Sources and Propagation of Schedule Volatility in an MRP System

by

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B.S. Mechanical Engineering
Virginia Polytechnic Institute and State University

Submitted to the Department of Mechanical Engineering and the Sloan School of Management in partial fulfillment of the requirements for the degrees of

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ABSTRACT

MRP systems often suffer from nervousness or schedule volatility, in which the system is constantly changing production and purchased part schedules. While the rescheduling may be driven by changes in the master schedule, MRP operating parameters, scrap or loss, or many other factors, lotting policies used by the MRP system may serve to amplify the effect of these changes on lower level schedules. Through analysis and comparison of different purchased part schedules used at Hamilton Sundstrand Corporation, the magnitude of this amplification is measured. Various proposals for reducing the schedule volatility problem including reduced lot sizes, fixed lot sizes, and pull systems are discussed and the impact on volatility and inventory levels is analyzed.

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Dedication

I would like to dedicate this thesis to my loving wife, Barbara, who supported me financially and mentally and without whose encouragement my wish to return to school full-time would have been impossible; to my parents, whose love and teaching have brought me here; and to my grandfather, who received his Master of Science in Electrical Engineering from the Massachusetts Institute of Technology and who instilled in me the dream to attend this Institution.

I would also like to dedicate this thesis to our unborn child – this work embodies my hope and dreams for your future.

"All this I tested by wisdom and I said, "I am determined to be wise" - but this was beyond me. Whatever wisdom may be, it is far off and most profound – who can discover it? So I turned my mind to understand, to investigate and to search out wisdom and the scheme of things…."

Ecclesiastes 7:23-25, NIV

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1. Introduction

The objective of this thesis is to discuss the sources of volatility in schedules created using modern MRP systems. By analyzing actual schedule data obtained from Hamilton Sundstrand, a division of United Technologies Corporation, it will be shown how the MRP system can produce highly volatile schedules. The resulting instability at the purchased part level may be so high, in fact, that suppliers are unable to maintain acceptable service levels without excessive inventory levels. Since suppliers may be unwilling or unable to hold large amounts of inventory, with the corresponding inventory costs and risk of obsolescence, downstream production may suffer when part shortages occur.

This thesis will also demonstrate, using actual schedule data, how lot size policies in the MRP system contribute to the problem by amplifying the magnitude of schedule changes. These policies work in such a way that small changes to the master schedule may appear as very large quantity changes to suppliers. The resulting amplification requires that suppliers maintain much higher inventory levels for a given service level than would otherwise be warranted based on the variation in aggregate customer demand.

Finally, some proposals for reducing schedule volatility are presented. The thesis also examines some alternate planning and ordering methods being considered, and discusses the probable ramifications on schedule volatility and inventory levels.

1.1 Background

The problem with schedule volatility in MRP systems is not new, nor is it a concern only for Hamilton Sundstrand. In fact, one year earlier, a fellow Leaders for Manufacturing internship was concerned with exactly this problem. Thomas Hoag (1999) at Pratt & Whitney (another company within United Technologies) looked at various sources of volatility in the MRP schedule and the cost of making changes to schedules. Based on this analysis, he recommended rules regarding when a change should or should not be made.

Although we will use Hamilton Sundstrand's terminology for changes in purchasing or production schedules, what we refer to as schedule volatility (or instability) is generally described as *nervousness* in the academic literature. This term was used by Steele (1975) to describe:

> "...excessive changes to low-level requirements when there are no major changes in the master schedule"

The problem with schedule volatility in MRP systems is in fact so widespread, that it is discussed briefly in operations textbooks such as Arnold (1991) and Nahmias (1997).

Schedule volatility is caused by many factors, including changes in the master production schedule (MPS), scrap and loss, changes in the bill of material, and changes in MRP system parameters. The factors leading to nervousness are discussed in more detail in Steele (1975) and Mather (1977).

Although the causes of schedule volatility should be minimized so as to improve stability, much of the problem with instability arises as a result of lot size policies. Steele (1975) discusses how lot-sizing problems contribute to, and even amplify changes at low-levels in the MRP system. He also suggests the use of fixed order quantity lot sizes as opposed to period of supply lot sizes to help stabilize MRP schedules. Mather (1977) expands on this work and suggests that:

> "...most reschedules that occur in MRP programs today are not caused by reactions to customer wishes. They result from application of sophisticated mathematical routines for calculating lot-sizes..."

He also presents some good examples demonstrating how lot-sizing issues contribute to schedule volatility.

Although it has long been recognized that lot size problems contribute to schedule volatility, it has been difficult to determine a good solution. Since lot sizes are established to minimize total cost, recognizing that each purchase order or work order has an associated fixed cost, some researchers have proposed assessing a cost to rescheduling. Kropp (1979) suggests incorporating the additional fixed cost of changing the schedule into the logic used to dynamically determine the lot size in the MRP system. In theory, such a system would only make a change when, in fact, it is economically justified. Kropp (1984) expands on this suggestion by proposing a modified Wagner-Whitin algorithm that includes the "cost of nervousness" in the fixed costs. Unfortunately, the difficulty in attaching a cost to instability or the complexity of incorporating this logic into MRP systems may have prevented this solution from gaining popularity.

Minifie (1986) suggests using dampening mechanisms to reduce the effect of changes on low-level schedules. These mechanisms may include safety stock or safety lead-time, time fences, and/or different lot sizing techniques. Time fences provide rules regarding when changes can be made in the schedule. For example, a time fence may state that an order cannot be deferred within four weeks of the scheduled production date.

These and other techniques to improve schedule stability were evaluated by Blackburn (1986), using simulation to investigate the effectiveness of freezing the schedule within the planning horizon, lot for lot policies after stage 1, safety stocks, forecast beyond the planning horizon, and a change cost procedure. The fact that this simulation was conducted using dynamic lot sizing algorithms such as Wagner-Whitin or Silver-Meal makes it difficult to compare the results to Hamilton Sundstrand, who uses only very simple lot size policies, such as fixed lot size or period of supply. However, it should be noted that safety stock was helpful in reducing schedule volatility, however, since relatively large levels of inventory were required, this method was judged ineffective on the basis of cost.

Ho (1989) also used simulation to determine the affect of various lot sizing rules and dampening procedures on cost and schedule volatility. This work concluded that a fixed lot size rule significantly reduced the instability in the MRP schedules as compared to a dynamic lot size rule such as lot-for-lot. However, the conclusion also suggested that the reduction in schedule stability was balanced by an increase in total costs, since the fixed order quantity was more likely to result in a part shortage. The cost of this system with additional safety stock was not evaluated.

Although considerable effort has been devoted to understanding schedule volatility and using simulation to determine the theoretical benefits of various lotting policies and dampening methods, there seems to be little or no data on the actual magnitude to which lotting policies affect schedule volatility. Without such data, it may be difficult to convince a company that a significant problem exists, or that simply addressing the causes of instability may be insufficient to solve the problem. Although at least two divisions of United Technologies have experienced significant problems with schedule volatility, there was no clear understanding of the size of the problem, or the contribution of lotting policies.

Almost all of the research to date has used simulation results to determine the performance characteristics of various proposed solutions, without any data on the functionality and actual benefits in real manufacturing environments. It is difficult to convince companies to change procedures when the benefits cannot be quantified.

In addition, the implementation of complex algorithms to determine what size lots are ordered or produced, or when to allow or forbid a schedule change may be hindered by the inability of users to understand the logic. Although such systems may perform better, users may like the ability to look at an MRP schedule and understand how it was generated. This probably explains why Hamilton Sundstrand typically only uses fixed or period-of-supply lot sizes, and why many MRP systems do not utilize more complex algorithms.

This thesis uses actual schedule data to quantify the schedule volatility problem and the effect of lotting policies. Based on this analysis, some relatively simple proposals are suggested for reducing the amount of schedule instability experienced by suppliers. These proposals are than evaluated based on results from former Sundstrand plants and using a simple analysis of inventory levels. It is believed that this will better convince people of the nature of the problem and what steps can be taken to allow improvement.

1.2 Thesis Overview

Using actual schedule data collected over a fifteen-week period, this thesis presents evidence that schedule volatility is a major contributor to poor on-time delivery from suppliers. Suppliers are generally required to maintain approximately one to two months worth of demand for each part in inventory, and discussions of schedule volatility and on-time delivery often focus on why suppliers who maintain this inventory should be expected to deliver even with schedule changes. This analysis demonstrates that significantly higher levels of inventory are required to maintain acceptable service levels.

