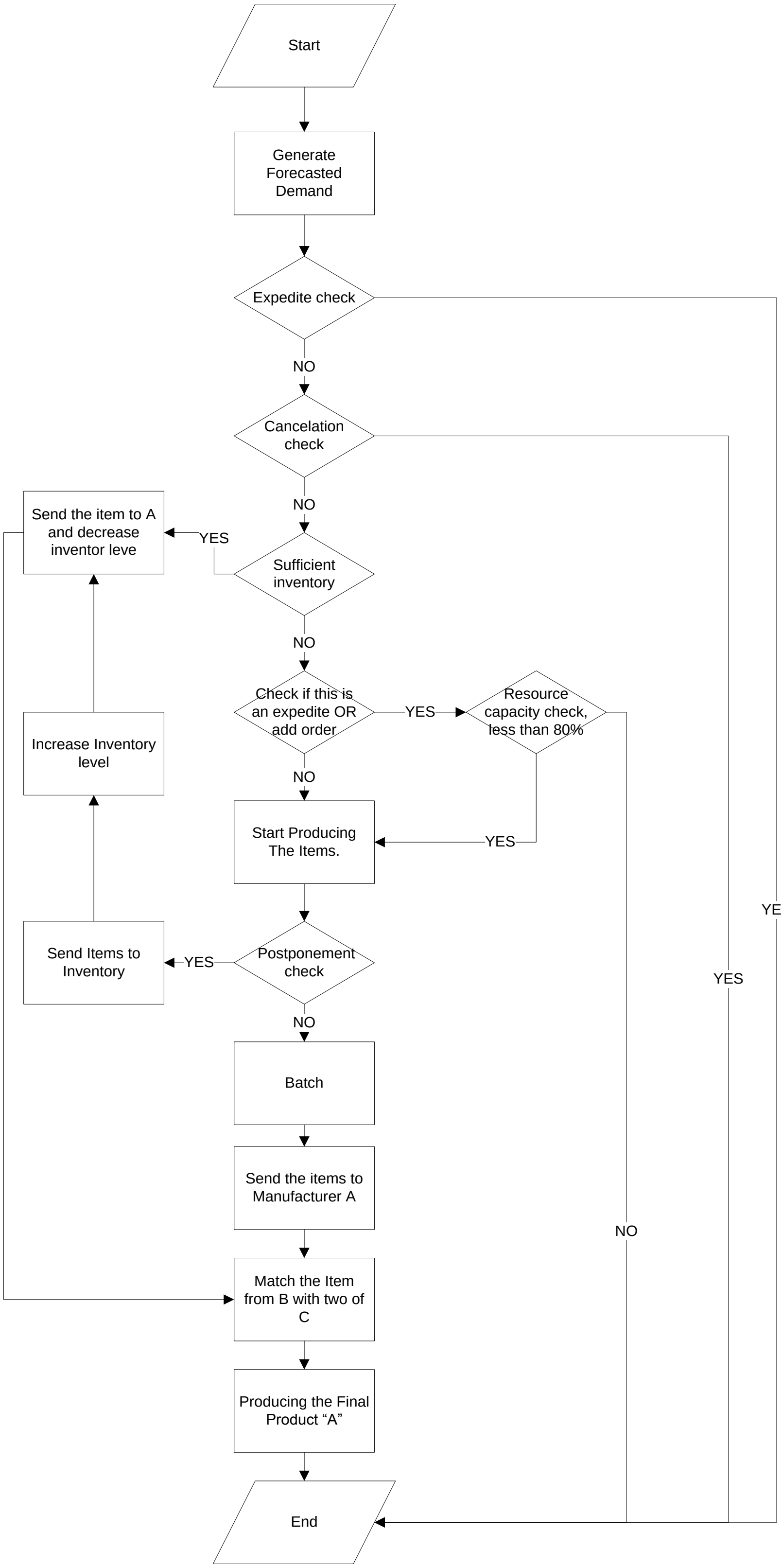

Figure 3.3: Simulation logic.

The simulation results will not give a full view of the system stability without computing the instability metrics, presented in the following section. This will help the production managers make the right lot-size decision, or the suppliers should set a sufficient slack capacity in order to improve the stability of the entire supply chain.

3.5 Instability metrics

The outputs of the simulation runs, which incorporate the disruption, are used as input to the instability metrics. The proposed instability metrics are considered to measure the severity of the disruptions effect to the supply chain. The new metrics introduce the congestion effect to Kabak & Ornek (2009) instability metrics, in addition to the quantity and time changes. The units' movement on the shop floor needs a space, and the increasing WIP level in case of the disruption will cause system congestion while the shop floor space is limited. These consist of two metrics that can measure the four disruption cases mentioned above. The proposed metrics parameters are as follows:

j	Company level in supply chain structure, j = 1. . .m,
i	Items at level j, i = 1. . .n_j,
p	Disruption time period occurrence,
bp	Beginning of the planning period,
Q_{ij}	Planned order quantity for item i at level j,
Q_{ij}^{D}	Disrupted planned order quantity for item i at level j,
WIP_{ij}	WIP level for the planned order quantity for item i at level j,
WIP_{ij}^{D}	WIP level for the disrupted planned order quantity for item i at level j,

$\delta(.)$	Binary number= $\begin{cases} 1, & \text{expedited released planned orders} \\ 0, & \text{otherwise} \end{cases}$,
WP	Weight function for planned orders, and $WP = A(p - bp)^{-B}$, where A and B are constants and A = 1.5 and B = 1.2, and $p > 1$,
$W(j)$	level weight function,
$W(E)$	Weight function for expedited released planned orders, $W(E) = Z * (E)^F$ where Z and F are constants and Z=1.0 and F=1.2,
w_1	a relative weight parameter for quantity-oriented instability, $0 < w_1 < 1$,
w_2	a relative weight parameter for expedited released plan orders instability, $0 < w_3 < 1$, and $w_1 + w_2 = 1$,
I^Q	Quantity-oriented instability,
I^{Stp}	Setup-oriented expedited released plan orders instability,
I	Total instability, $I = (w_1 * I^Q) + (w_2 * I^{Stp})$,
S	Stability, $S = 1 - I$,

The new metrics presented, as follow:

The quantity instability metric:

$$I^Q = \left(\left(\frac{\sum_{j=1}^{m} \left[\sum_{i=1}^{n_j} \left(Q_{ij} - Q_{ij}^D \right) * WP \right] * W(j)}{\sum_{j=1}^{m} \left[\sum_{i=1}^{n_i} Q_{ij} \right] * W(j)} \right) * \left(1 + \frac{\sum_{j=1}^{m} \left[\sum_{i=1}^{n_j} \left(WIP_{ij} - WIP_{ij}^D \right) * WP \right] * W(j)}{\sum_{j=1}^{m} \left[\sum_{i=1}^{n_j} WIP_{ij} \right] * W(j)} \right) \right) \tag{3-22}$$

where I^Q is a quantity and congestion instability metric for the entire supply chain. The quantity changes are measured by the difference between the total quantity of the simulation run with and without disruption. That quantity is then multiplied by the weighted period for the planning horizon. After that, the calculation will be repeated until the last item in n_j, the total sum of the calculations, are multiplied by the echelon level weight $W(j)$, to reflect the severity effect of this change in the supply chain echelons. The $W(j)$ will increase as the supply chain increases to reflect the bullwhip effect. Then, to normalize the metric, the total different change quantity is divided from the maximum quantity change for each period, multiplied by $W(j)$.

At the end, the quantity change part is multiplied by one, plus the change in WIP level to capture the congestion effect by inflating the quantity deviation measure. In the case of increasing the quantity, the WIP level will increase to meet the demand. The difference between the initial WIP and the increased WIP is multiplied by the weight of time of this change occurrence. Then, the total is multiplied by $W(j)$. Finally, to normalize the metric, we divide the total calculation by the maximum WIP level for each period change, multiplied by $W(j)$.

The setup instability metric:

$$I^{Stp} = \left(\left(\frac{\sum_{j=0}^{m} \left[\sum_{i=1}^{n_j} \left(\delta * (Q_{ij}^{D}) \right) * [W(E)] \right] W(j)}{\sum_{j=0}^{m} \left[\sum_{i=1}^{n_i} \max \left(Q_{ij}^{D} * [W(E)] \right) \right] W(j)} \right) * \left(1 + \frac{\sum_{j=1}^{m} \left[\sum_{i=1}^{n_j} \left(WIP_{ij} - WIP_{ij}^{D} \right) * WP \right] * W(j)}{\sum_{j=1}^{m} \left[\sum_{i=1}^{n_j} WIP_{ij}^{D} \right] * W(j)} \right) \right) \tag{3-23}$$

where, I^{Stp} is the setup and congestion instability metric for the entire supply chain. The setup is required for expediting the orders, and this is measured by multiplying the expediting quantity by the expediting weight function. Then, the calculation is repeated until the last item in n_j, and multiplied by the echelon weight of the supply chain. Finally, the last calculation divided by the maximum quantity can be expedited in each period, and multiplied by the maximum expedited weight function for every item in n_j. This total is multiplied by the echelon weight of the supply chain. At the last step, we multiply the setup part with the congestion factor as explained in Eq. (3-22).

Total instability equation:

$$I = (w_1 * I^Q) + (w_2 * I^{Stp}) \qquad (3\text{-}24)$$

In order to calculate the total instability for the whole supply chain parties, the values of equations (3-22) and (3-23) are multiplied by the corresponding weight, and are added. The total of the weight (w_1 and w_2) should be equal to one. The weight is assigned to the instability metric based on the severity effect of the quantity change or the setup.

Stability equation:

$$S = 1 - I \qquad (3\text{-}25)$$

As the instability values are between zero and one, the stability can be calculated using equation (3-25).

The proposed instability metrics will show the significance of studying different batch sizes and supplier capacities, and integrating them into the stability of the supply chain. This is illustrated in the case study presented in the next Chapter.

Chapter 4

4 Numerical results

A lot-size problem under demand uncertainty is studied in this case study by considering the congestion effects and disruptions on the nodes of the supply chain. Considering these factors will allow determining supplier capacities and lot size decisions in order to provide better stability to supply chain operations. The lot-size and supplier capacity is assessed by the proposed instability metrics. The case study incorporates three different demand variability scenarios, which are high, medium and low, to represent the demand uncertainty, and three batch sizes and two supplier capacity scenarios. The batch size is analyzed to observe the effect of the different level of batching on the stability of the supply chain.

The case study is divided into three sections. First, MILP is conducted to find the optimal production rate, with respect to the production, inventory, raw material release, and WIP cost. Second, a simulation model is built for validating the MILP results. The four disruption cases are modeled in the simulation model. Third, to facilitate the managerial decision about the proper choice of the lot-size and supplier capacities, the instability metrics are implemented in order to assess the stability of the supply chain environment.

The computations are performed by a personal desktop computer with Intel Core 2 Duo CPU 2.33 GHz, 2GB RAM on a Microsoft Windows XP Professional operating system.

4.1 Optimization model

The lot-size problem considered in this study is for a supply chain with two suppliers, one client, and a warehouse following the example mentioned in (Askin & Goldberg (2002)). The input data for the work station process time at each echelon, and the suppliers (B and C) arrival rate and SCV are as shown in Table 4.1 and 4.2 respectively. While, the arrival rate and the SCV for the downstream stage A should be calculated.

Table 4.1: The process time of the workstations

Workstation i	**E[T_s(i)]**	**C_s^2 (i)**
B	0.144	0.130
C	0.072	0.062
A	0.100	0.140

Table 4.2: The arrival rate and SCV for the suppliers

The mean arrival rate	**λ**	**C_a^2(i)**		
		HV	**MV**	**LV**
B	0.150/h	1.8225	0.81	0.0144
C	0.076/h	1.8225	0.81	0.0144

The data regarding the disruption frequency, disruption duration, and the SCV of the disruption duration are shown in Table 4.3, where disruption duration is following normal distribution with Mean (E[T_r(i)]) and SCV of (C_r^2 (i)). In Table 4.4, the disruption effect on the processing time of the resources and the corresponding SCV results are presented.

Table 4.3: Disruption occurrence, disruption duration, and SCV

Workstation i	**E[T_d(i)]**	**E[T_r(i)]**	**C_r^2 (i)**
B	40 h	10 h	0.50
C	40 h	10 h	0.09
A	80 h	20 h	0.10

Table 4.4: The effective process time and SCV

Workstation i	**E[T$_e$(i)]**	C_e^2 **(i)**
B	0.180	16.80
C	0.090	24.28
A	0.125	35.34

The SCV of the departure rate from the suppliers are shown in Table 4.5, as these results are derived by equation. (3-5).

Table 4.5: The SCV of departure from B and C

Workstation i	C_d^2		
	HV	**MV**	**LV**
B	12.22	11.91	11.67
C	17.84	17.55	17.32

For the assembly stage of the supply chain, the arrival rate and the SCV of the producer A is according to the departure rate from the less frequent supplier, C.

The arrival rate and SCV of manufacturer A is as shown in Table 4.6.

Table 4.6: The arrival rate and SCV of A

The mean arrival	λ	C_a^2		
		HV	MV	LV
A	0.076 Item/h	41.96	41.06	40.35

The batch mean arrival rate and SCV of manufacturer A is as shown in Table 4.7 where the batch size is derived from EOQ formula for each supplier, EOQ$_B$=820 and EOQ$_C$=1160.

Table 4.7: The batch arrival rate and SCV of A

The arrival rate of a batch	λ	C_a^2		
		HV	MV	LV
A_B	0.00018/h	0.051	0.050	0.049
A_C	0.00006/h	0.036	0.035	0.035

To synchronize the batch size between the suppliers, the batch size of the less frequent supplier is considered. The MILP framework and assumptions will be discussed in the next section.

4.1.1 The MILP model

Due to the nature of the relationship between the WIP level and the throughput, CF is a concave function. The fuzzy clustering method (Nejad (2011)) is proposed to linearize the concave function; this will be presented in Subsection 4.1.1.1. After that, the MILP model is discussed in Subsection 4.1.1.2.

4.1.1.1 The fuzzy clustering method

For simplicity and to decrease the computation time, a total of 10 lines have been used to represent the curve. Using Subclust function in the MATLAB platform has performed the fuzzy clustering method. First, the second derivative of the clearing function is computed, in order to divide the CF curve into segments based on the curvature degree. We divide the curve into two main segments. Second, the WIP level and the CF values corresponding to the WIP level are entered to the MATLAB in order to get the tangent points for each line. Finally, the equation for each line is calculated by deriving the first derivative of the tangent points.

The above processes are done for each server of the supply chain. As a result, the Mixed Integer Non-Linear Programming (MINLP) is converted to MILP model by using the fuzzy clustering method. In the following Sub-section, the optimization model for generating the MRP schedule is built and the solutions are presented.

4.1.1.2 The MILP model

In order to study the effect of the customers demand uncertainty on the supply chain stability, three different demand variability levels are analyzed: high, medium, and low. The initial customer demand is generated following a normal distribution with mean, standard deviation, and coefficient of variation as shown in Table 4.8. The MILP model is built in the Microsoft Excel 2010; OpenSolver is used to solve the model on the Excel platform.

Table 4.8: Demand characteristic

Demand Variability	Mean	Standard Deviation	Coefficient of Variation
High	1050	1417	1.35
Medium	1050	945	0.90
Low	1050	126	0.12

In addition, the impact of the batch size and the supplier capacity is studied in the model. First, the batch size is calculated using EOQ equation for the less frequent supplier, C. As shown in Table 4.9, the MILP results are generated using a range of batch size values. Second, the initial resource capacity for the supply chain parties is set according to the first feasible solution of the MILP subject to high demand variability, and the same capacity is used for the other cases. In order to observe the impact of supplier capacity to the stability, we propose to increase the first feasible solution capacity level by 50 pieces per period in order to observe the impact of capacity change.

Table 4.9: Batch size for the suppliers

Supplier	Batch Size		
	EOQ/2	EOQ	2*EOQ
B	290	580	1160
C	580	1160	2320

Table 4.10 represents the cost coefficients of the objective function. The costs of the setup, holing (inventory), WIP, raw material release for work station A is higher than B and C, and it is decreasing as we move upstream in the supply chain.

Table 4.10: Cost of the objective function coefficients

Workstation	Cost			
	Setup	Holding	WIP	Raw Material Release
A	80	3	2	1
B	70	2	1	0.5
C	50	1	0.5	0.25

Tables 4.11 and 4.12 represent the utilization of suppliers B and C respectively, as CF is considered in the MILP. The utilization of supplier B at different demand variability levels show that increasing its capacity reduces the utilization levels. We see an opposite trend for the utilization of supplier C in the case of high demand variability and medium demand variability at the EOQ batch size. The main reason of that is the number of production periods decreases.

Table 4.11: Supplier B utilization

Supplier	Batch Size	Demand Variability					
		HV	MV	LV	HVE	MV	LVE
B	290	0.4006	0.4041	0.3005	0.3950	0.3980	0.2962
	580	0.4195	0.4156	0.3005	0.4023	0.3980	0.2962
	1160	0.4006	0.3637	0.3005	0.3950	0.3582	0.2962

Table 4.12: Supplier C utilization

Supplier	Batch Size	Demand Variability					
		HV	MV	LV	HVE	MVE	LVE
C	290	0.3875	0.4415	0.3229	0.4272	0.4380	0.3204
	580	0.3875	0.4242	0.3229	0.4272	0.4380	0.3204
	1160	0.3874	0.3973	0.3229	0.4272	0.3941	0.3204

The optimal costs of each scenario are illustrated in Table 4.13. It is clear from the table that increasing the supplier capacity is decreasing the total cost, and the large batch size is decreasing the total cost too.

Table 4.13: The total cost of different batch sizes and demand variability and extra supplier capacity

	Resource Capacity					
Demand Variability	A 3285 / B 3500 / C 6514			A 3285 / B 3550 / C 6546		
	Batch Size			Batch Size		
	290	580	1160	290	580	1160
HV	34185.2	33343.8	33160.8	33991.4	33142.6	32973.1
MV	30355.5	30072.8	29854.9	30300.2	29861.3	29809.9
LV	27735	27725.1	27720.6	27734.1	27724.3	27719.7

The Figure 4.1 shows that there is a strong relationship between the batch size and the demand variability. In the high demand variability, the small batch size will have the highest total cost, as a result of the increased number of the setups. In addition, the release rate and the WIP level will increase accordingly. In contrast, the total cost will decrease as the batch size is increasing. In other words, there is an inverse relation between the batch size and the total cost in case of high demand variability.

The effect of the different batch sizes will be less significant in the case of medium and low demand variability. There is a slight effect on the total cost in this case. In contrast, in the case of low demand variability, the batch size is not affecting the total cost, as it is shown in Figure 4.1.

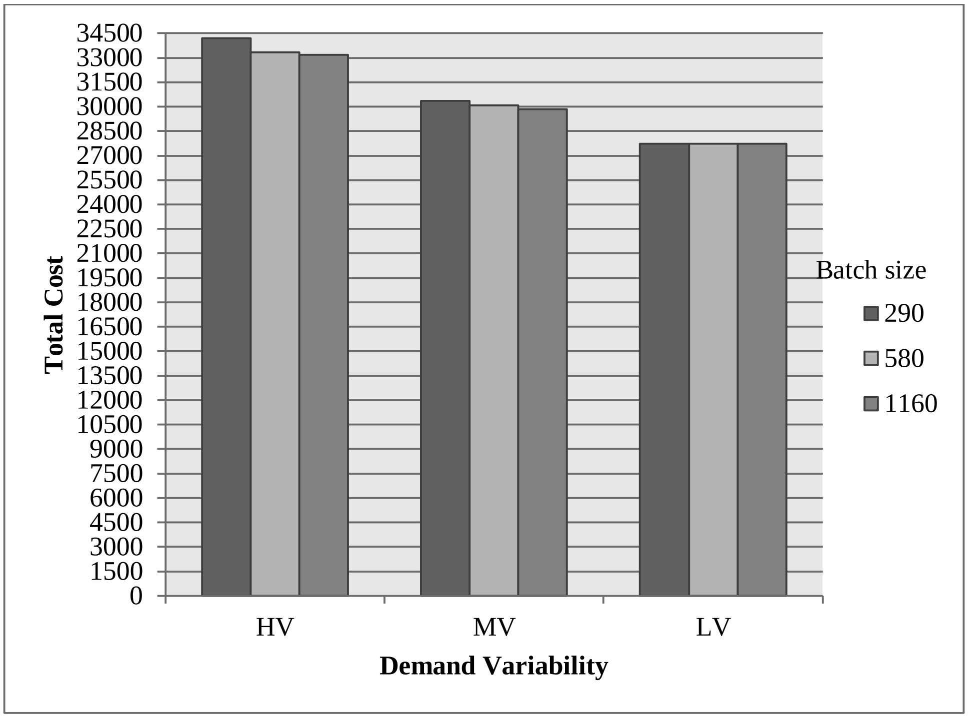

Figure 4.1: The effect of the batch size on different demand variability

Table 4.14 shows the percentage reduction in the total cost by adding a small amount of capacity to suppliers. There is a significant correlation between the high demand variability and the suppliers' capacity, and this correlation decreases as the demand variability decreases. Moreover, there is also a significant correlation between the batch size and the suppliers' capacity. The higher reduction is originating from the batch size calculated by the EOQ equation. The reason for that is the nonlinear shape of the CF, which is a concave curve, integrated into the MILP, as illustrated in Figure 4.2. In contrast, the low demand variability is not affected by suppliers' capacity and the batch size. In order to validate the MILP outputs and to test the stability of the supply chain operations, the solutions for each scenario have been implemented in the simulation environment.

Table 4.14: The percentage reduction in the total cost

Demand Variability	Batch Size

	290	580	1160
HV	0.569	0.603	0.566
MV	0.182	0.703	0.151
LV	0.003	0.003	0.003

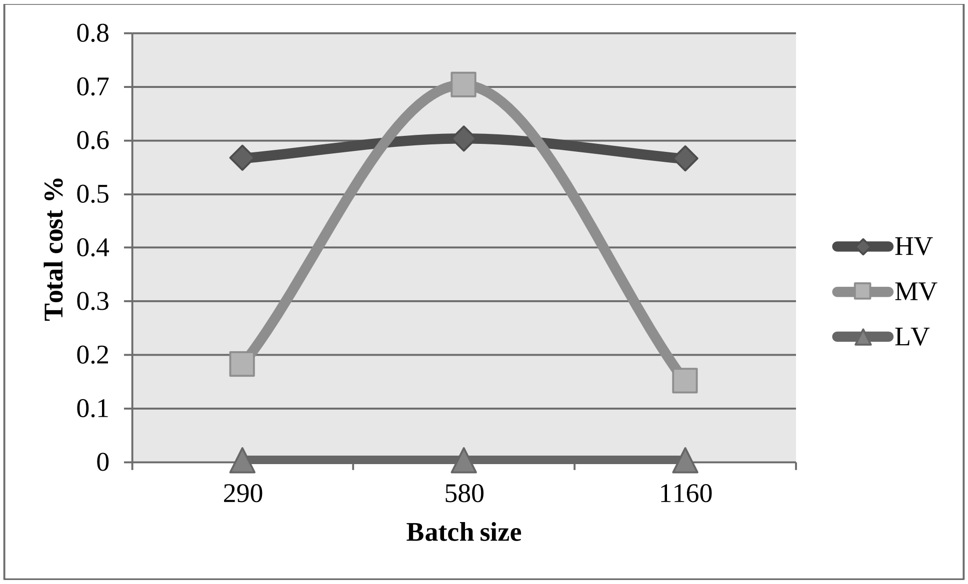

Figure 4.2: The effect of the batch size and supplier capacity on the CF

4.2 Simulation model

The use of simulation allows incorporating the random nature of disruptions and testing the supply chain settings obtained from the MILP model. The uncertainty regarding the type and the impact of the disruptions are represented by random variables. In addition, the randomness may also be observed in the process times at each node of the supply chain. The simulation settings for the disruptions, and the resources process time for the suppliers are shown in Table 4.15 and 4.16, respectively. The MRP schedule modeled in simulation will run as it is generated for the MILP, and disruptions are modeled as an external characteristic to the system, according to the simulation logic explained in Section 3.2.

Table 4.15: Disruptions setting

Disruption Type	First Occurrence	Time Between Occurrence	Disruption Time

Expedite	0.1 h	80 h	10 h
Cancel	21 h	80 h	10 h
Add	41 h	80 h	10 h
Postponement	61 h	80 h	10 h

Table 4.16: Resource processing time

Resource	Normal Distribution	
	Mean	Standard Deviation
A	0.125 h	0.7430
B	0.180 h	0.7380
C	0.09 h	0.4436

Different scenarios of the MILP model were run in the simulation model. Table 4.17 is showing the simulation model setup such as replication length and number of replications.

Table 4.17: Simulation runs setup

Run Setup	Value
Working hours per day	8
Working days per month	20
Replication length	240 day
Number of replications	5

Table 4.18, 4.19, and 4.20, is illustrating the demand loss for the different batch sizes in the case of high, medium, and low variability. As shown in table 4.18 integrating the CF into the MRP schedule is improving the demand loss. The simulation runs results are showing the loss in the order quantity, as a result of considering the congestion effect in the MILP model. In other words, neglecting the effect of the congestion in the MRP will lead to a higher demand loss, and modeling the MILP according to that assumption will not give an accurate behavior of the system. In contrast, this effect cannot be seen in low demand variability, as there is a considerable amount of idle capacity. As a result of this, the production and WIP level for MILP with CF or without are the same.

Table 4.18: Demand loss in the case of high demand variability

Batch Size	High Demand Variability		
	Without CF	With CF	Improvement
290	3270	3244	26
580	3585	3499	86
1160	4084	3984	100

Table 4.19: Demand loss in the case of medium demand variability

Batch Size	Medium Demand Variability		
	Without CF	With CF	Improvement
290	2215	1974	241
580	4606	4250	356
1160	3799	2889	913

Table 4.20: Demand loss in the case of low demand variability

Batch Size	Low Demand Variability		
	Without CF	With CF	Improvement
290	3443	3443	0
580	3463	3463	0
1160	3425	3425	0

The rest of the simulation results will be elaborated in the next Section, as the simulation outputs are used to assess the instability metrics.

4.3 Instability metrics

The instability metrics are the last stage in validating the outcome of the MILP. The different lot-size, suppliers' capacity, and demand variability effect into stability of the supply chain structure considered in this work are measured by the proposed instability metrics. The stability results of the suppliers are presented in Table 4.21, for the initial capacity (IC), and Table 4.22 for the proposed capacity (PC). The IC is the capacity that we get by solving the MILP for the high demand variability for the suppliers, while; the PC is increasing the IC by a small increment, which is 50 items per period.

Table 4.20: Suppliers stability with initial capacity

Supplier	Batch Size	Demand Variability		
		HV	MV	LV
B	290	0.486	0.586	0.465
C		0.719	0.751	0.715
B	580	0.518	0.454	0.490
C		0.719	0.703	0.720
B	1160	0.567	0.597	0.551
C		0.718	0.745	0.732

Table 4.21: Suppliers' stability with the proposed capacity

Supplier	Batch Size	Demand Variability		
		HV	MV	LV
B	290	0.486	0.587	0.465
C		0.719	0.776	0.715
B	580	0.523	0.454	0.498
C		0.721	0.704	0.721
B	1160	0.568	0.598	0.551
C		0.718	0.746	0.732

The instability metrics show that the batch size is affecting the stability of the supply chain. Figure 4.3 and 4.4 illustrate that large batch size will give more stability for supplier B. This is due to the fact that the reduced numbers of setups increase the uptime for the suppliers. In contrast, for supplier C, large batch size will give more stability only in the case of low demand variability. Small batch size for the medium demand variability will give more stability, and there is almost no difference between the batch sizes in the case of high demand variability.

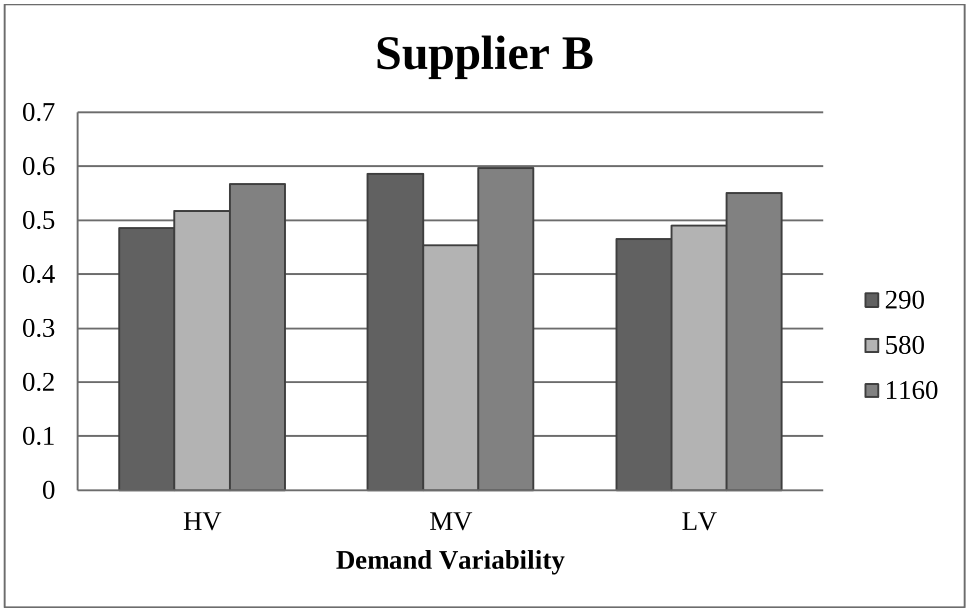

Figure 4.3: The effect of Batch size to the stability of supplier B

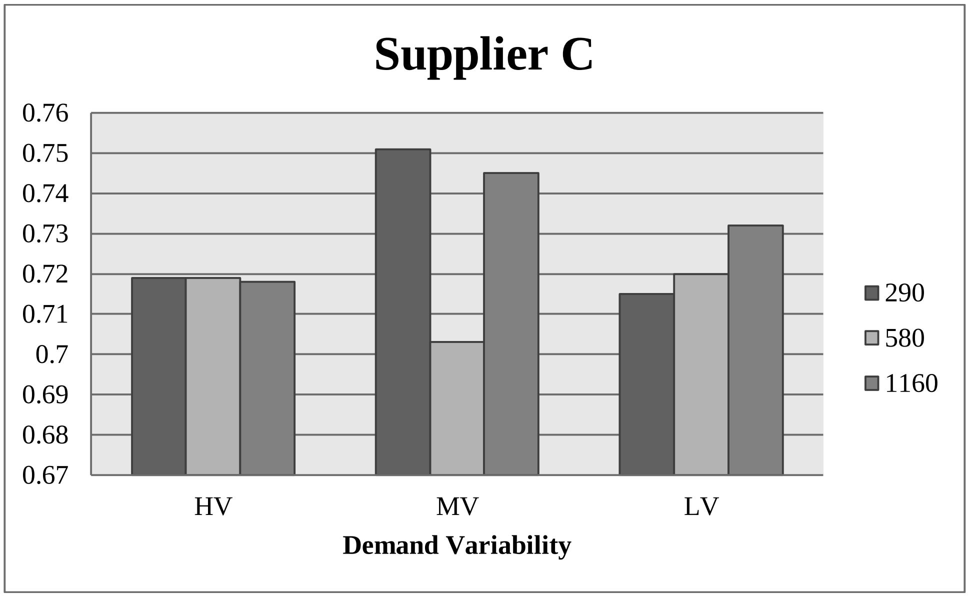

Figure 4.4: The effect of batch size to the stability of supplier C

The Figures 4.5 and 4.6 show the effect of the suppliers' capacity on the stability of the whole supply chain. First, in the case of high demand variability, the stability of supplier B is significantly affected by increasing the capacity at the EOQ batch size. This effect decreases in the case of large batch size, while there is no improvement in the small batch size. Moreover, the same conclusion can be drawn for supplier C in the case of the EOQ batch size. However, there is no improvement in stability in the cases of small and large batch size.