By comparing the volatility of two related schedules, it can be shown that lotting policies contribute significantly to the problem of schedule instability. While the influence of lotting policies on schedule instability has been discussed at length in the academic literature, this analysis, using actual schedule data, demonstrates the magnitude to which such policies contribute to the problem at Hamilton Sundstrand. This lends credibility to the argument that schedule volatility can only be improved by addressing the lotting policies used within the MRP system and the manner in which demand requirements are communicated to suppliers.

1.3 Thesis Outline

This thesis is divided into seven sections: Introduction, Project Description, Problem Definition, Schedule Volatility Analysis, Time Volatility Analysis, Proposals for Reducing Volatility, and Conclusions / Recommendations. Section 1 (Introduction) gives background to the problem of schedule volatility, how it may affect suppliers and production, and prior research regarding volatility and lotting policies. Section 2 (Project Description) discusses the internship setting, and the main issues of concern for the Purchasing Department of Hamilton Sundstrand. Section 3 (Problem Definition) discusses some initial actions that were taken to deal with schedule volatility and describes some of the main sources of instability in the MRP schedules. The next two sections present the results of an analysis of approximately four months of schedule data for purchased parts. Section 4 (Schedule Volatility Analysis) demonstrates the level of instability that exists in these schedules, and the ramifications for suppliers' service level and inventory. This section also demonstrates how lotting policies contribute to schedule instability. While this section primarily focuses on quantity changes within the schedule, Section 5 (Time Volatility Analysis) presents the results of an analysis of time volatility. Section 6 (Proposals for Reducing Schedule Volatility) presents some suggestions for reducing the impact of lotting policies on schedule instability and looks at the inventory ramifications of these proposals. Finally, Section 7 (Conclusions / Recommendations) suggests a course of action for improving schedule volatility over time.

2. Project Description

This project was performed at the Hamilton Sundstrand Division of the United Technologies Corporation. The focus of this project was an attempt to determine the root cause(s) of excessive week to week changes in the quantity requirements of purchased parts as seen in the schedules provided to suppliers. These changes are collectively referred to as *schedule volatility*, and were perceived by Hamilton Sundstrand as potentially the largest single cause of overdue shipments of parts from suppliers. Overdue shipments were in turn considered a major cause of high Work-In-Process (WIP) inventory levels and undesirable customer on-time service performance.

This section contains background material describing Hamilton Sundstrand, the motivation for improving schedule volatility, an overview of the function of a typical MRP system, and the suppliers' view of the schedule volatility problem.

2.1 Company Description

Hamilton Sundstrand is a large supplier of aerospace components for military and commercial aircraft based in Windsor Locks, CT. It is a wholly owned subsidiary of the United Technologies Corporation in Hartford, CT. Hamilton Sundstrand was formed during the merger of Hamilton Standard and Sundstrand Corporation in 1999.

Hamilton Sundstrand supplies a large variety of aerospace components including jet engine fuel controllers, jet engine starters, auxiliary power units (APUs) for aircraft, and aircraft environmental control units (ECUs), as well as such products as propellers, space suits and other space shuttle systems, and environmental systems for submarines. The products can be generally categorized as high variety, high lead-time, relatively high cost and low volume.

The business can be divided into two parts, Original Equipment Manufacturers (OEM) and Aftermarket Replacement Parts (Spares). The OEM business is generally make-to-order, with schedules being provided by customers as far as two years in advance. The spares business is make-to-stock, with production schedules based on forecasts.

The nature of the spares business makes forecasting difficult and often very inaccurate. Hamilton Sundstrand provides spare parts for current production aircraft, as well as out-of-production aircraft. Since the out-of-production-spares (OOPS) may be for planes with very few aircraft still flying in the world, Hamilton Sundstrand is supporting parts that may have gone into production 50 or 60 years ago. This makes forecasting and obtaining purchased parts, particularly electronic components, very difficult. In such an environment, Hamilton Sundstrand requires close working relationships with the supply base to support changing needs and flexible production of low volume, obsolete parts.

2.2 Motivation

Starting at the beginning of 2000, the number of overdue shipments from suppliers began to steadily rise. As the number of overdue shipments began to rise, production had increasing difficulty completing finished items for delivery to customers. This resulted in an increase in inventory levels, as WIP inventory grew. In addition, on-time delivery to customers suffered, as Hamilton Sundstrand was unable to complete parts in the planned lead-time. This in turn led to increased customer dissatisfaction.

Representatives from the purchasing department met with many of the suppliers with particularly high levels of overdue parts. Specifically, they requested that the suppliers identify areas of improvement and actions that would enable them to decrease their overdue by 50%. The suppliers agreed to identify actions, but expressed their belief that approximately 50% of the problem was caused by significant changes in the delivery schedules provided weekly by Hamilton Sundstrand.

2.3 MRP System Overview

Hamilton Sundstrand uses a typical MRP system to track customer requirements and forecasted needs, plan production schedules, and determine purchase parts requirements. The system used is J.D. Edwards, but is comparable with many of the popular MRP products including Oracle or SAP.

The basic operation of the MRP system is to determine how many parts on what dates must be delivered in order to meet customer demand. Similarly, the production start dates of subassemblies manufactured in the factory are determined by the MRP system. It does this by starting with the dates and quantity of expected customer demand (i.e. when the end item is needed). This schedule may be either a firm order (as generally the case with OEM parts) or a forecast schedule (as generally provided by the spares group). Taking this Master Production Schedule (MPS), the system then determines what components and what quantity of each component are used in the end product, based on a Bill of Materials (BOM). Finally, the system determines the required delivery date of purchased parts, and the required start date of production parts by subtracting the lead-time for each component from the date of the demand. This is done for every end item and for every level of assembly in an end item consisting of components built from other assemblies that may in turn be composed of other sub-assemblies.

Consider the following examples:

End Item A is needed in 4 weeks and is built from assemblies Q and R

Assembly Q requires one week to build and is used once in Item A

Assembly R requires two weeks to build and is used twice in Item A

Thus, the MRP schedule would look like this:

	Week 1	Week 2	Week 3	Week 4
Item A				1
Assembly Q			1	
Assembly R		2		

Assume Assembly R is composed of purchased parts x and y

Part x is used once in Assembly R

Part y is used three times in Assembly R

Thus, the MRP schedule for the purchased parts would look like this:

	Week 1	Week 2	Week 3	Week 4
Assembly R		2		
Part x		2		
Part y		6		

The schedule for Parts x and y would then be provided to the supplier for those parts, who would be expected to deliver two of Part x and six of Part y during the second week.

In any given week, Hamilton Sundstrand has over 15,000 different part numbers with a requirement in the next 12 weeks. The actual number of active part numbers is much higher. Although the above calculations are relatively simple, and can be performed quickly by a computer, the high product complexity of Hamilton Sundstrand's operation requires very fast computers. Even so, it takes approximately eight hours to complete all the calculations to determine production schedules and purchased part requirements. Therefore, this calculation is performed only once a week, on Sunday, and a new schedule provided Monday morning to suppliers either via the Internet or by EDI (Electronic Data Interchange).

2.4 Supplier Viewpoint

When asked to improve their overdue by 50% by the end of the year, the suppliers responded by saying that about 50% of their overdue problem was caused by changes in the MRP schedule of requirements that Hamilton provided each week. They cited numerous examples where parts were apparently not needed until several weeks in the future, and suddenly large quantities were required in the current week, or were in fact already overdue. This made it impossible for the supplier to deliver parts on time based on the MRP schedule. As suppliers rearranged their production schedules to try and expedite these orders, the disruptions resulted in delays on other orders, thereby increased the overdue problem.

Hamilton Sundstrand responded by citing the contractual requirements that suppliers had to maintain finished goods inventory on all parts they supplied (generally one to two months of average demand). The feeling was that if the supplier was in fact fulfilling this requirement, there should be no problem with adjusting to schedule changes.

The suppliers maintained they were indeed fulfilling the contract, but that a schedule change was often so large in magnitude, that it would deplete the entire inventory on the part, and still the supplier would be overdue on the remaining quantity. Later audits suggested that the suppliers were generally maintaining inventory as required.

2.5 Summary

In summary, Hamilton Sundstrand manufacturers a large variety of components in low quantities and purchases many thousands of different components from the supply base. Throughout the year 2000, the number of overdue shipments from suppliers increased steadily, leading to large WIP inventories and unsatisfactory customer service levels.

After meeting with suppliers, Hamilton Sundstrand determined that weekly changes in the delivery schedules provided to suppliers were both frequent and often very large in magnitude. These changes certainly contributed to supplier overdue, and may in fact have been a very large factor (as high as 50%) in the level of overdue shipments.

3. Problem Definition

In order to lower Direct Material Purchase (DMP) cost and reduce on-hand inventory, Hamilton Sundstrand has signed Long-Term Agreements (LTAs) with many suppliers. Suppliers on LTA are provided a schedule of requirements each week either over the Internet or by EDI. This schedule contains weekly quantity requirements for the next eight weeks, and monthly quantity requirements for the following ten months, with any remaining quantity lumped together in the 13th month. The suppliers use these schedules for long-term capacity planning, raw material planning, shop schedule planning, and shipment data. Unfortunately, many of the parts on this schedule are seemingly subject to large changes, in both quantity and date. These changes are such that the supplier, even with one to two months of inventory on the shelves, is often unable to support the schedule requirements.

Not only do the magnitude of the changes create problems with the supplier shipping on-time, but the frequent changes require considerable time and effort, both to track, and to reload the shop accordingly. This reduces the actual capacity of the supplier's operation and can thereby further increase the number of late shipments.

Based on suppliers' statements and Hamilton Sundstrand's initial investigation, this problem could account for as much as 50% of all overdue parts from a supplier. Interestingly enough, suppliers maintain that generally speaking, given a long enough period of time (for example a year), the quantity shipped in that year matches the original forecast. By reducing schedule volatility, Hamilton Sundstrand should be able to improve supplier on-time performance and potentially reduce inventory levels at the supplier.

3.1 Problem Scope

The schedule volatility problem includes all parts that are supplied by an external supplier for both OEM and spares needs. In fact, the MRP system lumps all requirements for common parts within a defined operating unit together. For this project, we have limited our investigation to legacy Hamilton locations in Connecticut. This excludes international operations, Hamilton operations outside of Connecticut, and all legacy Sundstrand operations. Within this definition, there are three production branch plants and two spares branches.

By lumping all requirements within these three branch plants and two spares branches, the MRP system avoids the possibility that a supplier may have to ship many small shipments of the same part to different location. All the requirements for a part are sent to one branch plant (the primary branch), and requirements for other branch plants are handled through interplant transfers. In this case, the primary branch acts like a supplier to all the other branches.

During the initial investigation, we considered only changes that resulted in an overdue part, where the part was not previously overdue, and where, during the previous week, the supplier's schedule did not show a requirement in the current week. We call such a case a "surprise overdue" part. This means that the supplier had no reason to believe the part would be overdue when the new schedule was created during the weekend; hence, the part was a surprise overdue.

3.2 Initial Actions

Initially, we limited our investigation to surprise overdue parts. These parts were particularly important because suppliers were being penalized for failing to deliver parts that they had no reason to believe were needed. As such, these parts were a major source of concern to both Hamilton Sundstrand and suppliers. By examining the source of the schedule change that caused these parts to be suddenly overdue, we hoped to better understand the sources of schedule volatility. Figure 3.1 shows a graph of surprise overdue by production area as a part of all the new parts that were overdue that week. (New overdue parts are parts that were not overdue the previous week. A surprise overdue can also occur for a previously overdue part, if the supplier delivered the overdue requirement and believed they were thereby caught up. However, for simplicity's sake, we ignore such occurrences).

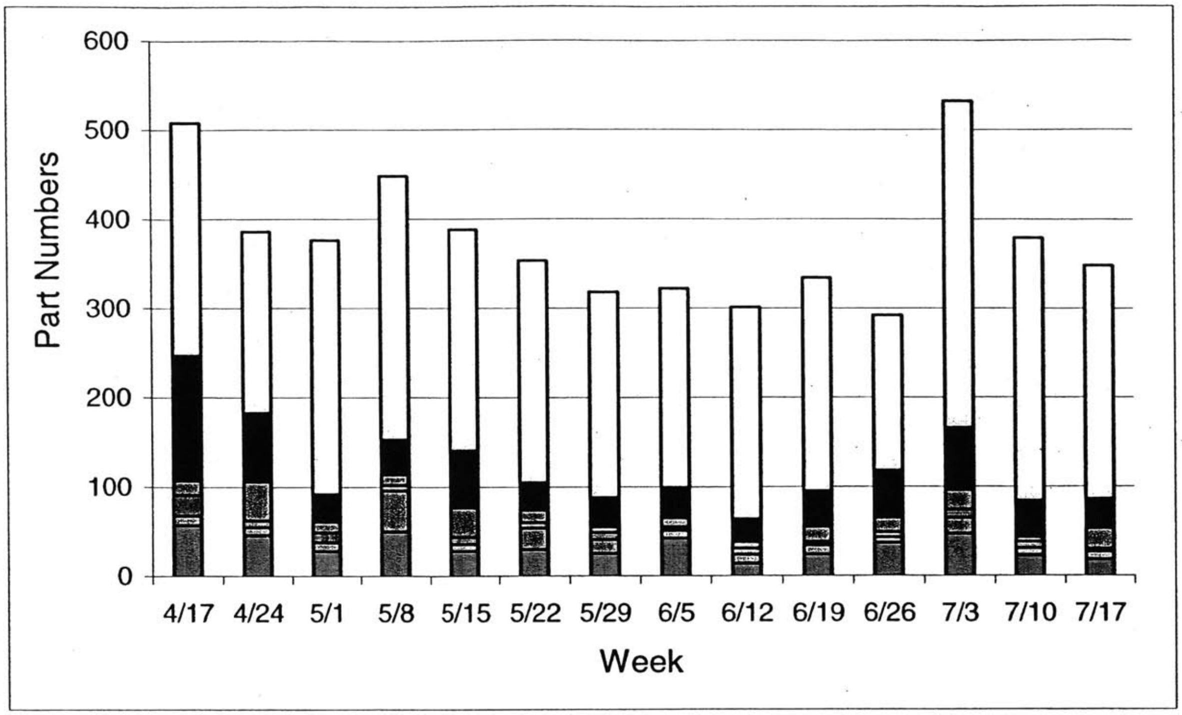


Figure 3.1: Graph of Surprise Overdue Parts relative to all New Overdue Parts by week

The lower segments of the bar combined represent the number of surprise overdue parts in different areas within the plant, while the entire bar represents the total number of new overdue parts. It can be seen that approximately 25% to 50% of all new overdue parts each week were surprises. This supports the statement from the suppliers that approximately 50% of the overdue problem is caused by schedule volatility. It should also be evident from the number of parts in this category (as shown on the y-axis) that this is not a small problem.

Having created a measurement for assessing the schedule volatility problem, we began to investigate the causes that led to each of these surprise overdue parts. This was done by having planners painstakingly review each part to determine what changes were made during the previous week, and thereby led to a schedule change. This could be quite laborious since a change might occur at any level in the Bill of Materials, could be driven by scrap or loss, or any number of reasons. Some of the major sources of volatility will be considered in the next section.

3.3 Sources of Volatility

In a large company, producing a wide variety of end items, with a large number of customers, and a large number of purchased parts, literally hundreds of people are capable of making changes which effect the schedule of purchased parts. The popular description of the field of "Chaos", in which a butterfly flapping its wings can affect the weather hundreds of miles away, is an apt depiction of the situation that occurs in this environment. We will consider five areas in which schedule changes can be generated. These five areas are: Demand Changes, Inventory Changes, Work Order Changes, MRP Setting Changes, and Message Processing. This listing is not meant to provide an exhaustive description of all possible sources of volatility, but should give the reader a good idea of many possible scenarios that arise.

3.3.1 Demand Changes

Customer demand changes are the most obvious cause of schedule changes. This includes both OEM demand, generally for an end item, as well as spares demand, which may be for an end item, for a subassembly, or for a purchased part.

OEM customers generally provide a schedule for many months, or even years into the future. Since many aerospace customers are working with several years of backlog orders and military customers generally have fixed schedules from the armed forces, these schedules tend to be very reliable. If demand changes occur, they are generally very small in magnitude or relatively far into the future.