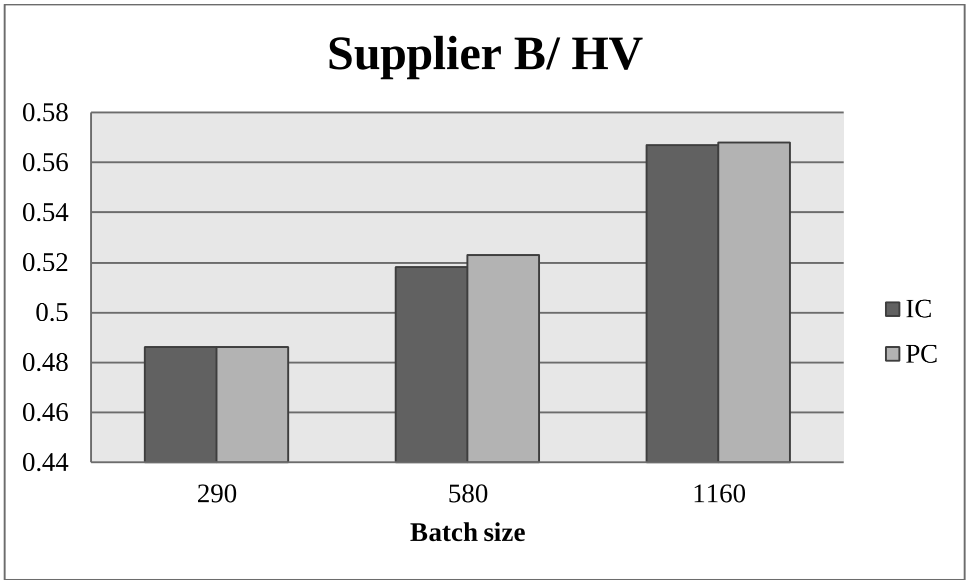

Figure 4.5: Supplier B’s capacity effect on the batch size in high demand variability

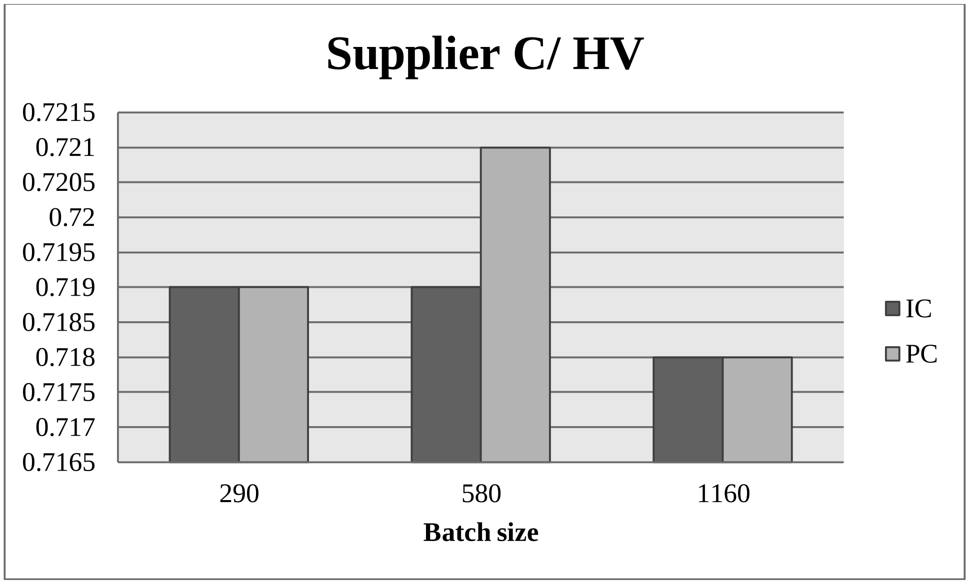

Figure 4.6: Supplier C’s capacity effect on the batch size in high demand variability

Second, in the case of medium demand variability, the capacity of supplier B does not affect the stability of the chain. However, an improvement in the stability of supplier

B can be seen in the case of low demand variability with EOQ batch size, and the same conclusion can be drawn for supplier C in the case of low demand variability. In contrast, for medium demand variability, the stability improvement can be seen in the case of small batch size, and this improvement is increased in the case of EOQ and large batch size.

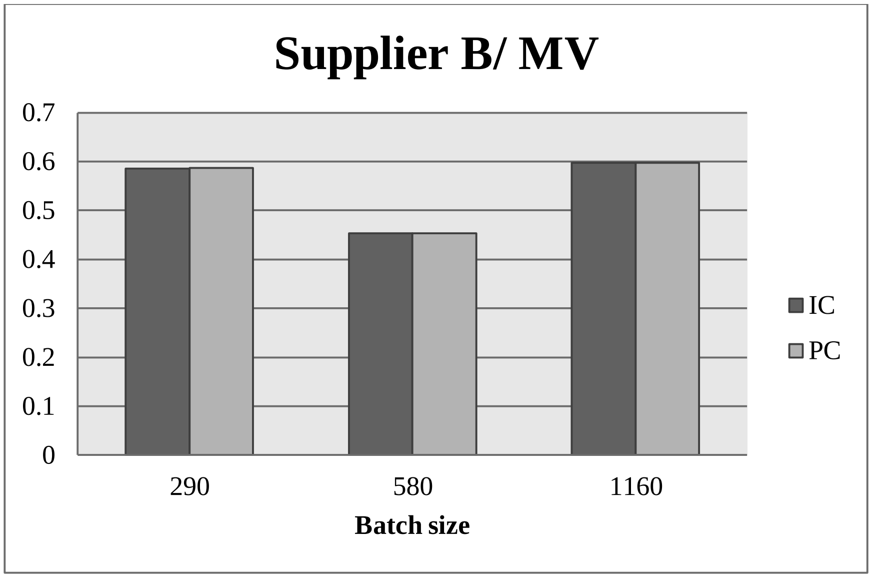

Figure 4.7: Supplier B’s capacity effect on the batch size in medium demand variability

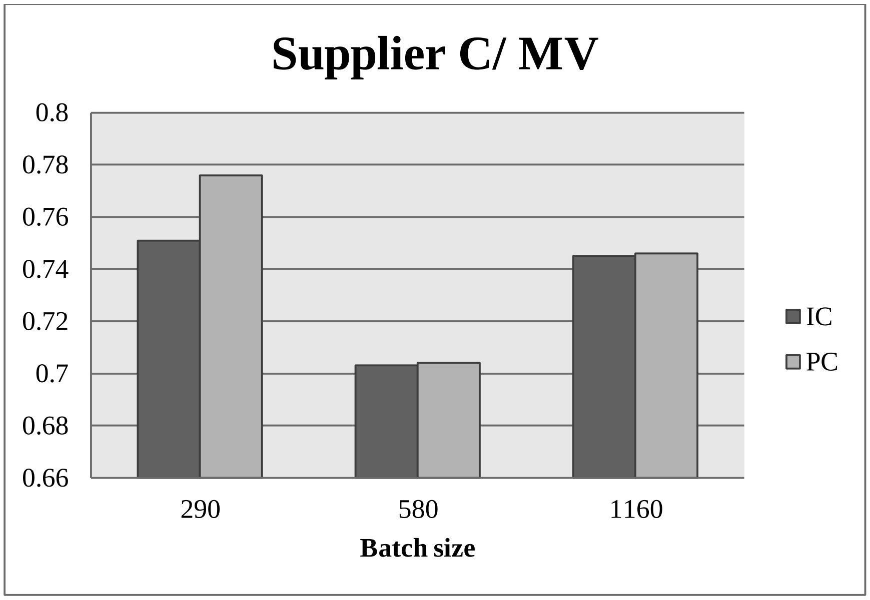

Figure 4.8: Supplier C’s capacity effect on the batch size in medium demand variability

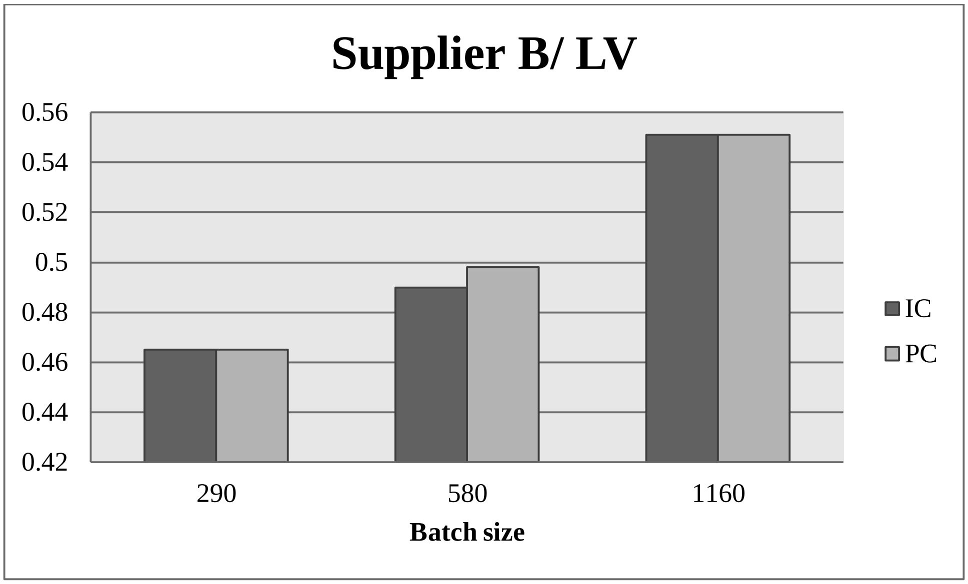

Figure 4.9: Supplier B’s capacity effect on the batch size in low demand variability

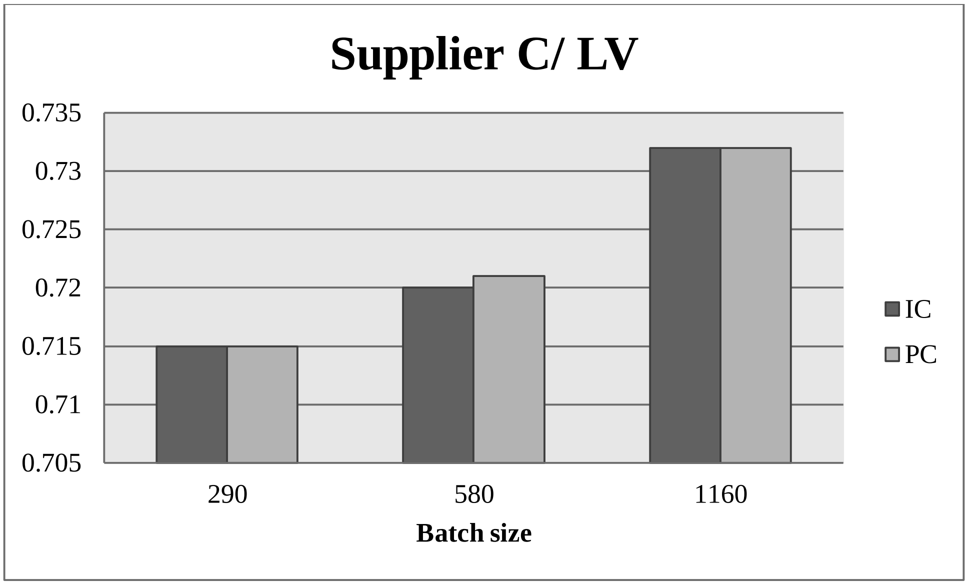

Figure 4.10: Supplier C’s capacity effect on the batch size in low demand variability

From Tables (4.20) and (4.21) and Figures (4.3) to (4.10), we conclude that large lot-sizes will give more stability to the entire supply chain parties, especially, in medium demand variability. The main reason of that is there exist some idle periods in the MRP in the case of medium demand variability. These periods will act as a capacity buffer and absorb the disruption. In contrast, it is very hard in low demand variability to accommodate these disruptions, as there is a production in each period.

Chapter 5

5 Conclusions and future research direction

Maintaining a high customer service level with low-production cost requires establishing a stable production plan. Due to the forecast errors, the uncertainty is inherent to any production plan. The forecast may change, as the released production plan gets closer to the execution. In addition, the supplier reliability may worsen the uncertainty. The real time information tracking systems will increase company's service level, but in order to get the benefit of the technology, the production managers must respond to the information update quickly. However, frequently re-planning the production plan will increase the production plan instability as well. Furthermore, the effect of the congestion is ignored in the production plans, and that will lead to infeasible plan as the lead time will increase exponentially.

Under these conditions, the production managers will attempt to mitigate the impact of uncertainty by using buffering or dampening strategies. Usually, buffering approach is going to increase the production cost by having safety stock or unused capacity, and of the dampening strategy by freezing the production plans will reduce the service level.

Therefore, the main objective of this thesis is improving the stability of the supply chain in the presence of demand variability and disruption to the MRP. We first construct MRP for the entire supply chain parties subject to congestion and disruption effect, in order to get a feasible and a stable plan. The second objective is to assess the effect of the lot size and supplier capacity on the stability in order to improve the service level of the supply chain. To accomplish these objectives, the following issues have been dealt with:

- First, an MILP model is developed to construct the MRP for the entire supply chain parties. The MILP model incorporates the congestion effect. Furthermore, due to the nonlinear characteristic of the congestion, as a result of the nonlinear relationship between the WIP level and the throughput, fuzzy clustering method is used to linearize the curve.
- Second, a simulation model is built in Arena to validate the results of MILP and to introduce the different disruption scenarios.
- Third, instability metrics with respect to the congestion effect are developed to measure the stability of the entire supply chain. In performing this assessment, the impact of congestion is incorporated in the metrics to accurately measure the system instability.
- Different batch sizes and supplier capacity are tested in this work, in order to improve the stability of the supply chain in the presence of demand variability and disruption to the MRP.

The proposed optimization model and stability metrics will help the production managers to make the right decision in choosing the batch size and the proper supplier capacities, in order to improve the stability in the presence of the demand variability and disruptions.

5.1 Conclusions

The conclusions of the numerical experiments performed in this thesis can be classified into the following three categories:

The MILP model

1. Increasing the supplier capacity by a small increment has a significant improvement on the total cost in the case of high demand variability, and this improvement decreases as the demand variability decreases.
2. The utilization of resources can be observed and adjusted as a result of integrating the CF to the MILP. The results of the MILP show that the utilization for both suppliers is high in the case of medium demand variability because the disruption effect is absorbed in the MRP schedule, as there are some idle periods in the MRP.
3. The total production cost of low demand variability and large batch size for the whole supply chain is lower than the medium and high demand variability. In addition, supplier capacity is not affecting the total cost in the case of low demand variability. In contrast, high demand variability is significantly correlated to the supplier capacity.
4. The MILP results show that there is a significant correlation between the supplier capacity and the batch size. The percentage reduction in the total cost is higher in the case of using the EOQ batch size.

The simulation model

Considering the congestion effect into their MRP schedule increases the company service level. The simulation results show that the demand loss in the scenario of neglecting the congestion effect increases as the batch size increases. In other words, neglecting the congestion effect in modeling the lot sizing decisions will result in an unrealistic representation of to the system behavior.

The instability metrics

1. The stability of the supply chain increases by increasing the batch size.
2. Having slack capacity at the suppliers improves the stability of the supply chain, and this effect can be seen in the case of high, medium, and low demand variability.

5.2 Future research direction

Further research is recommended in the following areas:

- Considering the supplier capacity as endogenous and introducing the cost of the extra capacity in the objective function equation can improve the lot sizing decisions. In other words, the capacity of the suppliers can be incorporated as a decision variable (factor) in the MILP.
- Using the instability metrics for the rolling horizon of the MRP in the context of supply chain is also another research direction.