Spare parts are built to a forecast. For reasons that are out of the scope of this thesis, forecasts in the aerospace industry tend to be very inaccurate. As such, the production schedules generated as a result of these forecasts are subject to larger magnitude, more frequent changes as compared to OEM schedules. In addition, Aircraft On-the Ground orders (AOGs) mean that a very expensive aircraft is not flying due to a need for a replacement part. These orders typically are given very high priority.

In order to dampen the impact of forecast inaccuracies on supplier schedules, the spares group works to very strict rules governing when they are permitted to change a production schedule. Generally speaking, they cannot place an order for a part or move a requirement to an earlier date, if this change occurs within the longest lead-time of any component in the assembly. Furthermore, they cannot move a requirement to a later date if the current requirement date is within three months of the day on which they wish to make the change. Exceptions to the above rules can be made at the discretion of planners or managers, if the movement will not affect inventory coverage through the longest lead-time of any component part, or if the change is necessary to support an AOG. If indeed these rules are being followed, spares should not be a big contributor to schedule volatility.

3.3.2 Inventory Changes

The MRP system determines the supplier schedule by looking at the date of all requirements and the current available inventory. In other words, if there are already ten parts in stock, the first supplier requirement will be driven by the date when the 11th part is needed. Therefore, schedule changes can occur not only as a result of date changes, but also as a result of changes in inventory levels. In a perfect world, inventory would change only when a part was built, but in practice inventory changes can occur for other reasons. The following is a partial list of factors that cause inventory to change:

- Scrap or Loss (can be negative if parts are found or reworked…)
- Parts are expensed (removed from inventory) before being used
- Parts transferred to another branch plant
- Misallocation of parts (generally considered a work order change)

It is a reality of manufacturing that mistakes will occur, that processes will go out of control, and therefore that unusable parts will be created. Although most MRP systems allow a scrap factor to be used so that additional requirements will be purchased to account for scrap, the low volume nature of the aerospace industry is not conducive to the use of a scrap factor. Generally speaking, Hamilton Sundstrand does not use a scrap factor for any parts. Also, Hamilton Sundstrand uses a large number of very small, inexpensive parts and often some of these parts are lost. Typically, Hamilton Sundstrand has better than a 95% inventory accuracy (meaning that the quantity in inventory as determined by a physical inventory count agrees with the quantity shown in MRP), so we would not expect this to be a major source of volatility.

Another cause of inventory inaccuracy occurs frequently at Hamilton Sundstrand. There is a classification of parts, called binstock parts, which are generally very inexpensive, commodity components like standard washers or fasteners. Rather than force the operators to go to the storeroom every time they need a single washer, the operators take a relatively large quantity and fill a small drawer at their workstation. To prevent the need to count every cheap little part at every workstation whenever inventory is counted, these parts are expensed immediately upon removal from the storeroom. When the parts are expensed, **they no longer appear in inventory**, even though there are outstanding requirements in the MRP system for those parts, and those parts physically exist in the factory. In other words, the operator may need two washers to build an assembly, so he goes to the storeroom and removes 50 washers. In doing so, he may remove the entire supply of that washer at the storeroom. These 50 washers immediately disappear from inventory in the MRP system, which now thinks there are no parts in the building, even though 48 pieces still exist on the operator's desk. The operator may use the 48 pieces over a period of several weeks, to build orders as scheduled by the MRP system. However, the entire time, the MRP system thinks it needs to order 48 washers so as to complete the outstanding orders. The system will therefore issue an order for 48 pieces. In the meantime, while the supplier is trying to ship 48 pieces he did not previously believe were needed, the operator may in fact finish building the items that use those washers. In doing so, the MRP system no longer sees a need for the washers, and may cancel the order.

There are many binstock parts used at Hamilton Sundstrand and the contribution of these parts to schedule volatility is widely understood. However, the inexpensive, commodity nature of binstock parts has generally meant that they were ignored. It was often felt that due to their commodity nature, suppliers should be able to react quickly to schedule changes. It should be noted that binstock parts are excluded from the calculation of surprise overdue (as well as from the on-time delivery metrics). This means that the extent of the schedule volatility is really only seen by suppliers, who treat binstock parts no differently than normal parts, and therefore see more schedule movement than Hamilton Sundstrand actually tracks in their metrics.

Part transfers generally should occur as the result of a legitimate requirement from another branch plant. As such, transfers generally should not cause unforeseen changes in inventory levels. A problem did exist in the implementation of the MRP system at Hamilton Sundstrand that could lead to a circular demand for transferred parts. In such a case, the transfer of parts from plant A to plant B, would generate a need to transfer the same part back from plant B to plant A. This problem did not appear to be a factor in the generation of schedule volatility and will not be considered in this thesis.

Part misallocation generally means that inventory was used to satisfy a later requirement, thereby leaving the inventory levels insufficient to satisfy an earlier requirement. The supplier would normally expect that inventory would be applied to the earliest requirement, then to the next earliest requirement, and so forth chronologically. Consider the following example: Area A has a requirement for 5 pieces of part x this week, Area B has a requirement for 5 pieces of part x also, but the requirement is not schedule until three weeks from now. For some reason, Area B consumes their requirement of part x, leaving zero parts in inventory for Area A. Next week, the supplier for part x will see an overdue requirement for 5 pieces. Since generally part misallocation occurs as a result of changes in work orders (i.e. Area B built their work order three weeks early), this problem is usually included in work order changes.

3.3.3 Work Order Changes

The MRP system works by determining when assemblies and end items need to be built, and when purchased parts need to arrive, to support a given demand. Instructions to the shop regarding when items should be built are called *work orders*. When a person from the shop accepts the recommendation from the MRP system, the work order is given a number and is called a *firm work order*. Any time that this person firms up a work order for a different date or quantity as suggested by the MRP system, or anytime that a person changes a firm work order, this change may result in a schedule change for a supplier. These changes may occur as a result of incorrectly following procedures, or may be a legitimate change. The following work order changes occur most frequently:

- Splitting/Combining Work Orders
- Moving Work Orders
- Allocating Parts to Work Orders out of Sequence

The quantity on the work order is determined using various rules. These rules dictate the lot size used for a work order and are set by planners with input from the shop floor. If the factory changes work order quantities for a given part on a regular basis, this would suggest that a different rule should be used. Unfortunately, no rule can anticipate the daily changing needs of the shop floor. Changing the quantity on a work order generally occurs when an area in the plant wishes to run several work orders together to save setup time. Work orders may also be combined for many other reasons. For example, a piece of equipment used in the manufacturing process may need to undergo a lengthy refurbishment and parts are being completed ahead of schedule in anticipation of the machine being unavailable. Similarly, a large work order may be split into several work orders. Such a change may occur if there is insufficient inventory for every component part to complete the entire work order quantity.

Work orders may be moved for a variety of reasons. The changing needs and conditions that arise during the daily operations of the plant may dictate a production schedule that differs from the original MRP planning. The larger the plant and the larger the number of products, the more likely these changes will occur. For example, if an important purchased part cannot be delivered on time, the factory may elect to move the work order that uses this part to a later date, and elect to build other parts instead. When the work orders are manually changed to reflect this, the resultant supplier schedules will reflect the movements.

The largest single cause of schedule volatility due to work order changes is misallocation. By this we generally mean that parts were allocated to work orders out of sequence. This can occur when a part is used in different areas. If one area builds parts further in advance than another area, inventory may be applied to work orders in a manner that differs from the sequence that the MRP system had planned.

3.3.4 MRP Setting Changes

There are many factors that are input into the MRP system that control how the system determines the dates and quantities for work orders and purchase parts. Changes to these factors can result in changes in the supplier schedules. The main factors that affect the MRP planning process are:

- BOM relationships and quantities
- Manufacturing Lead Times
- Safety Stock Level
- Receiving Lead Time
- Lot Size Policies

All of the requirements planning are based on end item demand and a corresponding BOM for this end item. If a change is made in the BOM, a schedule change may result, even without a change in end item demand. For example, if the BOM specifies the end item uses part x and then is changed to use part x', the schedule for part x will reflect this change. If the BOM specifies that an end item uses two feet of material y, and then is changed to require 2.2 feet of material y, the corresponding requirement for material y will change.

The MRP system also uses a fixed manufacturing lead time to determine when the shop should start building a work order so as to meet a given customer demand. If the system is set for a lead-time of two weeks, and subsequent analysis determines that the process actually requires three weeks, the lead-time in the system should be changed to reflect this. This change will, however, require that suppliers deliver the component parts one week earlier.

Generally, the MRP system does not plan for material to arrive until the inventory level reaches zero. In many situations, it may be practical to have the MRP system maintain some minimum level of inventory. By setting a safety stock level, the MRP system will attempt to order material so that the inventory never falls below this level. Changes to the level will be reflected in changes to the supplier schedules.

Receiving lead-time is the time it takes for material that arrives on the dock to be processed and moved to the stockroom or manufacturing floor. If the MRP system determines that parts are required for a work order on Thursday, and the receiving lead-time is two days, the supplier schedule will show a need for parts on Tuesday. Typically this lead-time is relatively small, however, in some cases it may be considerably longer so as to be used as a safety factor to insure that problem suppliers deliver the parts before they are actually needed.

The final factor that affects MRP planning is the lotting policy. There are two main lotting policies used at Hamilton Sundstrand. These are: fixed order quantity and period of supply. Fixed order quantity means that the MRP system always orders parts from suppliers or plans work orders in a given quantity. Period of supply means that the MRP system looks out in the future for a given period of time, lumping all of the requirements for the part during that period into one order. Changes in lotting policy can cause changes in the supplier schedule. In addition, lotting policies themselves can have a dramatic impact on schedule volatility and will be discussed in great detail later in the text.

3.3.5 Message Processing

The MRP system used by Hamilton Sundstrand is driven by messages. This means that the system generates messages instructing different users what tasks should be performed and when they should be performed. A typical message to the shop floor might be to build five of part x on a specific date. A typical message to a buyer might be to purchase five of component y on a specific date. For the system to work correctly, every person who works with the system must answer their messages without making any changes. Failure to answer a message, or performing a task differently than suggested in the message, may cause changes that appear as schedule volatility to the suppliers.

An example of an incorrect response to a message was given in the work order changes section. The system suggests a quantity and date for a work order (a message) and the shop floor person chose to build a different quantity on a different date when he or she created the firm work order.

Other messages might suggest that a purchase order or work order should be completed earlier (expedited) or later (deferred) or cancelled. Purchase orders or work orders might receive a message to be split into two or more purchase orders or work orders. In many cases, acting on a message may cause a schedule change (for example as a result of a customer demand change), while failing to act on a message may also cause a schedule change (if the shop floor reschedules a work order, the MRP system might automatically reschedule the corresponding purchase orders).

3.3.6 Pareto Results

This lengthy description of sources of volatility in the MRP system should provide some idea of the difficulty in determining the main factors driving supplier schedule volatility. In order to better understand what the leading causes were, Hamilton Sundstrand planners spent hours each week determining the root cause behind every part on the surprise overdue list. The results are shown in a Pareto diagram in Figure 3.2.

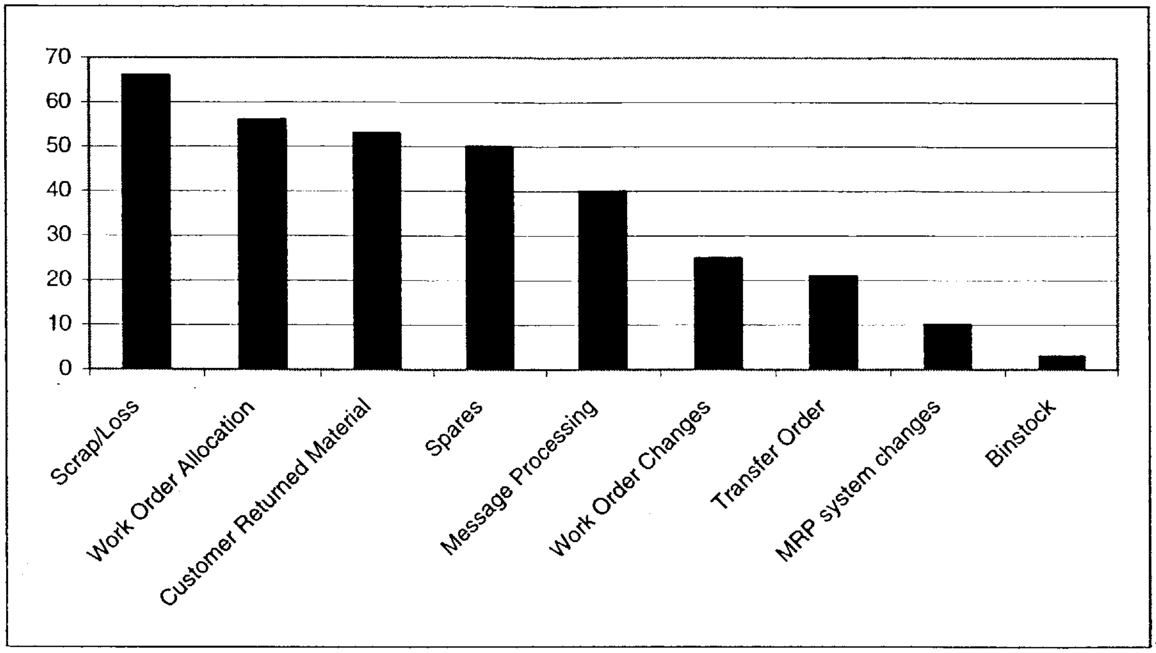


Figure 3.2: Root Causes of Surprise Overdue Parts

In this diagram, the vertical axis represents the number of occurrences of each root cause. The root causes are listed on the horizontal axis. Based on the results shown in Figure 3.2, it was determined that Work Order Allocation and Spares were the main sources affecting the schedule volatility problem seen by the suppliers. Although scrap and loss were the largest cause on the Pareto, generally scrap and loss are very small quantity changes, while the suppliers were complaining about very large quantity changes. Furthermore, it was felt that problems with spares and work orders could be most easily addressed.

Customer returned material (CRMs) refers to parts that are returned by the customer for rework for one reason or another. These parts may require new components in order to address the customer complaint. This is especially true when the changes require replacement of a circuit board assembly. Often when parts are reworked, seals must be replaced after disassembly during the subsequent assembly. Once again, these should generally deal with small quantities and therefore were not thought to be a major driver of the problem faced by the suppliers.

3.4 Initial Results

Based on the results of the Pareto analysis, Hamilton Sundstrand implemented several corrective actions. These included:

- Reduction of the number of people who could handle work orders
- Re-Training on work order handling
- Detailed tracking and analysis of work order changes
- Detailed tracking and analysis of spares sales order changes

After implementing the changes and tracking work order and spares changes for many weeks, no noticeable improvement was seen. Improvement was measured by reduction in surprise overdue (Figure 3.3 shows the surprise overdue results for the remainder of 2000) and by subjective analysis from the supply base. Although improvement was limited, the tracking did uncover the following facts:

- Many work orders and spares sales orders were changed manually each week
- These changes were generally done correctly, and for correct reasons
- The changes were generally small in magnitude compared to the changes noted by the suppliers
- The MRP system automatically made many more changes each weekend when it was run than were manually made during the week

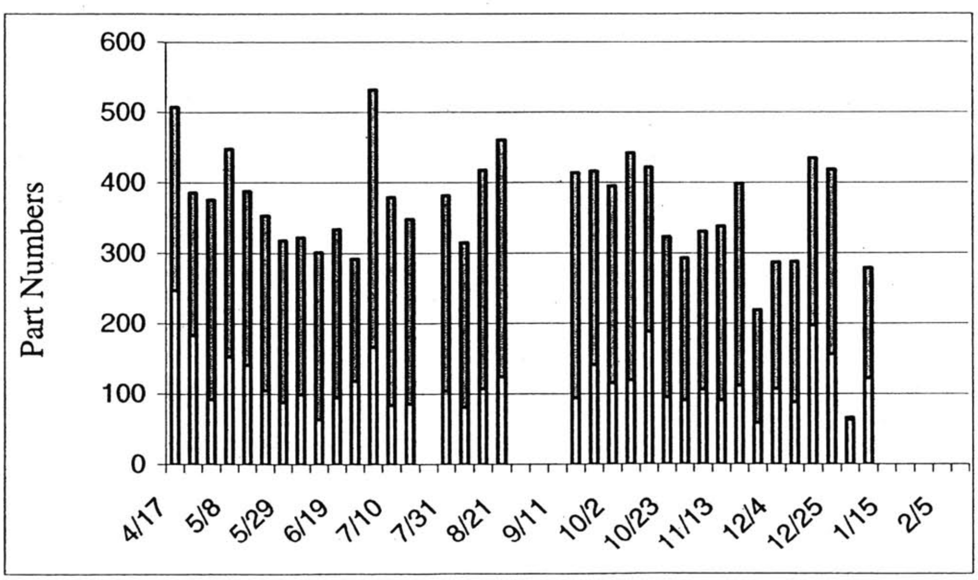


Figure 3.3: Surprise overdue (unshaded) compared to total new overdue (entire bar)

3.5 Summary

The MRP system is a very complex system, with many manual interactions, and many opportunities for changes that create schedule volatility. Generally people make changes for the right reasons, using the correct methods, and therefore, attempting to reduce schedule volatility through training and tracking are ineffective. Finally, the magnitude of changes made manually, appear small relative to the magnitude of changes about which the suppliers complained, and the number of changes made manually appear small relative to the number of changes made by the system.