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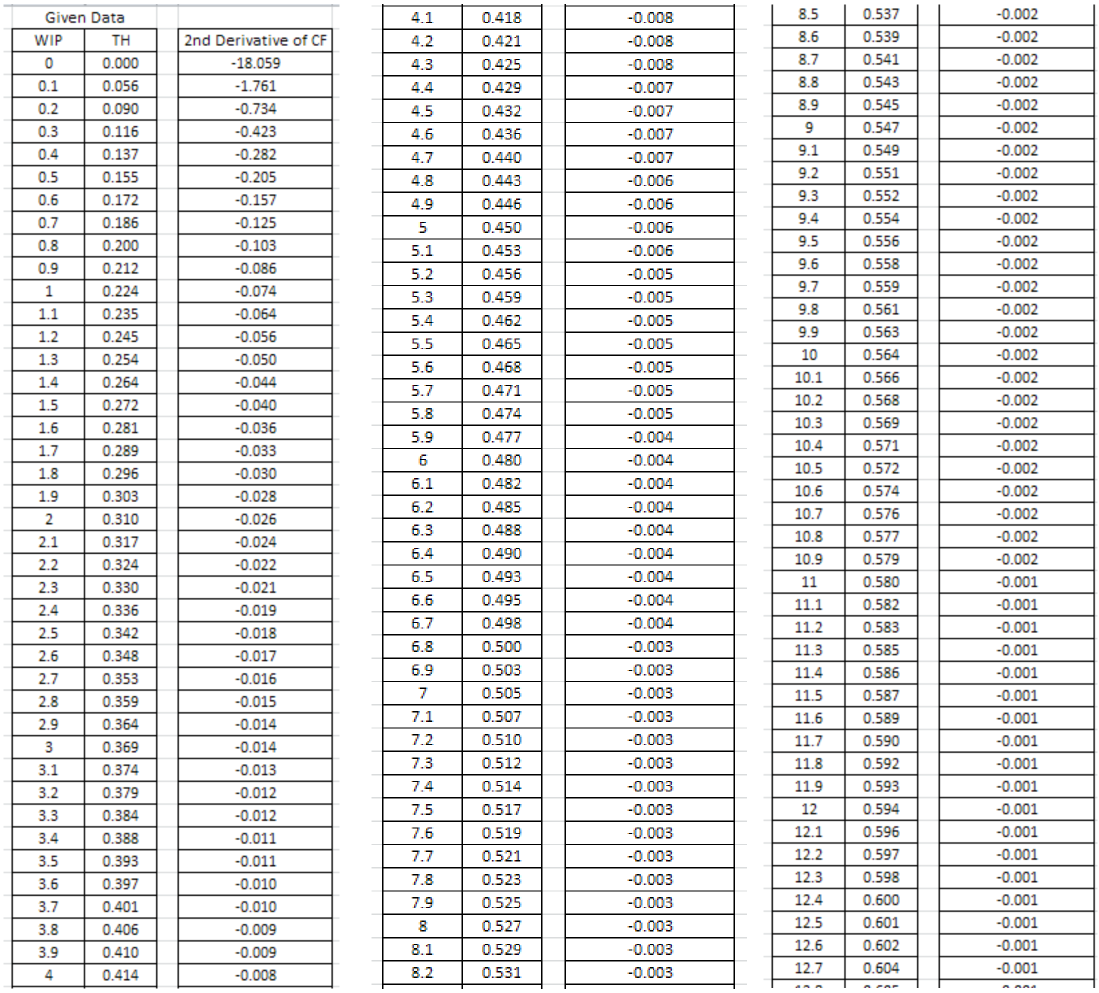
Appendices

Appendix A: Clearing Function Linearization

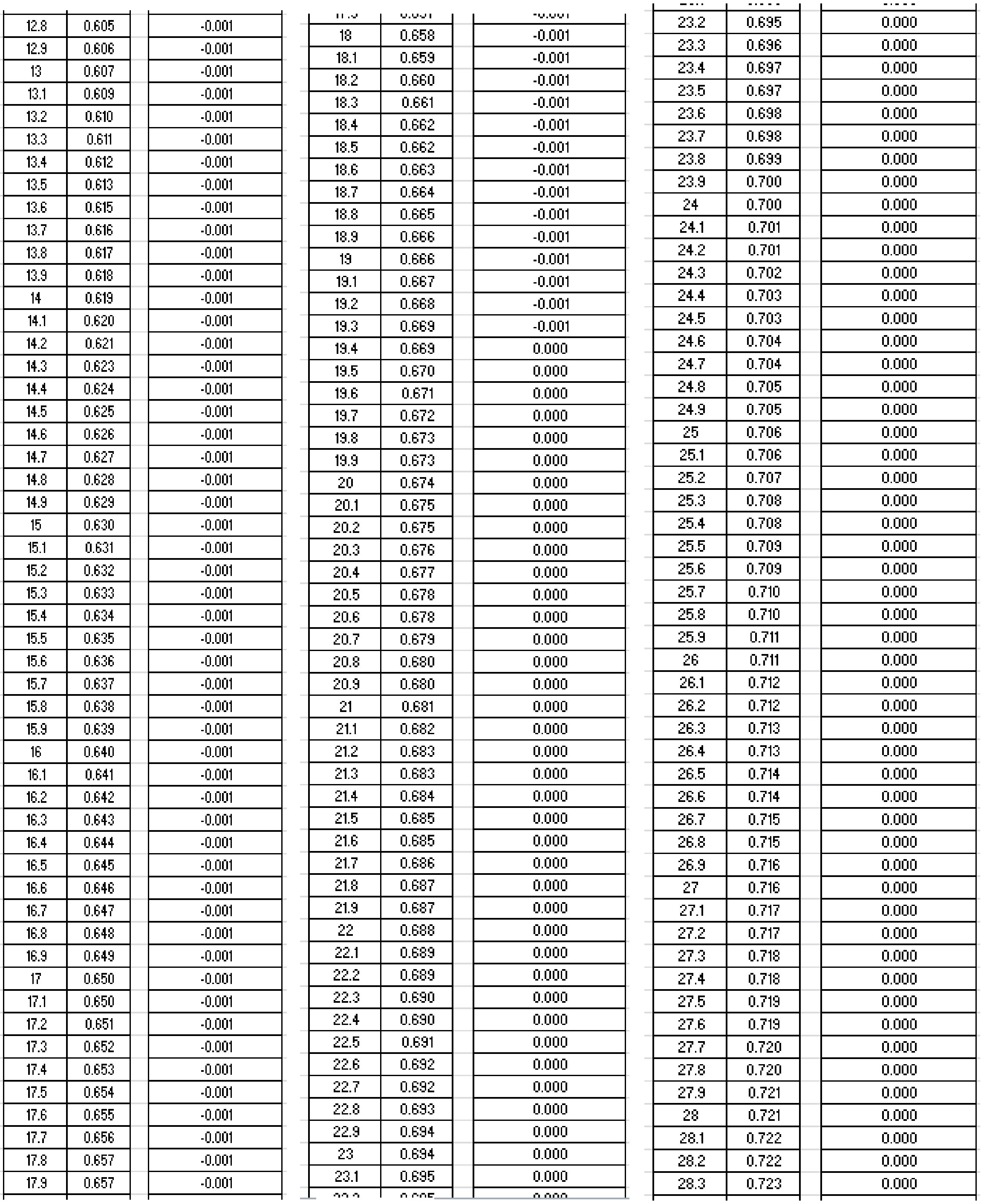
A.1: Given Data

Input Data

Q=	580
S=	6
μ=	0.125
Ca=	1.35
Cs=	5.94
C^2=	18.55305



Given Data		
WIP	TH	2nd Derivative of CF
0	0.000	-18.059
0.1	0.056	-1.761
0.2	0.090	-0.734
0.3	0.116	-0.423
0.4	0.137	-0.282
0.5	0.155	-0.205
0.6	0.172	-0.157
0.7	0.186	-0.125
0.8	0.200	-0.103
0.9	0.212	-0.086
1	0.224	-0.074
1.1	0.235	-0.064
1.2	0.245	-0.056
1.3	0.254	-0.050
1.4	0.264	-0.044
1.5	0.272	-0.040
1.6	0.281	-0.036
1.7	0.289	-0.033
1.8	0.296	-0.030
1.9	0.303	-0.028
2	0.310	-0.026
2.1	0.317	-0.024
2.2	0.324	-0.022
2.3	0.330	-0.021
2.4	0.336	-0.019
2.5	0.342	-0.018
2.6	0.348	-0.017
2.7	0.353	-0.016
2.8	0.359	-0.015
2.9	0.364	-0.014
3	0.369	-0.014
3.1	0.374	-0.013
3.2	0.379	-0.012
3.3	0.384	-0.012
3.4	0.388	-0.011
3.5	0.393	-0.011
3.6	0.397	-0.010
3.7	0.401	-0.010
3.8	0.406	-0.009
3.9	0.410	-0.009
4	0.414	-0.008
4.1	0.418	-0.008
4.2	0.421	-0.008
4.3	0.425	-0.008
4.4	0.429	-0.007
4.5	0.432	-0.007
4.6	0.436	-0.007
4.7	0.440	-0.007
4.8	0.443	-0.006
4.9	0.446	-0.006
5	0.450	-0.006
5.1	0.453	-0.006
5.2	0.456	-0.005
5.3	0.459	-0.005
5.4	0.462	-0.005
5.5	0.465	-0.005
5.6	0.468	-0.005
5.7	0.471	-0.005
5.8	0.474	-0.005
5.9	0.477	-0.004
6	0.480	-0.004
6.1	0.482	-0.004
6.2	0.485	-0.004
6.3	0.488	-0.004
6.4	0.490	-0.004
6.5	0.493	-0.004
6.6	0.495	-0.004
6.7	0.498	-0.004
6.8	0.500	-0.003
6.9	0.503	-0.003
7	0.505	-0.003
7.1	0.507	-0.003
7.2	0.510	-0.003
7.3	0.512	-0.003
7.4	0.514	-0.003
7.5	0.517	-0.003
7.6	0.519	-0.003
7.7	0.521	-0.003
7.8	0.523	-0.003
7.9	0.525	-0.003
8	0.527	-0.003
8.1	0.529	-0.003
8.2	0.531	-0.003
8.5	0.537	-0.002
8.6	0.539	-0.002
8.7	0.541	-0.002
8.8	0.543	-0.002
8.9	0.545	-0.002
9	0.547	-0.002
9.1	0.549	-0.002
9.2	0.551	-0.002
9.3	0.552	-0.002
9.4	0.554	-0.002
9.5	0.556	-0.002
9.6	0.558	-0.002
9.7	0.559	-0.002
9.8	0.561	-0.002
9.9	0.563	-0.002
10	0.564	-0.002
10.1	0.566	-0.002
10.2	0.568	-0.002
10.3	0.569	-0.002
10.4	0.571	-0.002
10.5	0.572	-0.002
10.6	0.574	-0.002
10.7	0.576	-0.002
10.8	0.577	-0.002
10.9	0.579	-0.002
11	0.580	-0.001
11.1	0.582	-0.001
11.2	0.583	-0.001
11.3	0.585	-0.001
11.4	0.586	-0.001
11.5	0.587	-0.001
11.6	0.589	-0.001
11.7	0.590	-0.001
11.8	0.592	-0.001
11.9	0.593	-0.001
12	0.594	-0.001
12.1	0.596	-0.001
12.2	0.597	-0.001
12.3	0.598	-0.001
12.4	0.600	-0.001
12.5	0.601	-0.001
12.6	0.602	-0.001
12.7	0.604	-0.001



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13.2	0.610		-0.001
13.3	0.611		-0.001
13.4	0.612		-0.001
13.5	0.613		-0.001
13.6	0.615		-0.001
13.7	0.616		-0.001
13.8	0.617		-0.001
13.9	0.618		-0.001
14	0.619		-0.001
14.1	0.620		-0.001
14.2	0.621		-0.001
14.3	0.623		-0.001
14.4	0.624		-0.001
14.5	0.625		-0.001
14.6	0.626		-0.001
14.7	0.627		-0.001
14.8	0.628		-0.001
14.9	0.629		-0.001
15	0.630		-0.001
15.1	0.631		-0.001
15.2	0.632		-0.001
15.3	0.633		-0.001
15.4	0.634		-0.001
15.5	0.635		-0.001
15.6	0.636		-0.001
15.7	0.637		-0.001
15.8	0.638		-0.001
15.9	0.639		-0.001
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16.3	0.643		-0.001
16.4	0.644		-0.001
16.5	0.645		-0.001
16.6	0.646		-0.001
16.7	0.647		-0.001
16.8	0.648		-0.001
16.9	0.649		-0.001
17	0.650		-0.001
17.1	0.650		-0.001
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17.3	0.652		-0.001
17.4	0.653		-0.001
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18.3	0.661		-0.001
18.4	0.662		-0.001
18.5	0.662		-0.001
18.6	0.663		-0.001
18.7	0.664		-0.001
18.8	0.665		-0.001
18.9	0.666		-0.001
19	0.666		-0.001
19.1	0.667		-0.001
19.2	0.668		-0.001
19.3	0.669		-0.001
19.4	0.669		0.000
19.5	0.670		0.000
19.6	0.671		0.000
19.7	0.672		0.000
19.8	0.673		0.000
19.9	0.673		0.000
20	0.674		0.000
20.1	0.675		0.000
20.2	0.675		0.000
20.3	0.676		0.000
20.4	0.677		0.000
20.5	0.678		0.000
20.6	0.678		0.000
20.7	0.679		0.000
20.8	0.680		0.000
20.9	0.680		0.000
21	0.681		0.000
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21.2	0.683		0.000
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21.5	0.685		0.000
21.6	0.685		0.000
21.7	0.686		0.000
21.8	0.687		0.000
21.9	0.687		0.000
22	0.688		0.000
22.1	0.689		0.000
22.2	0.689		0.000
22.3	0.690		0.000
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22.6	0.692		0.000
22.7	0.692		0.000
22.8	0.693		0.000
22.9	0.694		0.000
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23.1	0.695		0.000
23.2	0.695		0.000
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23.6	0.698		0.000
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23.8	0.699		0.000
23.9	0.700		0.000
24	0.700		0.000
24.1	0.701		0.000
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24.7	0.704		0.000
24.8	0.705		0.000
24.9	0.705		0.000
25	0.706		0.000
25.1	0.706		0.000
25.2	0.707		0.000
25.3	0.708		0.000
25.4	0.708		0.000
25.5	0.709		0.000
25.6	0.709		0.000
25.7	0.710		0.000
25.8	0.710		0.000
25.9	0.711		0.000
26	0.711		0.000
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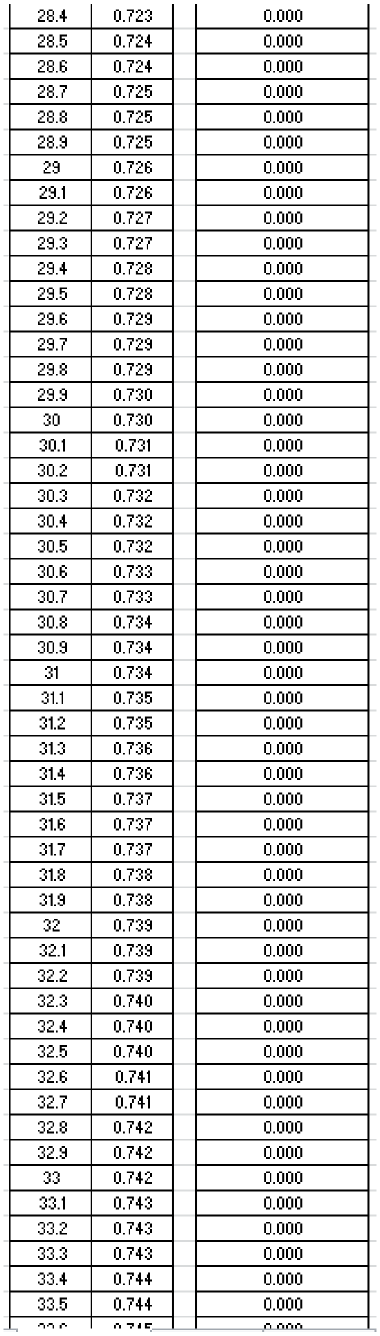
26.2	0.712		0.000
26.3	0.713		0.000
26.4	0.713		0.000
26.5	0.714		0.000
26.6	0.714		0.000
26.7	0.715		0.000
26.8	0.715		0.000
26.9	0.716		0.000
27	0.716		0.000
27.1	0.717		0.000
27.2	0.717		0.000
27.3	0.718		0.000
27.4	0.718		0.000
27.5	0.719		0.000
27.6	0.719		0.000
27.7	0.720		0.000
27.8	0.720		0.000
27.9	0.721		0.000
28	0.721		0.000
28.1	0.722		0.000
28.2	0.722		0.000
28.3	0.723		0.000