Based on this summary, we determined that the schedule volatility must result from some mechanism within the MRP system. It seemed clear that the system must be in some way magnifying or amplifying the changes input into the system, thereby creating a much larger change at the output of the system – the supplier schedules. Furthermore, we felt that the only mechanism capable of this amplification were the lot size policies used throughout the MRP system. As discussed in the Introduction, lotting policies can lead to MRP nervousness. In order to understand the magnitude of this effect, we collected and analyzed schedule data.

4. Schedule Volatility Analysis

In order to determine the effect of lotting policies on schedule volatility, we measured the number of schedule changes and the average magnitude of the changes for a large sample of parts (over 2000 randomly selected part numbers). We compared the volatility of these parts using two different schedules produced by the MRP system. The first schedule we will term the "Supplier Schedule" and it refers to the schedule of requirements that is provided to the suppliers for their production planning and shipping use. The second schedule is what we term "Discrete Demand" and this refers to the internal schedule used by buyers and expeditors. The main difference between the two schedules is the application of a lotting policy based on a predefined part Strata Code.

This section will demonstrate how lotting policies might affect schedule volatility, define how Strata Codes are used at Hamilton Sundstrand, and present evidence that lotting policies actually amplify the magnitude of small schedule changes in a manner which is very disruptive to suppliers. For detailed information regarding the schedule volatility analysis, refer to the Appendix.

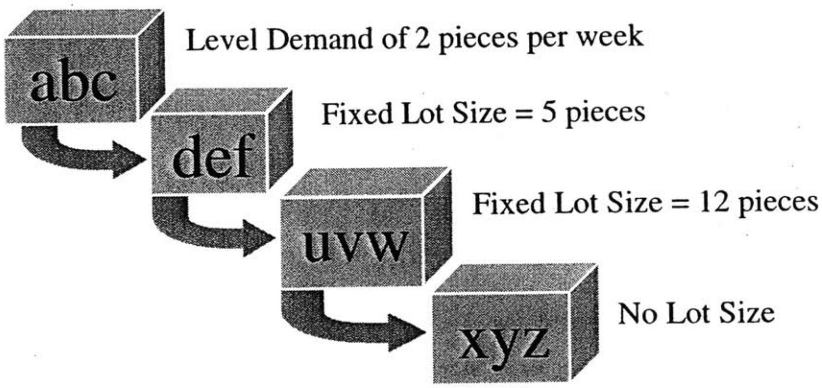
4.1 Lotting Policies

Companies frequently apply lotting policies to take advantage of economies from running larger batches of product or purchasing in bulk. Setup times and costs may dictate that large quantities (as compared to demand) be produced at one time. Frequently suppliers offer discounts to customers purchasing large quantities. Even with the extensive use of long-term agreements at Hamilton Sundstrand, in which suppliers agree to supply parts for a fixed price, there are often minimum order sizes. In addition, transportation economies dictate that small, inexpensive parts be shipped at less frequent intervals.

For these reasons, MRP systems provide functionality to automatically lot production of parts or purchasing of parts. Generally, there are two types of lotting policies used at Hamilton Sundstrand: fixed lot sizes, and period of supply. While both lotting policies are used, we will primarily focus on period of supply policies and their relation to the supplier schedule. Examples of both policies are presented in the next sections.

4.1.1 Fixed Lots

A fixed lot size generally means that production or purchasing of a given part size is always done at a fixed quantity. For example, twenty parts are always run in the furnace together, or parts are always purchased in packages of 100. Consider the example of an end item "abc", composed of a subassembly "def", which in turn utilizes another subassembly "uvw". "uvw" in turn contains a purchased part "xyz". We will assume that demand for "abc" is level at two pieces per week. Furthermore, assume there is no manufacturing lead-times for any of the components, that each part uses only one of the lower level components, and that parts are always produced or ordered in fixed lots as shown in the diagram below:



A typical schedule for these components might look like:

Table 4.1

	Overdue	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8
Item "abc"	2	2	2	2	2	2	2	2	2
Ass. "def"	5	0	5	0	0	5	0	5	0
Ass. "uvw"	12	0	0	0	0	12	0	0	0
Part "xyz"	12	0	0	0	0	12	0	0	0

We see that although the demand for Item "abc" is perfectly level, the demand for the purchased part is not at all level.

Consider what happens to the schedule for Part "xyz" if a small change is made to the schedule. In this example, let's assume that for some reason the customer wishes to receive three parts in wk 4 and 1 in wk 5. The schedule now becomes:

Table 4.2

	Overdue	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8
Item "abc"	2	2	2	2	3	1	2	2	2
Ass. "def"	5	0	5	0	5	0	0	5	0
Ass. "uvw"	12	0	0	0	12	0	0	0	0
Part "xyz"	12	0	0	0	12	0	0	0	0

A careful examination of the new schedule shows that the change at the end item level amounted to only ½ week of average demand (1 piece change compared to 2 pieces/week average demand). In comparison, the magnitude of the change at the part level was 6 weeks average demand (12 piece change / 2 pieces/week average demand). Here we observe the methodology by which lotting policies can amplify the magnitude of schedule changes.

4.1.2 Periods of Supply

A second frequently used lotting policy is called "Periods of Supply". In this case, parts are not produced or ordered in fixed lot sizes, but rather the MRP system lumps together x days of requirements. If for example the lotting policy is 4 weeks of demand, the computer would count four weeks from the first requirement for a part, add up any and all demand for the part during this period, and produce or order this entire quantity at one time. Such a system is frequently used to prevent suppliers from frequently shipping very inexpensive parts such as seals or fasteners.

Consider the example of a part for which the supplier is permitted to ship 7 weeks of demand at one time. We will assume that a few parts are scrapped, causing an immediate need for several pieces. The supplier has more than enough parts in stock to satisfy the small immediate need. For the sake of demonstration, we will ignore the fact that the MRP system is run weekly, and assume instantaneous changes in the schedule. The same effect occurs in the real MRP system with weekly schedule updates.

The actual requirement for this part is:

Table 4.3

Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8	Wk 9	Wk 10	Wk 11
0	0	0	0	100	0	0	225	0	195	0

Therefore, the supplier sees a lotted schedule that looks like:

Table 4.4

Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8	Wk 9	Wk 10	Wk 11
0	0	0	0	520	0	0	0	0	0	0

In this case, the requirement for 520 pieces in week five represents the cumulative demand of 100 in week 5, 225 in week 8, and 195 in week 10.

Now, let us assume that some inventory is lost or scrapped, thereby creating an immediate need for 5 pieces. The actual requirement schedule and the supplier schedule now would look something like:

Table 4.5

Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8	Wk 9	Wk 10	Wk 11
5	0	0	0	100	0	0	225	0	195	0
105	0	0	0	0	0	0	420	0	0	0

We see that although the plant really only requires 5 parts immediately and nothing else in the schedule has changed, the supplier perceives that part of the requirement for 520 pieces, specifically 105 pieces, is needed immediately.

Let us further assume that the supplier has 75 pieces in stock and, in an effort to support Hamilton Sundstrand as well as possible, immediately ships these pieces, and begins production on the remaining 30. In doing so, it is necessary to rearrange his entire production schedule. In the meantime, the 75 pieces arrive, and are applied against the actual requirements schedule, causing the following schedule changes:

Table 4.6

Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8	Wk 9	Wk 10	Wk 11
0	0	0	0	30	0	0	225	0	195	0
0	0	0	0	450	0	0	0	0	0	0

The 75 pieces satisfy the demand for 5 in week 1, as well as part of the demand for 100 in week 5. Meanwhile, the supplier schedule now shows the first need in wk 5. The supplier is forced to hold on to the 30 pieces he just made, after having disrupted his production schedule to produce these parts against a perceived immediate need. Furthermore, he needs to plan production of the remaining 420 pieces three weeks earlier.

Here again we see how small changes in the schedule can be converted to very large changes in the supplier schedule due to lotting policies.

It is important to note that lotting policies have a second effect. If the requirement for 195 pieces in wk 10 as shown in Table 4.6 were suddenly needed one week earlier, the supplier would see absolutely no change. In other words, if changes occur entirely within the lotting period, suppliers will see no affect. In this situation, lotting policies actually serve to dampen the effect of schedule volatility.

We therefore see two competing affects of lotting policies: in general, we would expect lotting policies will reduce the **number** of changes in the supplier schedule, while simultaneously increasing the **magnitude** of changes that do occur. It is therefore important to determine the relative occurrences of these affects so as to understand which affect is dominant.

4.1.3 Strata Policy

Hamilton Sundstrand provided a unique opportunity to determine the impact of lotting policies on schedule volatility. There are two frequently used schedules for purchased parts that are produced by the MRP system each week. These two schedules differ primarily in the application of a period of supply lotting policy. The schedule for actual part requirements is the Discrete Demand schedule, and is used by the purchasing department to manually order parts from suppliers that are not on long-term agreement. The bulk of suppliers, however, receive a Supplier Schedule, in which requirements are lotted based on a Strata Code.

All parts are given a Strata Codes of A, B, C or D. The correct code is determined for each part based on the prior year's annual dollar volume. Strata A represents the parts with the highest annual dollar volume, and are therefore generally the most expensive parts. Strata D parts are the lowest dollar volume, and are generally the least expensive parts.

Both Strata A and B parts are lotted in weekly periods, that means that suppliers only ship one week of demand, while Strata C parts are lotted in 8 week periods, and Strata D parts are lotted in 17 week periods. With perfectly stable schedules, this means that suppliers would ship Strata A and B parts at most weekly, Strata C parts every two months, and Strata D parts every four months.

4.2 Supplier Schedule Volatility

Using the analysis method described in the Appendix, we examined the schedules of 2020 parts selected at random. We measured the number of schedule changes and the average magnitude of the schedule changes that the supplier would have seen looking at an eight-week schedule. For this thesis we define the schedule for a part by lumping all requirements for that part during an entire week (from Monday through Sunday) together. We consider a time horizon consisting of eight of these weekly "buckets" for consecutive weeks, hence, the eight-week schedule. In this definition, a schedule change means that when the new schedule was created on the following Sunday MRP run, one or more of the eight weekly lumped quantity requirements has changed.

For the analysis, we looked at fifteen consecutive MRP schedules. We compared the first schedule (created in this case in the beginning of October) with a schedule created one week later, and then compared that schedule with the following week's schedule. We continued this for 15 weeks, from the beginning of October through Mid January. The results and a discussion of the results are presented in the following sections.

4.2.1 Volatility Analysis Results

The analysis confirmed the suppliers' complaint regarding large magnitude and frequent changes. A summary of the results is as follows:

- 82% of all parts had at least one schedule change
- On average there were 0.46 changes/part/week
- Average magnitude of change was equal to 21 weeks of demand

It is clear that almost all parts had schedule changes, and that a supplier with 100 parts would expect to see on average 46 schedule changes each week. What was most surprising was the magnitude of the changes. The average schedule change represented a quantity change equal to 21 weeks of average demand for the part. Certainly this would be difficult for a supplier to understand or cope with.

In order to better understand this result, we looked at the distribution of average magnitude change for all the parts. Figure 4.1 shows a histogram of average magnitude change. The vertical axis on the left side of the chart applies to the bar chart and shows the number of parts (out of all 2000 parts) where the average magnitude change was between zero and two weeks for the first column, between 2 and 4 weeks for the second column, and so forth. The vertical axis on the right side of the chart applies to the line graph, and shows the cumulative percentage of all parts. For example, 50% of all the parts had a schedule change magnitude of 6 weeks or less.

It seems evident that the changes are indeed very large, but the average magnitude change of 21 weeks given above is driven by several very large quantities. Since the magnitude of change is calculated using an average weekly demand, and average weekly demand is subject to large sources of uncertainty (refer to the Appendix for more information), we felt further examination was necessary to better understand this calculation.

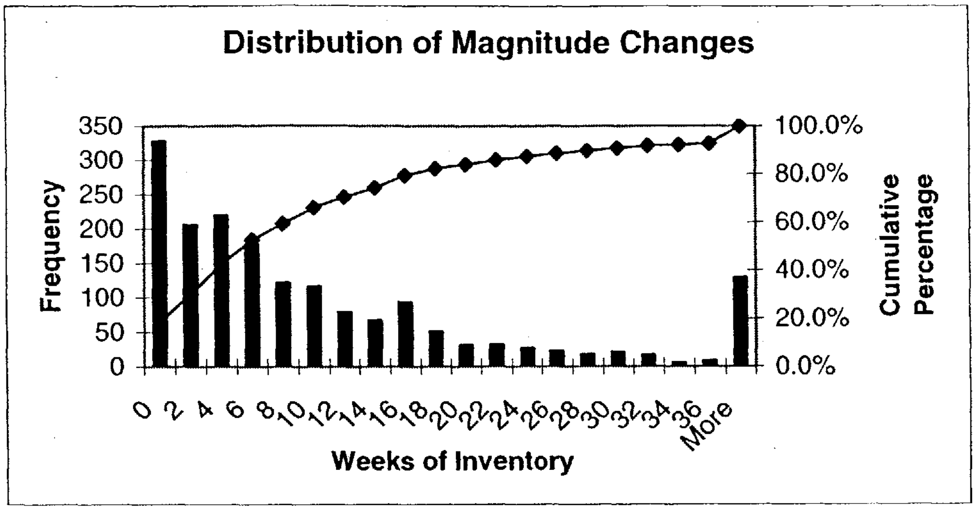


Figure 4.1: Distribution of Magnitude Changes in the Supplier Schedules

4.2.2 Binstock Adjustment

Change Magnitude is calculated using an average weekly demand, and the largest source of error in calculating average weekly demand is on-hand inventory. There is a classification of parts at Hamilton Sundstrand which is treated in such a manner that on-hand inventory as given in the MRP system is almost always wrong. These parts are called binstock parts. Due to the accounting treatment of binstock parts, the MRP system only considers the quantity in the storeroom, and does not track the (sometimes large) quantities of parts on the plant floor. When binstock parts are excluded from the calculation of average change magnitude, the results fall from an average of 21 weeks of demand, to 14 weeks of demand. This demonstrates that even with the largest source of error removed, the magnitude of schedule changes is still very large.

4.2.3 Outliers

The histogram in Figure 4 showed that the average magnitude of the schedule changes was driven by a number of parts with very large magnitude changes. As a final check, we consider the 10% of parts with the largest magnitude changes as outliers, and repeated the calculation. Even in this extreme case, the average magnitude of the supplier schedule change was seven weeks of demand. For a supplier with one month of safety stock, such a change could easily deplete their inventory.

4.3 Volatility Amplification

It is clear that the supplier schedules show frequent changes, and that the magnitudes of the changes are extremely large. This section will demonstrate how lotting policies work to amplify the magnitude of changes in the MRP system. We repeat the volatility analysis on the discrete demand schedule and show how the difference in results between the discrete demand schedule and the supplier schedule is attributable to lotting policies.

4.3.1 Discrete Demand Results

The discrete demand schedule is the schedule of requirements used internally by buyers and expeditors in the purchasing department. This schedule more closely represents the actual internal demand for purchased parts. The supplier schedule is created from the discrete demand schedule by the MRP system through the application of lotting policies. The lotting policy is in turn dependent on a strata code. Each part in the system is given a strata code, based on the annual dollar volume of usage. Higher dollar volume parts are strata A or strata B, and are purchased in lots equal to one week of demand. Strata C parts are much less expensive and are purchased in lots equal to eight weeks of demand. Strata D parts are the most inexpensive parts, and are purchased in lots equal to 17 weeks of demand.