28.4	0.723		0.000
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28.7	0.725		0.000
28.8	0.725		0.000
28.9	0.725		0.000
29	0.726		0.000
29.1	0.726		0.000
29.2	0.727		0.000
29.3	0.727		0.000
29.4	0.728		0.000
29.5	0.728		0.000
29.6	0.729		0.000
29.7	0.729		0.000
29.8	0.729		0.000
29.9	0.730		0.000
30	0.730		0.000
30.1	0.731		0.000
30.2	0.731		0.000
30.3	0.732		0.000
30.4	0.732		0.000
30.5	0.732		0.000
30.6	0.733		0.000
30.7	0.733		0.000
30.8	0.734		0.000
30.9	0.734		0.000
31	0.734		0.000
31.1	0.735		0.000
31.2	0.735		0.000
31.3	0.736		0.000
31.4	0.736		0.000
31.5	0.737		0.000
31.6	0.737		0.000
31.7	0.737		0.000
31.8	0.738		0.000
31.9	0.738		0.000
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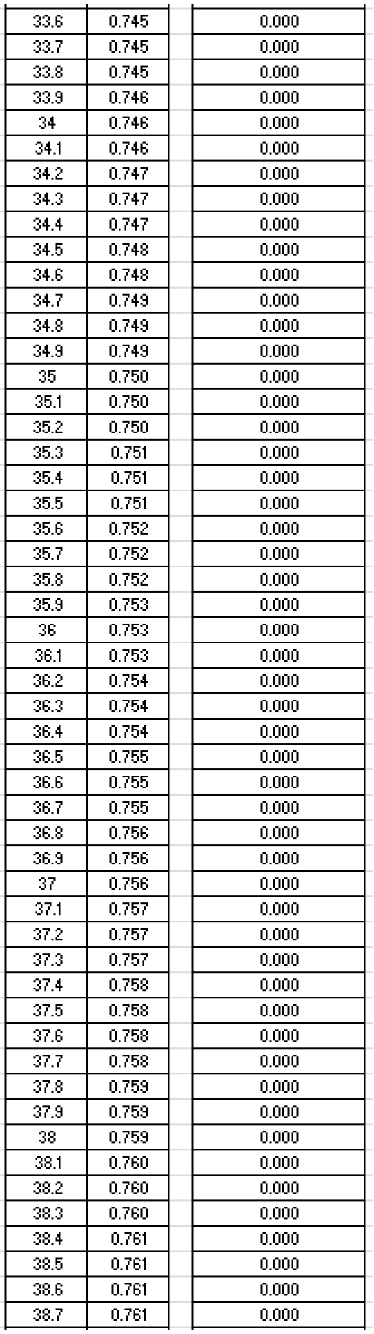
32.1	0.739		0.000
32.2	0.739		0.000
32.3	0.740		0.000
32.4	0.740		0.000
32.5	0.740		0.000
32.6	0.741		0.000
32.7	0.741		0.000
32.8	0.742		0.000
32.9	0.742		0.000
33	0.742		0.000
33.1	0.743		0.000
33.2	0.743		0.000
33.3	0.743		0.000
33.4	0.744		0.000
33.5	0.744		0.000



33.6	0.745		0.000
33.7	0.745		0.000
33.8	0.745		0.000
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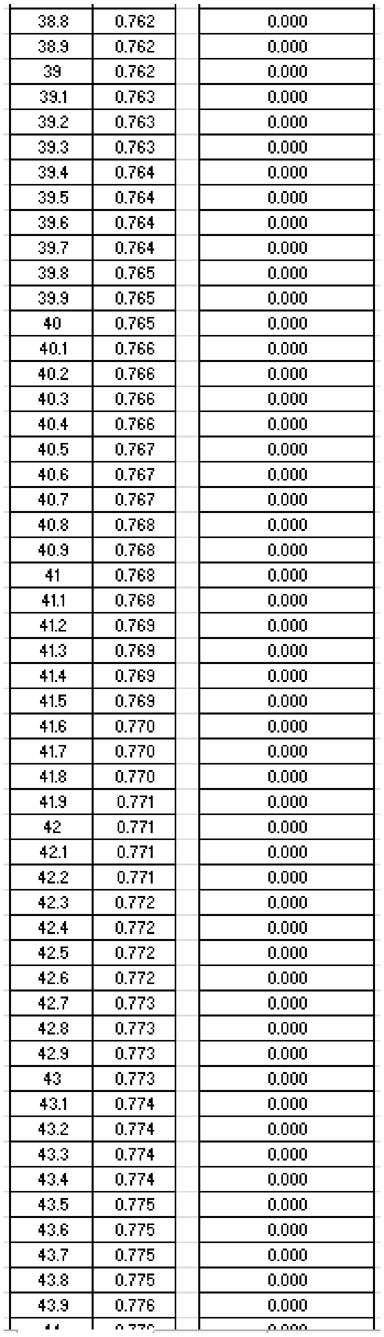
34	0.746		0.000
34.1	0.746		0.000
34.2	0.747		0.000
34.3	0.747		0.000
34.4	0.747		0.000
34.5	0.748		0.000
34.6	0.748		0.000
34.7	0.749		0.000
34.8	0.749		0.000
34.9	0.749		0.000
35	0.750		0.000
35.1	0.750		0.000
35.2	0.750		0.000
35.3	0.751		0.000
35.4	0.751		0.000
35.5	0.751		0.000
35.6	0.752		0.000
35.7	0.752		0.000
35.8	0.752		0.000
35.9	0.753		0.000
36	0.753		0.000
36.1	0.753		0.000
36.2	0.754		0.000
36.3	0.754		0.000
36.4	0.754		0.000
36.5	0.755		0.000
36.6	0.755		0.000
36.7	0.755		0.000
36.8	0.756		0.000
36.9	0.756		0.000
37	0.756		0.000
37.1	0.757		0.000
37.2	0.757		0.000
37.3	0.757		0.000
37.4	0.758		0.000
37.5	0.758		0.000
37.6	0.758		0.000
37.7	0.758		0.000
37.8	0.759		0.000
37.9	0.759		0.000
38	0.759		0.000
38.1	0.760		0.000
38.2	0.760		0.000
38.3	0.760		0.000
38.4	0.761		0.000
38.5	0.761		0.000
38.6	0.761		0.000
38.7	0.761		0.000



38.8	0.762		0.000
38.9	0.762		0.000
39	0.762		0.000
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39.3	0.763		0.000
39.4	0.764		0.000
39.5	0.764		0.000
39.6	0.764		0.000
39.7	0.764		0.000
39.8	0.765		0.000
39.9	0.765		0.000
40	0.765		0.000
40.1	0.766		0.000
40.2	0.766		0.000
40.3	0.766		0.000
40.4	0.766		0.000
40.5	0.767		0.000
40.6	0.767		0.000
40.7	0.767		0.000
40.8	0.768		0.000
40.9	0.768		0.000
41	0.768		0.000
41.1	0.768		0.000
41.2	0.769		0.000
41.3	0.769		0.000
41.4	0.769		0.000
41.5	0.769		0.000
41.6	0.770		0.000
41.7	0.770		0.000
41.8	0.770		0.000
41.9	0.771		0.000
42	0.771		0.000
42.1	0.771		0.000
42.2	0.771		0.000
42.3	0.772		0.000
42.4	0.772		0.000
42.5	0.772		0.000
42.6	0.772		0.000
42.7	0.773		0.000
42.8	0.773		0.000
42.9	0.773		0.000
43	0.773		0.000
43.1	0.774		0.000
43.2	0.774		0.000
43.3	0.774		0.000
43.4	0.774		0.000
43.5	0.775		0.000
43.6	0.775		0.000
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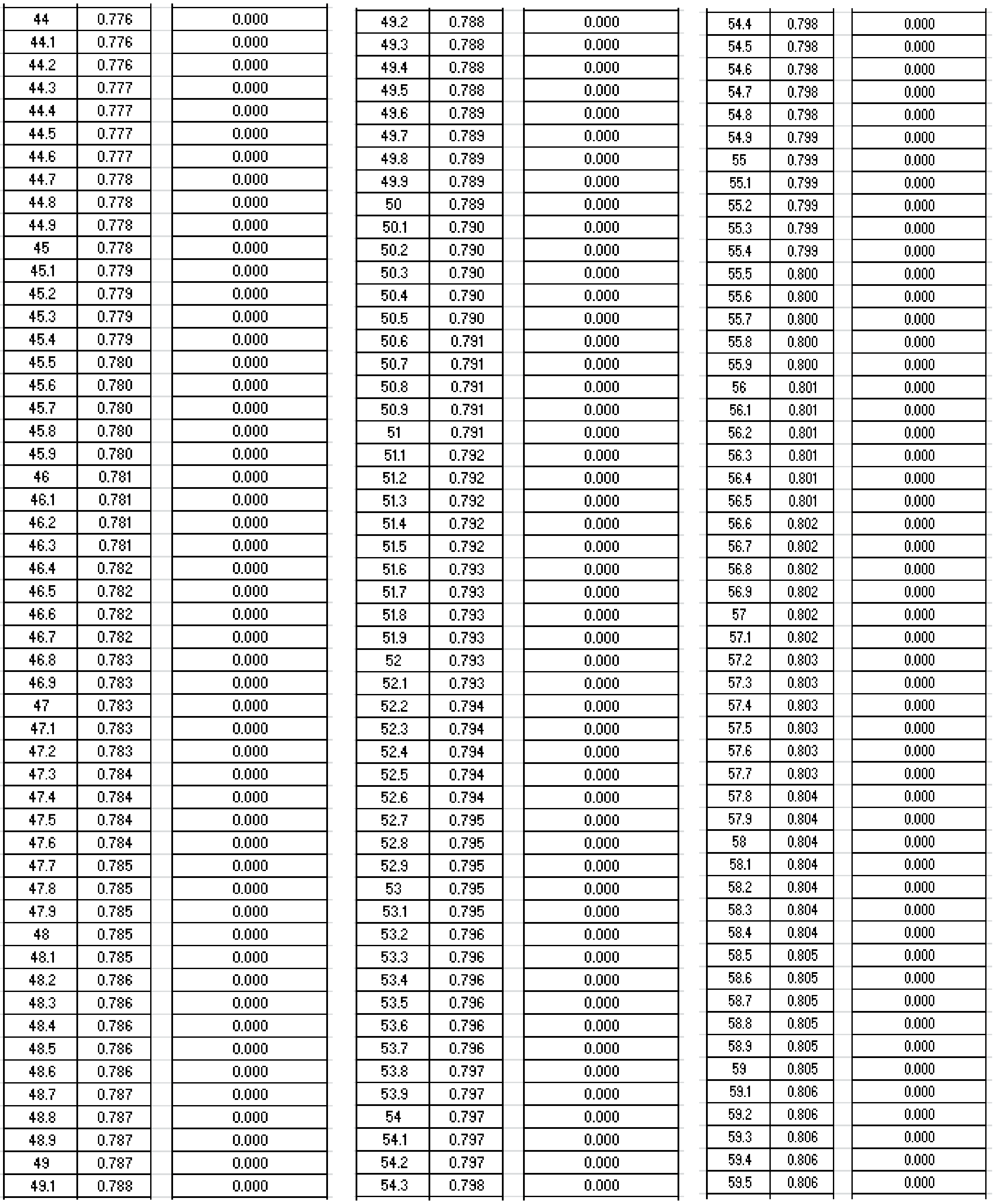
43.8	0.775		0.000
43.9	0.776		0.000



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44.1	0.776		0.000
44.2	0.776		0.000
44.3	0.777		0.000
44.4	0.777		0.000
44.5	0.777		0.000
44.6	0.777		0.000
44.7	0.778		0.000
44.8	0.778		0.000
44.9	0.778		0.000
45	0.778		0.000
45.1	0.779		0.000
45.2	0.779		0.000
45.3	0.779		0.000
45.4	0.779		0.000
45.5	0.780		0.000
45.6	0.780		0.000
45.7	0.780		0.000
45.8	0.780		0.000
45.9	0.780		0.000
46	0.781		0.000
46.1	0.781		0.000
46.2	0.781		0.000
46.3	0.781		0.000
46.4	0.782		0.000
46.5	0.782		0.000
46.6	0.782		0.000
46.7	0.782		0.000
46.8	0.783		0.000
46.9	0.783		0.000
47	0.783		0.000
47.1	0.783		0.000
47.2	0.783		0.000
47.3	0.784		0.000
47.4	0.784		0.000
47.5	0.784		0.000
47.6	0.784		0.000
47.7	0.785		0.000
47.8	0.785		0.000
47.9	0.785		0.000
48	0.785		0.000
48.1	0.785		0.000
48.2	0.786		0.000
48.3	0.786		0.000
48.4	0.786		0.000
48.5	0.786		0.000
48.6	0.786		0.000
48.7	0.787		0.000
48.8	0.787		0.000
48.9	0.787		0.000
49	0.787		0.000
49.1	0.788		0.000
49.2	0.788		0.000
49.3	0.788		0.000
49.4	0.788		0.000
49.5	0.788		0.000
49.6	0.789		0.000
49.7	0.789		0.000
49.8	0.789		0.000
49.9	0.789		0.000
50	0.789		0.000
50.1	0.790		0.000
50.2	0.790		0.000
50.3	0.790		0.000
50.4	0.790		0.000
50.5	0.790		0.000
50.6	0.791		0.000
50.7	0.791		0.000
50.8	0.791		0.000
50.9	0.791		0.000
51	0.791		0.000
51.1	0.792		0.000
51.2	0.792		0.000
51.3	0.792		0.000
51.4	0.792		0.000
51.5	0.792		0.000
51.6	0.793		0.000
51.7	0.793		0.000
51.8	0.793		0.000
51.9	0.793		0.000
52	0.793		0.000
52.1	0.793		0.000
52.2	0.794		0.000
52.3	0.794		0.000
52.4	0.794		0.000
52.5	0.794		0.000
52.6	0.794		0.000
52.7	0.795		0.000
52.8	0.795		0.000
52.9	0.795		0.000
53	0.795		0.000
53.1	0.795		0.000
53.2	0.796		0.000
53.3	0.796		0.000
53.4	0.796		0.000
53.5	0.796		0.000
53.6	0.796		0.000
53.7	0.796		0.000
53.8	0.797		0.000
53.9	0.797		0.000
54	0.797		0.000
54.1	0.797		0.000
54.2	0.797		0.000
54.3	0.798		0.000
54.4	0.798		0.000
54.5	0.798		0.000
54.6	0.798		0.000
54.7	0.798		0.000
54.8	0.798		0.000
54.9	0.799		0.000
55	0.799		0.000
55.1	0.799		0.000
55.2	0.799		0.000
55.3	0.799		0.000
55.4	0.799		0.000
55.5	0.800		0.000
55.6	0.800		0.000
55.7	0.800		0.000
55.8	0.800		0.000
55.9	0.800		0.000
56	0.801		0.000
56.1	0.801		0.000
56.2	0.801		0.000
56.3	0.801		0.000
56.4	0.801		0.000
56.5	0.801		0.000
56.6	0.802		0.000
56.7	0.802		0.000
56.8	0.802		0.000
56.9	0.802		0.000
57	0.802		0.000
57.1	0.802		0.000
57.2	0.803		0.000
57.3	0.803		0.000
57.4	0.803		0.000
57.5	0.803		0.000
57.6	0.803		0.000
57.7	0.803		0.000
57.8	0.804		0.000
57.9	0.804		0.000
58	0.804		0.000
58.1	0.804		0.000
58.2	0.804		0.000
58.3	0.804		0.000
58.4	0.804		0.000
58.5	0.805		0.000
58.6	0.805		0.000
58.7	0.805		0.000
58.8	0.805		0.000
58.9	0.805		0.000
59	0.805		0.000
59.1	0.806		0.000
59.2	0.806		0.000
59.3	0.806		0.000
59.4	0.806		0.000
59.5	0.806		0.000

59.6	0.806		0.000
59.7	0.807		0.000
59.8	0.807		0.000
59.9	0.807		0.000
60	0.807		0.000
60.1	0.807		0.000
60.2	0.807		0.000
60.3	0.807		0.000
60.4	0.808		0.000
60.5	0.808		0.000
60.6	0.808		0.000
60.7	0.808		0.000
60.8	0.808		0.000
60.9	0.808		0.000
61	0.808		0.000
61.1	0.809		0.000
61.2	0.809		0.000
61.3	0.809		0.000
61.4	0.809		0.000
61.5	0.809		0.000
61.6	0.809		0.000
61.7	0.810		0.000
61.8	0.810		0.000
61.9	0.810		0.000
62	0.810		0.000
62.1	0.810		0.000
62.2	0.810		0.000
62.3	0.810		0.000
62.4	0.811		0.000
62.5	0.811		0.000
62.6	0.811		0.000
62.7	0.811		0.000
62.8	0.811		0.000
62.9	0.811		0.000
63	0.811		0.000
63.1	0.812		0.000
63.2	0.812		0.000
63.3	0.812		0.000
63.4	0.812		0.000
63.5	0.812		0.000
63.6	0.812		0.000
63.7	0.812		0.000
63.8	0.813		0.000
63.9	0.813		0.000
64	0.813		0.000
64.1	0.813		0.000
64.2	0.813		0.000
64.3	0.813		0.000
64.4	0.813		0.000
64.5	0.813		0.000
64.6	0.814		0.000
64.7	0.814		0.000
64.8	0.814		0.000
64.9	0.814		0.000
65	0.814		0.000
65.1	0.814		0.000
65.2	0.814		0.000
65.3	0.815		0.000
65.4	0.815		0.000
65.5	0.815		0.000
65.6	0.815		0.000
65.7	0.815		0.000
65.8	0.815		0.000
65.9	0.815		0.000
66	0.815		0.000
66.1	0.816		0.000
66.2	0.816		0.000
66.3	0.816		0.000
66.4	0.816		0.000
66.5	0.816		0.000
66.6	0.816		0.000
66.7	0.816		0.000
66.8	0.817		0.000
66.9	0.817		0.000
67	0.817		0.000
67.1	0.817		0.000
67.2	0.817		0.000
67.3	0.817		0.000
67.4	0.817		0.000
67.5	0.817		0.000
67.6	0.818		0.000
67.7	0.818		0.000
67.8	0.818		0.000
67.9	0.818		0.000
68	0.818		0.000
68.1	0.818		0.000
68.2	0.818		0.000
68.3	0.818		0.000
68.4	0.819		0.000
68.5	0.819		0.000
68.6	0.819		0.000
68.7	0.819		0.000
68.8	0.819		0.000
68.9	0.819		0.000
69	0.819		0.000
69.1	0.819		0.000
69.2	0.819		0.000
69.3	0.820		0.000
69.4	0.820		0.000
69.5	0.820		0.000
69.6	0.820		0.000
69.7	0.820		0.000
69.8	0.820		0.000
69.9	0.820		0.000
70	0.820		0.000

A.2: Linearization summary

	Cluster center				
Cluster	WIP	TH	1th Derivative	α*WIP	β
1	0	0	0.923570002	0	0
2	2	0.310439	0.068889947	0.13778	0.17266
3	5.3	0.459075	0.030914551	0.163847	0.295228
4	7.5	0.516577	0.022218237	0.166637	0.34994
5	11.4	0.585958	0.014344058	0.163522	0.422436
6	20.4	0.676928	0.00719791	0.146837	0.530091
7	26	0.711292	0.00523896	0.136213	0.575079
8	32	0.73852	0.003934158	0.125893	0.612627
9	46.8	0.782512	0.002250683	0.105332	0.67718
10	59.3	0.805898	0.001556126	0.092278	0.71362

Appendix B: MILP

B.1: Input Data

D		Period											
		1	2	3	4	5	6	7	8	9	10	11	12
A	1	2600	13	10	3123	5	10	3082	253	10	10	3348	156
B	2	2600	13	10	3123	5	10	3082	253	10	10	3348	156
C	3	5200	26	20	6246	10	20	6164	506	20	20	6696	312

Holding Cost													
h		Period											
		1	2	3	4	5	6	7	8	9	10	11	12
A	1	3	3	3	3	3	3	3	3	3	3	3	3
B	2	2	2	2	2	2	2	2	2	2	2	2	2
C	3	1	1	1	1	1	1	1	1	1	1	1	1

WIP Cost													
w		Period											
		1	2	3	4	5	6	7	8	9	10	11	12
A	1	2	2	2	2	2	2	2	2	2	2	2	2
B	2	1	1	1	1	1	1	1	1	1	1	1	1
C	3	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Setup Cost												
	1	2	3	4	5	6	7	8	9	10	11	12
A	80	80	80	80	80	80	80	80	80	80	80	80
B	70	70	70	70	70	70	70	70	70	70	70	70
C	50	50	50	50	50	50	50	50	50	50	50	50

M
Larege #
1000000

C		
Line	A	B
1	1	0
2	0.159156	0.066177
3	0.076111	0.147092
4	0.041551	0.237432
5	0.02423	0.329583
6	0.01885	0.374107
7	0.015035	0.414262
8	0.012107	0.452324
9	0.007879	0.525289
10	0.004538	0.611428

B		
Line	A	B
1	1	0
2	0.178805	0.07723
3	0.082109	0.176109
4	0.042788	0.283619
5	0.023824	0.388705
6	0.018134	0.437669
7	0.014185	0.480787
8	0.011217	0.520742
9	0.007054	0.59484
10	0.003907	0.678122

A		
Line	A	B
1	0.92357	0
2	0.06889	0.17266
3	0.030915	0.295228
4	0.022218	0.34994
5	0.014344	0.422436
6	0.007198	0.530091
7	0.005239	0.575079
8	0.003934	0.612627
9	0.002251	0.67718
10	0.001556	0.71362

Line	A											
	Period											
	1	2	3	4	5	6	7	8	9	10	11	12
1	151471.5	114617.4	-1E-05	165784	168412	6.38E-06	165784	4.26E-07	263	1452.751	165784	-9.9E-07
2	9459.52	9104.575	95.22793	10501.19	13129.19	137.7967	10501.19	323.804	586.804	-3.9E-07	10501.19	422.8227
3	3527.041	4793.835	476.8961	3979.06	6607.06	521.3563	3979.06	715.6283	978.6283	312.8879	3979.06	819.0467
4	2256.035	3894.205	651.8213	2573.023	5201.023	696.7147	2573.023	892.8792	1155.879	472.0625	2573.023	997.3051
5	1180.602	3155.039	885.6233	1375.326	4003.326	930.9089	1375.326	1128.787	1391.787	691.603	1375.326	1234.125
6	342.1145	2621.728	1235.322	425.8784	3053.878	1280.964	425.8784	1480.397	1743.397	1028.359	425.8784	1586.563
7	163.1076	2526.378	1382.029	216.4544	2844.454	1427.768	216.4544	1627.628	1890.628	1171.517	216.4544	1734.021
8	68.78286	2487.775	1504.653	101.8696	2729.87	1550.457	101.8696	1750.6	2013.6	1291.778	101.8696	1857.145
9	-1.1E-06	2490.885	1715.78	6.946959	2634.947	1761.668	6.946959	1962.178	2225.178	1499.857	6.946959	2068.918
10	3.837614	2524.383	1835.101	-5.1E-08	2628	1881.024	-5.1E-08	2081.685	2344.685	1617.92	-5.1E-08	2188.505
	B											
1	72668.75	75281.75	830.5463	74780.1	77408.1	619.2824	74780.1	-5E-07	263	1840.939	74780.1	1.5E-06

2	11118.03	13731.03	-1.2E-06	11483.23	14111.23	1.6E-06	11483.23	54.32969	317.3297	3E-06	11483.23	142.1976
3	4184.673	6797.673	216.4528	4344.266	6972.266	241.3292	4344.266	374.9768	637.9768	97.47888	4344.266	473.1912
4	1600.8	4213.8	540.0245	1676.782	4304.782	575.0168	1676.782	740.9188	1003.919	372.6703	1676.782	843.3405
5	540.9875	3153.987	882.4045	576.646	3204.646	922.2754	576.646	1103.733	1366.733	691.7175	576.646	1208.184
6	283.9781	2896.978	1046.151	307.5368	2935.537	1087.486	307.5368	1273.611	1536.611	848.4626	307.5368	1378.671
7	137.6517	2750.652	1191.772	152.8147	2780.815	1234.122	152.8147	1423.486	1686.486	989.2251	152.8147	1528.968
8	54.02405	2667.024	1327.635	62.87509	2690.875	1370.75	62.87509	1562.549	1825.549	1121.437	62.87509	1668.349
9	7.55E-06	2613	1581.395	-9.9E-06	2628	1625.58	-9.9E-06	1820.794	2083.794	1370.075	-9.9E-06	1927.039
10	54.52235	2667.522	1868.664	47.82916	2675.829	1913.659	47.82916	2111.454	2374.454	1653.47	47.82916	2218.036
	C											
1	263032.8	98842.76	2916.993	265489.8	270701	2430.943	265489.8	70.42761	596.4276	5677.455	265489.8	2.73E-06
2	37921.83	16140.59	3.33E-06	38303.46	43514.66	-1.4E-06	38303.46	2.92E-07	526	69.37147	38303.46	168.7317
3	16173.52	8457.118	196.4109	16350.18	21561.38	244.4151	16350.18	477.5485	1003.549	1.26E-05	16350.18	669.9006
4	7491.881	5628.695	647.2795	7583.237	12794.44	715.2611	7583.237	1045.415	1571.415	340.2608	7583.237	1247.597
5	3446.193	4516.495	1178.58	3494.798	8705.998	1256.574	3494.798	1635.352	2161.352	816.1272	3494.798	1842.461
6	2293.124	4274.612	1447.192	2328.45	7539.65	1528.296	2328.45	1922.178	2448.178	1067.521	2328.45	2130.817
7	1531.362	4158.985	1693.566	1557.272	6768.472	1776.875	1557.272	2181.467	2707.467	1301.685	1557.272	2391.191
8	993.8628	4117.417	1929.845	1012.545	6223.745	2014.847	1012.545	2427.659	2953.659	1528.592	1012.545	2638.216
9	335.0733	4174.697	2388.307	343.3197	5554.52	2475.752	343.3197	2900.434	3426.434	1973.522	343.3197	3112.193
10	-6.8E-06	4405.476	2936.107	1.28E-05	5211.2	3025.484	1.28E-05	3459.546	3985.546	2510.63	1.28E-05	3672.255

Capacity

A	3285
B	3500
C	6514

Utilization	0.8

B.2: Output of MILP

B.2.1: High Demand Variability

B.2.1.1: Batch size : 290

			Period											
			1	2	3	4	5	6	7	8	9	10	11	12
X	A	1	2600	13	532	2606	0	486	2606	263	0	752	2606	156
	B	2	2613	0	532	2606	0	486	2606	263	0	752	2606	156
	C	3	5200	26	1065	5211	0	973	5211	526	0	1505	5211	312
W	A	1	108	95	0	111	0	0	111	0	0	1	111	0
	B	2	22	0	0	21	0	0	21	0	0	1	21	0
	C	3	41	15	1	42	0	1	42	0	0	1	42	0
I	A	1	0	0	522	5	0	476	0	10	0	742	0	0
	B	2	13	0	0	0	0	0	0	0	0	0	0	0
	C	3	0	0	0	0	0	0	0	0	0	0	0	0
R	A	1	2708	0	438	2716	0	376	2716	152	0	753	2715	156
	B	2	2635	0	511	2626	0	466	2626	242	0	753	2626	156
	C	3	5241	0	1050	5252	0	932	5252	485	0	1506	5252	312
Y	A	1	1	1	1	1	0	1	1	1	0	1	1	1
	B	2	1	0	1	1	0	1	1	1	0	1	1	1
	C	3	1	1	1	1	1	1	1	1	0	1	1	1

B.2.1.2: Batch size: 580

			Period											
			1	2	3	4	5	6	7	8	9	10	11	12
X	A	1	2600	13	510	2628	0	464	2628	263	0	730	2628	156
	B	2	2613	0	510	2628	0	464	2628	263	0	730	2628	156
	C	3	5200	26	1065	5211	0	973	5211	526	0	1505	5211	312
W	A	1	51	38	0	56	0	0	56	0	0	1	56	0
	B	2	22	0	0	22	0	0	22	0	0	1	22	0

	C	3	41	15	1	42	0	1	42	0	0	1	42	0
I	A	1	0	0	500	5	0	454	0	10	0	720	0	0
	B	2	13	0	0	0	0	0	0	0	0	0	0	0
	C	3	0	0	45	0	0	45	0	0	0	45	0	0
R	A	1	2651	0	472	2683	0	409	2683	208	0	731	2683	156
	B	2	2635	0	489	2650	0	442	2650	241	0	731	2649	156
	C	3	5241	0	1050	5252	0	932	5252	485	0	1506	5252	312
Y	A	1	1	1	1	1	0	1	1	1	0	1	1	1
	B	2	1	0	1	1	0	1	1	1	0	1	1	1
	C	3	1	1	1	1	0	1	1	1	0	1	1	1

B.2.1.3: Batch size: 1160

			Period											
			1	2	3	4	5	6	7	8	9	10	11	12
X	A	1	2600	13	510	2628	0	464	2628	263	0	730	2628	156
	B	2	2613	0	510	2628	0	464	2628	263	0	730	2628	156
	C	3	5200	26	1065	5211	0	973	5211	526	0	1505	5211	312
W	A	1	38	25	0.2	41	41	0.1	41	0.1	0	1	41	0
	B	2	22	0	0.4	22	22	0.3	22	0.1	0	1	22	0
	C	3	41	15	1	42	42	1	42	0.1	0	1	42	0
I	A	1	0	0	500	5	0	454	0	10	0	720	0	0
	B	2	13	0	0	0	0	0	0	0	0	0	0	0
	C	3	0	0	45	0	0	45	0	0	0	45	0	0
R	A	1	2638	0	485	2669	0	423	2669	222	0	731	2668	156
	B	2	2635	0	489	2650	0	442	2650	241	0	731	2649	156
	C	3	5241	0	1050	5252	0	932	5252	485	0	1506	5252	312
Y	A	1	1	1	1	1	0	1	1	1	0	1	1	1
	B	2	1	0	1	1	0	1	1	1	0	1	1	1
	C	3	1	1	1	1	0	1	1	1	0	1	1	1

B.2.2: Medium Demand Variability

B.2.2.1: Batch size: 290

	Period											
	1	2	3	4	5	6	7	8	9	10	11	12

X	A	1	1027	0	1756	343	1536	963	0	1346	2606	2604	0	439
	B	2	1027	0	1756	343	1536	963	0	1346	2616	2594	0	439
	C	3	2054	0	3512	686	3072	1926	0	2692	5211	5209	0	878
W	A	1	2	0	10	0	7	2	0	5	108	108	0	0
	B	2	1	0	5	0	3	1	0	2	20	20	0	0
	C	3	2	0	8	0	6	2	0	4	40	40	0	0
I	A	1	10	0	0	0	0	15	0	0	735	10	0	0
	B	2	0	0	0	0	0	0	0	0	10	0	0	0
	C	3	0	0	0	0	0	0	0	0	0	0	0	0
R	A	1	1029	0	1764	333	1543	958	0	1349	2709	2604	0	439
	B	2	1028	0	1760	338	1539	961	0	1347	2634	2593	0	439
	C	3	2056	0	3518	678	3077	1922	0	2694	5248	5209	0	878
Y	A	1	1	0	1	1	1	1	0	1	1	1	0	1
	B	2	1	0	1	1	1	1	0	1	1	1	0	1
	C	3	1	0	1	1	1	1	0	1	1	1	0	1

B.2.2.2: Batch size: 580

			Period											
			1	2	3	4	5	6	7	8	9	10	11	12
X	A	1	1027	0	1756	343	1536	963	0	1346	2572	2628	54	395
	B	2	1027	0	1756	343	1536	963	0	1346	2572	2628	54	395
	C	3	2054	0	3512	686	3072	1926	0	2692	5189	5211	108	790
W	A	1	2	0	8	0	5	2	0	4	46	54	0.02	0.13
	B	2	1	0	5	0	3	1	0	2	19	21	0.02	0.18
	C	3	2	0	8	0	6	2	0	4	40	40	0.02	0.33
I	A	1	10	0	0	0	0	15	0	0	701	0	44	0
	B	2	0	0	0	0	0	0	0	0	0	0	0	0
	C	3	0	0	0	0	0	0	0	0	45	0	0	0
R	A	1	1029	0	1762	335	1541	959	0	1348	2614	2636	0	395
	B	2	1028	0	1760	338	1539	961	0	1347	2588	2630	33	395
	C	3	2056	0	3518	678	3077	1922	0	2694	5224	5212	67	791
Y	A	1	1	0	1	1	1	1	0	1	1	1	1	1
	B	2	1	0	1	1	1	1	1	1	1	1	1	1
	C	3	1	0	1	1	1	1	1	1	1	1	1	1

B2.2.3: Batch size:1160

			Period											
			1	2	3	4	5	6	7	8	9	10	11	12
X	A	1	1027	0	1756	343	1536	963	0	1346	2572	2628	40	409
	B	2	1027	0	1756	343	1536	963	0	1346	2572	2628	40	409
	C	3	2054	0	3512	686	3072	1926	0	2692	5189	5211	79	819
W	A	1	2	0	7	0.11	5	2	0	3	35	40	0.01	0.13
	B	2	1	0	5	0.10	3	1	0	2	19	21	0.01	0.21
	C	3	2	0	8	0.23	6	2	0	4	40	40	0.01	0.36
I	A	1	10	0	0	0	0	15	0	0	701	0	30	0
	B	2	0	0	0	0	0	0	0	0	0	0	0	0
	C	3	0	0	0	0	0	0	0	0	45	0	0	0
R	A	1	1029	0	1761	336	1541	960	0	1348	2604	2633	0	409
	B	2	1028	0	1760	338	1539	961	0	1347	2588	2630	19	410
	C	3	2056	0	3518	678	3077	1922	0	2694	5224	5212	39	819
Y	A	1	1	0	1	1	1	1	0	1	1	1	1	1
	B	2	1	0	1	1	1	1	0	1	1	1	1	1
	C	3	1	0	1	1	1	1	0	1	1	1	1	1

B.2.3: Low Demand Variability

B.2.3.1: Batch size: 290

			Period											
			1	2	3	4	5	6	7	8	9	10	11	12
X	A	1	1143	1116	987	1291	998	1033	949	1148	1042	986	789	1138
	B	2	1143	1116	987	1291	998	1033	949	1148	1042	986	789	1138
	C	3	2286	2232	1974	2582	1996	2066	1898	2296	2084	1972	1578	2276
W	A	1	3	3	2	4	2	2	2	3	2	2	1	3
	B	2	2	2	1	2	1	1	1	2	1	1	1	2
	C	3	3	2	2	4	2	2	2	3	2	2	1	3
I	A	1	0	0	0	0	0	0	0	0	0	0	0	0
	B	2	0	0	0	0	0	0	0	0	0	0	0	0
	C	3	0	0	0	0	0	0	0	0	0	0	0	0
R	A	1	1146	1116	986	1293	996	1033	949	1149	1042	986	788	1141
	B	2	1145	1116	987	1292	997	1033	949	1149	1042	986	789	1140

	C	3	2289	2232	1973	2584	1994	2066	1898	2297	2084	1972	1577	2279
Y	A	1	1	1	1	1	1	1	1	1	1	1	1	1
	B	2	1	1	1	1	1	1	1	1	1	1	1	1
	C	3	1	1	1	1	1	1	1	1	1	1	1	1

B.2.3.2: Batch size: 580

			Period											
			1	2	3	4	5	6	7	8	9	10	11	12
X	A	1	1143	1116	987	1291	998	1033	949	1148	1042	986	789	1138
	B	2	1143	1116	987	1291	998	1033	949	1148	1042	986	789	1138
	C	3	2286	2232	1974	2582	1996	2066	1898	2296	2084	1972	1578	2276
W	A	1	2	2	2	3	2	2	2	2	2	2	1	2
	B	2	2	2	1	2	1	1	1	2	1	1	1	2
	C	3	3	2	2	4	2	2	2	3	2	2	1	3
I	A	1	0	0	0	0	0	0	0	0	0	0	0	0
	B	2	0	0	0	0	0	0	0	0	0	0	0	0
	C	3	0	0	0	0	0	0	0	0	0	0	0	0
R	A	1	1145	1116	986	1292	997	1033	949	1149	1042	986	788	1140
	B	2	1145	1116	987	1292	997	1033	949	1149	1042	986	789	1140
	C	3	2289	2232	1973	2584	1994	2066	1898	2297	2084	1972	1577	2279
Y	A	1	1	1	1	1	1	1	1	1	1	1	1	1
	B	2	1	1	1	1	1	1	1	1	1	1	1	1
	C	3	1	1	1	1	1	1	1	1	1	1	1	1

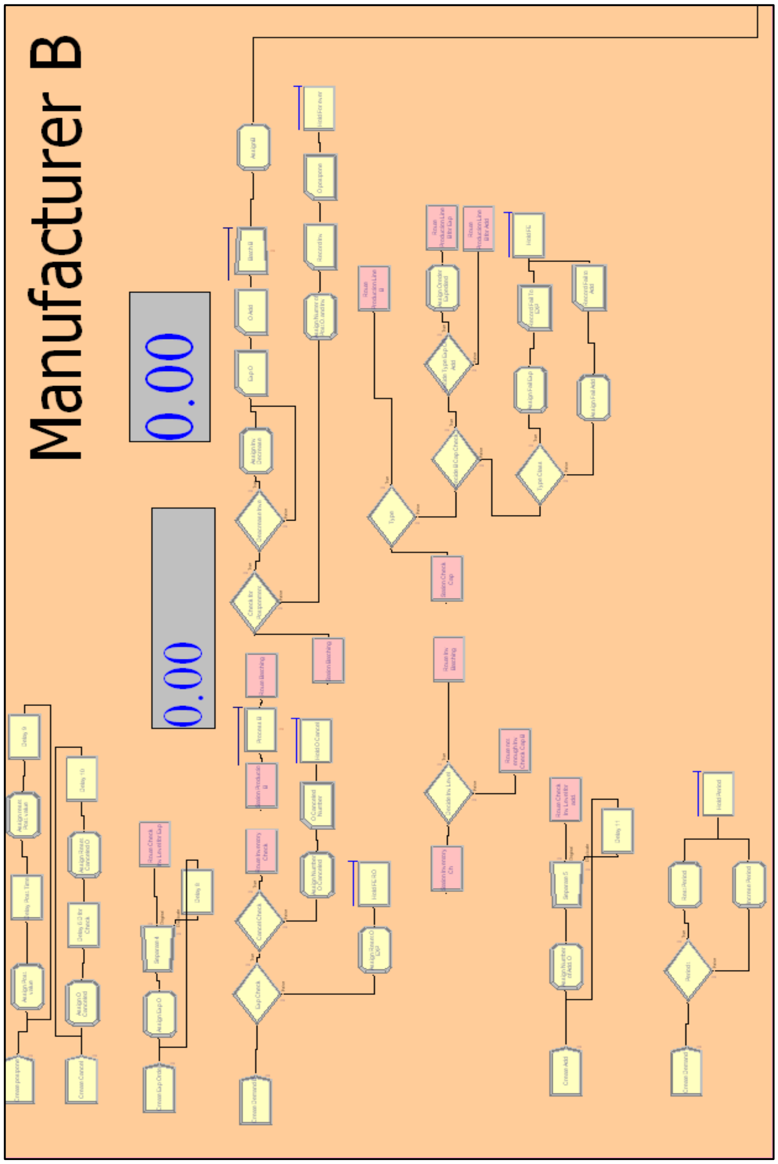
B.2.3.3: Batch size: 1160

			Period											
			1	2	3	4	5	6	7	8	9	10	11	12
X	A	1	1143	1116	987	1291	998	1033	949	1148	1042	986	789	1138
	B	2	1143	1116	987	1291	998	1033	949	1148	1042	986	789	1138
	C	3	2286	2232	1974	2582	1996	2066	1898	2296	2084	1972	1578	2276
W	A	1	2	2	2	3	2	2	1	2	2	2	1	2
	B	2	2	2	1	2	1	1	1	2	1	1	1	2
	C	3	3	2	2	4	2	2	2	3	2	2	1	3
I	A	1	0	0	0	0	0	0	0	0	0	0	0	0

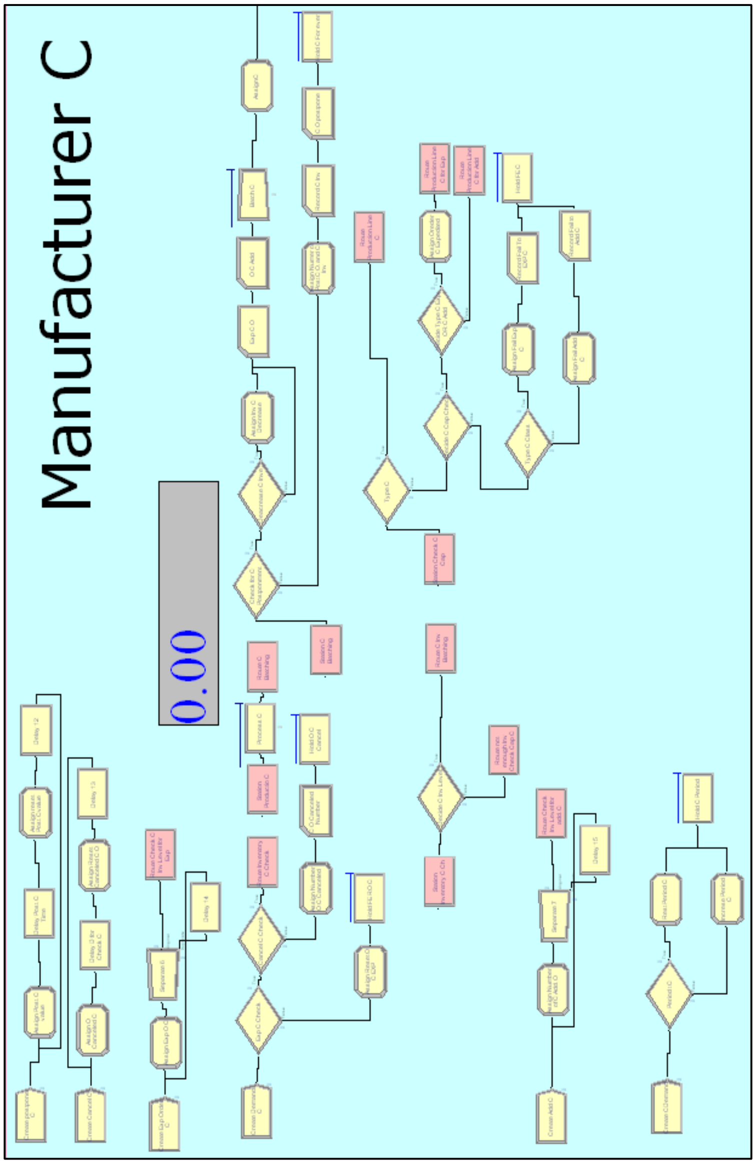
	B	2	0	0	0	0	0	0	0	0	0	0	0	0
	C	3	0	0	0	0	0	0	0	0	0	0	0	0
R	A	1	1145	1116	986	1292	997	1033	949	1149	1042	986	788	1140
	B	2	1145	1116	987	1292	997	1033	949	1149	1042	986	789	1140
	C	3	2289	2232	1973	2584	1994	2066	1898	2297	2084	1972	1577	2279
Y	A	1	1	1	1	1	1	1	1	1	1	1	1	1
	B	2	1	1	1	1	1	1	1	1	1	1	1	1
	C	3	1	1	1	1	1	1	1	1	1	1	1	1

Appendix C: Simulation Model

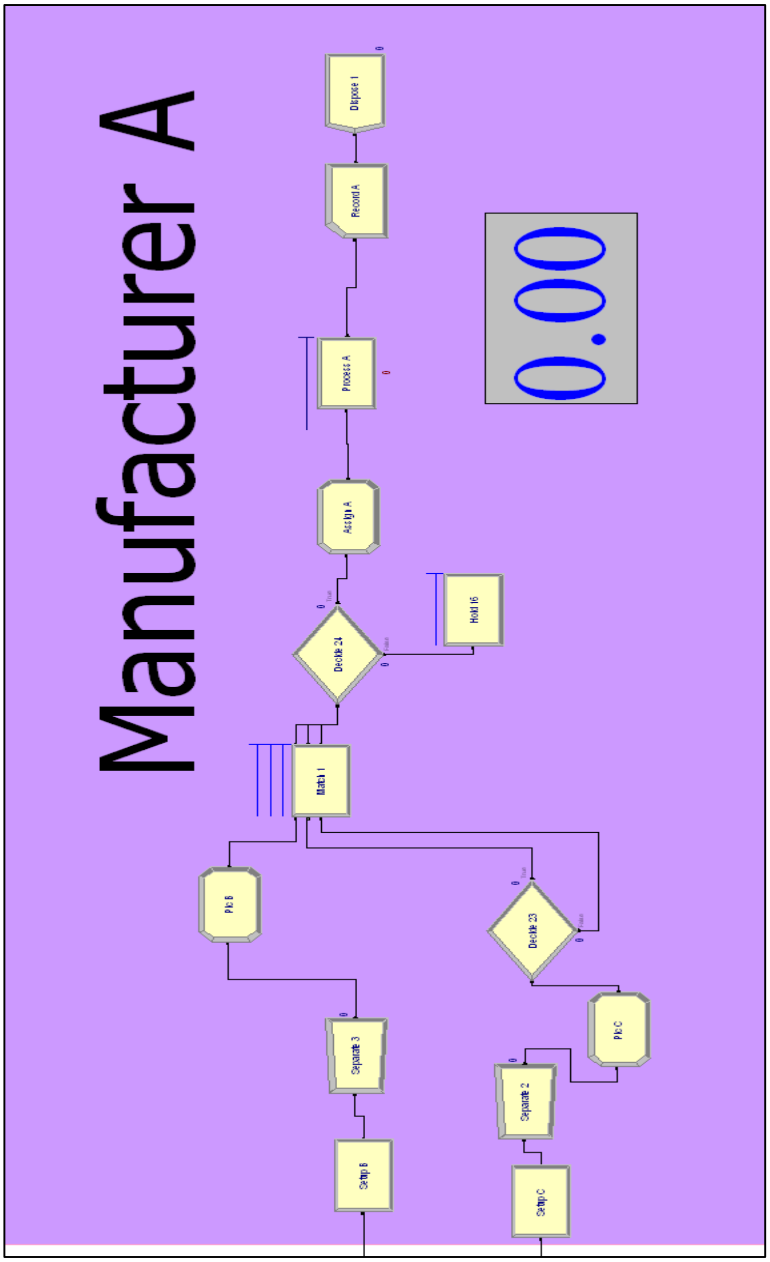
C.1.1: Arena Simulation Snapshot



Arena simulation model for supplier B



Arena simulation model for supplier C



Arena simulation model for customer A

C.1.2: Simulation Reports

Medium Demand Variability for Batch size 580

Replications: 5 Time Units: Days

Key Performance Indicators

System	Average
Number Out	8,493

Medium Demand Variability for Batch size 580

Replications: 5 Time Units: Days

Entity

Time

VA Time

	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity B	0.07952737	0.00	0.07922671	0.07986592	0.00	0.5316

NVA Time

	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity B	0.00	0.00	0.00	0.00	0.00	0.00

Wait Time

	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity B	7.2352	0.14	7.0661	7.3529	1.3162	40.5239

Transfer Time

	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity B	0.00	0.00	0.00	0.00	0.00	0.00

Other Time

	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity B	0.7500	0.00	0.7500	0.7500	0.7500	0.7500

Total Time

	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity B	8.0647	0.14	7.8957	8.1828	2.0799	41.3632

Other

Medium Demand Variability for Batch size 580

Replications: 5 Time Units: Days

Entity

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
Entity Add	7000.00	0.00	7000.00	7000.00
Entity Add C	13028.00	0.00	13028.00	13028.00
Entity B	12637.00	0.00	12637.00	12637.00
Entity C	25256.00	0.00	25256.00	25256.00
Entity C Cancel	1.0000	0.00	1.0000	1.0000
Entity C Exp	13028.00	0.00	13028.00	13028.00
Entity Cancel	1.0000	0.00	1.0000	1.0000
Entity Exp	7000.00	0.00	7000.00	7000.00
Entity Post	1.0000	0.00	1.0000	1.0000
Entity Post C	1.0000	0.00	1.0000	1.0000
Entity PP	12.0000	0.00	12.0000	12.0000
Entity PPC	12.0000	0.00	12.0000	12.0000

Number Out	Average	Half Width	Minimum Average	Maximum Average
Entity Add	0.00	0.00	0.00	0.00
Entity Add C	0.00	0.00	0.00	0.00
Entity B	8508.20	42.66	8447.00	8528.00
Entity C	15.0000	0.00	15.0000	15.0000
Entity C Cancel	0.00	0.00	0.00	0.00
Entity C Exp	0.00	0.00	0.00	0.00
Entity Cancel	0.00	0.00	0.00	0.00
Entity Exp	0.00	0.00	0.00	0.00
Entity Post	0.00	0.00	0.00	0.00
Entity Post C	0.00	0.00	0.00	0.00
Entity PP	0.00	0.00	0.00	0.00
Entity PPC	0.00	0.00	0.00	0.00

Medium Demand Variability for Batch size 580

Replications: 5 Time Units: Days

Entity

Other

WIP	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity Add	4637.50	0.00	4637.50	4637.50	0.00	7000.00
Entity Add C	8631.05	0.00	8631.05	8631.05	0.00	13028.00
Entity B	2339.27	3.09	2336.55	2341.77	0.00	4291.00
Entity C	11854.65	0.00	11854.65	11854.65	0.00	25241.00
Entity C Cancel	0.9996	0.00	0.9996	0.9996	0.00	1.0000
Entity C Exp	6459.72	0.00	6459.72	6459.72	0.00	13028.00
Entity Cancel	0.9996	0.00	0.9996	0.9996	0.00	1.0000
Entity Exp	3470.83	0.00	3470.83	3470.83	0.00	7000.00
Entity Post	0.8292	0.00	0.8292	0.8292	0.00	1.0000
Entity Post C	0.8292	0.00	0.8292	0.8292	0.00	1.0000
Entity PP	5.5000	0.00	5.5000	5.5000	0.00	12.0000
Entity PPC	5.5000	0.00	5.5000	5.5000	0.00	12.0000

Medium Demand Variability for Batch size 580

Replications: 5 Time Units: Days

Queue

Time

Waiting Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Batch B.Queue	6.4676	0.32	6.0059	6.6037	0.00	40.5239
Batch C.Queue	6.2596	0.37	6.0094	6.5853	0.00	40.5090
Match 1.Queue1	0.1331	0.23	0.00573843	0.4513	0.00	1.1172
Match 1.Queue2	0.5071	0.90	0.00577023	1.6738	0.00	11.2822
Match 1.Queue3	0.5071	0.90	0.00577023	1.6738	0.00	11.2822
Process A.Queue	0.7508	0.01	0.7404	0.7631	0.00	1.7684
Process B.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Process C.Queue	0.00	0.00	0.00	0.00	0.00	0.00

Other

Number Waiting	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Batch B.Queue	269.97	5.02	263.24	273.69	0.00	580.00
Batch C.Queue	534.38	36.17	504.77	574.35	0.00	1160.00
Hold 16.Queue	7599.02	44.92	7579.26	7663.51	0.00	17668.00
Hold C For ever.Queue	2594.10	701.61	1583.14	2849.12	0.00	5579.00
Hold C Period.Queue	5.5000	0.00	5.5000	5.5000	0.00	12.0000
Hold FE C.Queue	8320.37	621.13	8089.86	9215.32	0.00	18564.00
Hold FE RO C.Queue	1.2374	0.00	1.2374	1.2374	0.00	3.0000
Hold FE RO.Queue	1.2372	0.00	1.2372	1.2372	0.00	3.0000
Hold FE.Queue	4355.32	3.78	4351.40	4358.61	0.00	8534.00
Hold For ever.Queue	1470.07	16.82	1445.90	1476.84	0.00	2916.00
Hold O C Cancel.Queue	2525.15	0.00	2525.15	2525.15	0.00	5163.00
Hold O Cancel.Queue	1264.59	0.00	1264.59	1264.59	0.00	2592.00
Hold Period.Queue	5.5000	0.00	5.5000	5.5000	0.00	12.0000
Match 1.Queue1	4.8260	8.30	0.2080	16.3595	0.00	580.00
Match 1.Queue2	18.3821	32.45	0.2092	60.6770	0.00	580.00
Match 1.Queue3	18.3821	32.45	0.2092	60.6770	0.00	580.00
Process A.Queue	26.5718	0.54	26.0190	27.0539	0.00	562.00
Process B.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Process C.Queue	0.00	0.00	0.00	0.00	0.00	0.00

Medium Demand Variability for Batch size 580

Replications: 5 Time Units: Days

Resource

Usage

Instantaneous Utilization	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Resource A	0.0981	0.00	0.0964	0.0992	0.00	0.9741
Resource B	0.05845412	0.00	0.05714546	0.05964980	0.00	0.8229
Resource C	0.03872484	0.01	0.03620167	0.04764235	0.00	0.8106

Number Busy	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Resource A	1.6110	0.02	1.5829	1.6294	0.00	16.0000
Resource B	1.2787	0.03	1.2501	1.3048	0.00	18.0000
Resource C	1.5766	0.25	1.4739	1.9396	0.00	33.0000

Number Scheduled	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Resource A	16.4250	0.00	16.4250	16.4250	16.4250	16.4250
Resource B	21.8750	0.00	21.8750	21.8750	21.8750	21.8750
Resource C	40.7125	0.00	40.7125	40.7125	40.7125	40.7125

Scheduled Utilization	Average	Half Width	Minimum Average	Maximum Average
Resource A	0.0981	0.00	0.0964	0.0992
Resource B	0.05845412	0.00	0.05714546	0.05964980
Resource C	0.03872484	0.01	0.03620167	0.04764235

Medium Demand Variability for Batch size 580

Replications: 5 Time Units: Days

Resource

Usage

Total Number Seized	Average	Half Width	Minimum Average	Maximum Average
Resource A	8493.20	42.66	8432.00	8513.00
Resource B	6263.60	78.79	6224.00	6376.00
Resource C	13401.80	1,901.12	12693.00	16141.00

Medium Demand Variability for Batch size 580

Replications: 5 Time Units: Days

User Specified

Tally

Expression	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Record C Inv	1193.80	360.15	674.85	1324.13	1.0000	3388.00
Record Inv	702.65	15.37	680.54	708.84	1.0000	1818.00

Interval	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Record A	0.7964	0.01	0.7856	0.8090	0.00	1.9231

Counter

Count	Average	Half Width	Minimum Average	Maximum Average
C O Canceled Number	5163.00	0.00	5163.00	5163.00
C O postpone	4963.40	1,700.58	2513.00	5579.00
Exp C O	436.40	408.11	269.00	1023.00
Exp O	183.20	76.88	130.00	289.00
O Add	174.00	12.87	165.00	188.00
O C Add	325.00	34.61	282.00	360.00
O Canceled Number	2592.00	0.00	2592.00	2592.00
O postpone	2899.60	40.75	2841.00	2916.00
Record Fail to Add	5165.00	4.39	5161.00	5169.00
Record Fail to Add C	9610.40	14.91	9594.00	9627.00
Record Fail To EXP	3362.40	7.06	3357.00	3372.00
Record Fail To EXP C	6791.80	1,497.82	6240.00	8950.00

Values Across All Replications

Unnamed Project

Replications: 5 Time Units: Days

Unnamed Project

Replications:	5	Time Units:	Days

Key Performance Indicators

System

	Average
Number Out	8,493

Category Overview

Values Across All Replications

Unnamed Project

Replications: 5 Time Units: Days

Entity

Time

VA Time

	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity B	0.07952737	0.00	0.07922671	0.07986592	0.00	0.5316

NVA Time

	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity B	0.00	0.00	0.00	0.00	0.00	0.00

Wait Time

	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity B	7.2352	0.14	7.0661	7.3529	1.3162	40.5239

Transfer Time

	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity B	0.00	0.00	0.00	0.00	0.00	0.00

Other Time

	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity B	0.7500	0.00	0.7500	0.7500	0.7500	0.7500

Total Time

	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity B	8.0647	0.14	7.8957	8.1828	2.0799	41.3632

Other

Unnamed Project

Replications: 5 Time Units: Days

Entity

Other

Number In

	Average	Half Width	Minimum Average	Maximum Average
Entity Add	7000.00	0.00	7000.00	7000.00
Entity Add C	13028.00	0.00	13028.00	13028.00
Entity B	12637.00	0.00	12637.00	12637.00
Entity C	25256.00	0.00	25256.00	25256.00
Entity C Cancel	1.0000	0.00	1.0000	1.0000
Entity C Exp	13028.00	0.00	13028.00	13028.00
Entity Cancel	1.0000	0.00	1.0000	1.0000
Entity Exp	7000.00	0.00	7000.00	7000.00
Entity Post	1.0000	0.00	1.0000	1.0000
Entity Post C	1.0000	0.00	1.0000	1.0000
Entity PP	12.0000	0.00	12.0000	12.0000
Entity PPC	12.0000	0.00	12.0000	12.0000

Number Out

	Average	Half Width	Minimum Average	Maximum Average
Entity Add	0.00	0.00	0.00	0.00
Entity Add C	0.00	0.00	0.00	0.00
Entity B	8508.20	42.66	8447.00	8528.00
Entity C	15.0000	0.00	15.0000	15.0000
Entity C Cancel	0.00	0.00	0.00	0.00
Entity C Exp	0.00	0.00	0.00	0.00
Entity Cancel	0.00	0.00	0.00	0.00
Entity Exp	0.00	0.00	0.00	0.00
Entity Post	0.00	0.00	0.00	0.00
Entity Post C	0.00	0.00	0.00	0.00
Entity PP	0.00	0.00	0.00	0.00
Entity PPC	0.00	0.00	0.00	0.00

Category Overview

Values Across All Replications

Unnamed Project

Replications: 5 Time Units: Days

Entity

Other

WIP	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity Add	4637.50	0.00	4637.50	4637.50	0.00	7000.00
Entity Add C	8631.05	0.00	8631.05	8631.05	0.00	13028.00
Entity B	2339.27	3.09	2336.55	2341.77	0.00	4291.00
Entity C	11854.65	0.00	11854.65	11854.65	0.00	25241.00
Entity C Cancel	0.9996	0.00	0.9996	0.9996	0.00	1.0000
Entity C Exp	6459.72	0.00	6459.72	6459.72	0.00	13028.00
Entity Cancel	0.9996	0.00	0.9996	0.9996	0.00	1.0000
Entity Exp	3470.83	0.00	3470.83	3470.83	0.00	7000.00
Entity Post	0.8292	0.00	0.8292	0.8292	0.00	1.0000
Entity Post C	0.8292	0.00	0.8292	0.8292	0.00	1.0000
Entity PP	5.5000	0.00	5.5000	5.5000	0.00	12.0000
Entity PPC	5.5000	0.00	5.5000	5.5000	0.00	12.0000

Category Overview

Values Across All Replications

Unnamed Project

Replications: 5 Time Units: Days

Queue

Time

Waiting Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Batch B.Queue	6.4676	0.32	6.0059	6.6037	0.00	40.5239
Batch C.Queue	6.2596	0.37	6.0094	6.5853	0.00	40.5090
Match 1.Queue1	0.1331	0.23	0.00573843	0.4513	0.00	1.1172
Match 1.Queue2	0.5071	0.90	0.00577023	1.6738	0.00	11.2822
Match 1.Queue3	0.5071	0.90	0.00577023	1.6738	0.00	11.2822
Process A.Queue	0.7508	0.01	0.7404	0.7631	0.00	1.7684
Process B.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Process C.Queue	0.00	0.00	0.00	0.00	0.00	0.00

Other

Number Waiting	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Batch B.Queue	269.97	5.02	263.24	273.69	0.00	580.00
Batch C.Queue	534.38	36.17	504.77	574.35	0.00	1160.00
Hold 16.Queue	7599.02	44.92	7579.26	7663.51	0.00	17668.00
Hold C For ever.Queue	2594.10	701.61	1583.14	2849.12	0.00	5579.00
Hold C Period.Queue	5.5000	0.00	5.5000	5.5000	0.00	12.0000
Hold FE C.Queue	8320.37	621.13	8089.86	9215.32	0.00	18564.00
Hold FE RO C.Queue	1.2374	0.00	1.2374	1.2374	0.00	3.0000
Hold FE RO.Queue	1.2372	0.00	1.2372	1.2372	0.00	3.0000
Hold FE.Queue	4355.32	3.78	4351.40	4358.61	0.00	8534.00
Hold For ever.Queue	1470.07	16.82	1445.90	1476.84	0.00	2916.00
Hold O C Cancel.Queue	2525.15	0.00	2525.15	2525.15	0.00	5163.00
Hold O Cancel.Queue	1264.59	0.00	1264.59	1264.59	0.00	2592.00
Hold Period.Queue	5.5000	0.00	5.5000	5.5000	0.00	12.0000
Match 1.Queue1	4.8260	8.30	0.2080	16.3595	0.00	580.00
Match 1.Queue2	18.3821	32.45	0.2092	60.6770	0.00	580.00
Match 1.Queue3	18.3821	32.45	0.2092	60.6770	0.00	580.00
Process A.Queue	26.5718	0.54	26.0190	27.0539	0.00	562.00
Process B.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Process C.Queue	0.00	0.00	0.00	0.00	0.00	0.00

Category Overview

Values Across All Replications

Unnamed Project

Replications: 5 Time Units: Days

Resource

Usage

Instantaneous Utilization	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Resource A	0.0981	0.00	0.0964	0.0992	0.00	0.9741
Resource B	0.05845412	0.00	0.05714546	0.05964980	0.00	0.8229
Resource C	0.03872484	0.01	0.03620167	0.04764235	0.00	0.8106

Number Busy	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Resource A	1.6110	0.02	1.5829	1.6294	0.00	16.0000
Resource B	1.2787	0.03	1.2501	1.3048	0.00	18.0000
Resource C	1.5766	0.25	1.4739	1.9396	0.00	33.0000

Number Scheduled	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Resource A	16.4250	0.00	16.4250	16.4250	16.4250	16.4250
Resource B	21.8750	0.00	21.8750	21.8750	21.8750	21.8750
Resource C	40.7125	0.00	40.7125	40.7125	40.7125	40.7125

Scheduled Utilization	Average	Half Width	Minimum Average	Maximum Average
Resource A	0.0981	0.00	0.0964	0.0992
Resource B	0.05845412	0.00	0.05714546	0.05964980
Resource C	0.03872484	0.01	0.03620167	0.04764235

Category Overview

Values Across All Replications

Unnamed Project

Replications: 5 Time Units: Days

Resource

Usage

Total Number Seized	Average	Half Width	Minimum Average	Maximum Average
Resource A	8493.20	42.66	8432.00	8513.00
Resource B	6263.60	78.79	6224.00	6376.00
Resource C	13401.80	1,901.12	12693.00	16141.00

Category Overview

Values Across All Replications

Unnamed Project

Replications: 5 Time Units: Days

User Specified

Tally

Expression	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Record C Inv	1193.80	360.15	674.85	1324.13	1.0000	3388.00
Record Inv	702.65	15.37	680.54	708.84	1.0000	1818.00

Interval	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Record A	0.7964	0.01	0.7856	0.8090	0.00	1.9231

Counter

Count	Average	Half Width	Minimum Average	Maximum Average
C O Canceled Number	5163.00	0.00	5163.00	5163.00
C O postpone	4963.40	1,700.58	2513.00	5579.00
Exp C O	436.40	408.11	269.00	1023.00
Exp O	183.20	76.88	130.00	289.00
O Add	174.00	12.87	165.00	188.00
O C Add	325.00	34.61	282.00	360.00
O Canceled Number	2592.00	0.00	2592.00	2592.00
O postpone	2899.60	40.75	2841.00	2916.00
Record Fail to Add	5165.00	4.39	5161.00	5169.00
Record Fail to Add C	9610.40	14.91	9594.00	9627.00
Record Fail To EXP	3362.40	7.06	3357.00	3372.00
Record Fail To EXP C	6791.80	1,497.82	6240.00	8950.00