An analysis of the discrete demand schedules for the same 2020 parts yielded the following results:

- 86% of all parts had at least one schedule change
- On average there were 0.76 changes/part/week
- Average magnitude of change was equal to 6 weeks of demand

Comparing these results to the supplier schedule results shows:

Table 4.7

	Supplier Schedule	Discrete Demand
Parts with at least one schedule change	82%	86%
Average Changes/Part/Week	0.46	0.76
Average Magnitude of Changes	21 weeks of demand	6 weeks of demand

In Table 4.7, we see, as expected, that the discrete demand is characterized by more frequent changes. More parts had at least one change, and the number of changes was much higher. This demonstrates how lotting policies can work to dampen the number of changes that occur in a schedule. More noteworthy, however, is the difference in the magnitude of the changes. When a change occurs in the supplier schedule, that change is on average 3.5 times larger than the change in the discrete demand schedule. In essence, a supplier must have a safety stock 3.5 times as large to insure the same service level by working against the lotted supplier schedule as opposed to the discrete demand schedule.

4.3.2 Amplification Factor

We have suggested that lotting policies work to amplify the magnitude of schedule changes, and have demonstrated a large difference between the magnitude of the changes in the supplier schedules and the discrete demand schedule. These schedules differ mostly as a result of a period of supply lotting policy. In order to better understand the relationship between lotting policy and magnitude of schedule changes, we examined the parts individually.

For each part, we calculated an amplification factor, which is equal to the average magnitude of change in the supplier schedule, divided by the average magnitude of change in the discrete demand schedule. For parts with lotting policies of one week, we would normally expect there to be very little difference between the supplier schedule and the discrete demand schedule, and thus the factor should be around 1. For parts with large lotting policies (strata D) we would expect this factor to be very large.

4.3.3 Amplification vs. Strata

Figure 5 shows the distribution of ampflication factor by strata as a percentage of all parts of that strata.

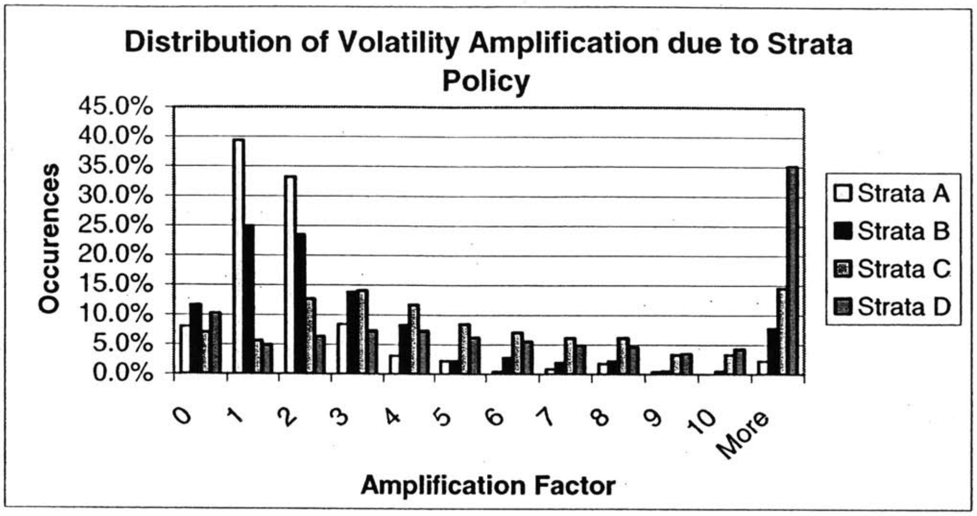


Figure 4.2: Amplification Factor vs. Strata Code

We see that strata A and B parts, both with one week lotting policies, have average amplification factors of approximately one, while the average amplification factor for strata C parts is approximately 3 or 4, and the average amplification factor for strata D parts is about 5.

It should be noted that average weekly demand was the largest source of error in the calculation of change magnitude and made exact interpretation of the magnitude of changes in the supplier and discrete demand schedules difficult. However, since average weekly demand is used in the calculation of average magnitude of change in both schedules, it cancels out in the calculation of amplification factor. Therefore, since the amplification factor is only dependent on the observed schedule changes, it is an exact measured value.

4.4 Summary

In summary, lotting policies have a large effect on both the number of changes in the schedule as well as the magnitude of those changes. As expected, these policies serve to dampen the quantity of changes, but in doing so amplify the magnitude of those changes.

This amplification factor was on average 3-4 for strata C parts and approximately 5 for strata D parts. Therefore, small schedule changes can lead to very large schedule changes at the supplier level. Furthermore, although we examined only the difference in the discrete demand and supplier schedules, lotting policies are used throughout the MRP system. It is not unusual for parts to be produced in batches of a fixed quantity or for the plant to run batches of a particular part only one a month (i.e. period of supply lotting equal to 4 weeks). Thus, there may exist an even larger amplification factor between changes made at the customer level and the resulting change at the supplier level.

5. Time Volatility Analysis

Having clearly identified how lotting policies can amplify the magnitude of a schedule change, it may seem obvious that lotting policies will also cause changes to amplify in time also. By time volatility, we mean movement of a requirement in time (for example a part is required one week earlier than originally scheduled). This refers to all cases where a demand already existed in the system and still exists after a change is made in the system, but is scheduled for a different time.

Logically, it might seem likely that for a one week lotting policy, a change could cause the lot to be needed as much as one week earlier or later. For an eight week lotting policy, the change might be as large as plus or minus eight weeks. However, a careful review of the fixed lot example in section 4 suggests no such phenomenon. In fact, looking carefully at Tables 4.1 and 4.2, we see that a movement of the initial requirement to one week earlier caused all schedules to adjust by exactly one week.

Using the analysis method described in the Appendix, we analyzed the time volatility of the MRP schedule.

5.1 Analysis Results

Figure 5.1 shows the distribution of movement within the supplier schedule for the 2020 sample parts. The graph is a histogram of all the schedule changes which meet the time volatility criteria outlined in the appendix. This represents all of the clearly identifiable requirement movements in the schedule. It is apparent that most movements are about two weeks, i.e. either parts are needed two weeks earlier or two weeks later. On average, parts are needed later as often as they are need earlier. That means it is just as likely that a supplier will need to deliver parts before expected as it is that they will need to hold parts longer than expected.

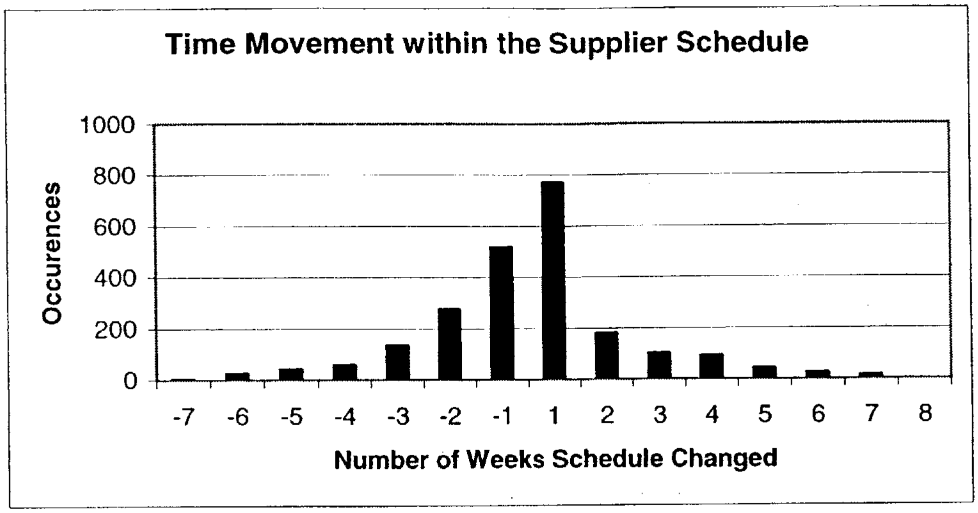


Figure 5.1: Time Volatility in the Supplier Schedule

5.2 Time Volatility Amplification

A similar analysis of the discrete demand schedule yielded very similar results as were obtained from the supplier schedule. For each part, we considered the ratio of the movement of the supplier schedule to the movement of the discrete demand schedule. The results are shown in Figure 5.2. In almost every case, the ratio was between 0 and 1, which shows that either the two schedules moved exactly the same amount, or the supplier schedule moved less than the discrete demand schedule (most likely due to the dampening effect of lotting policies). This suggests that no ampflication is occuring in time volatility and in some cases the lotting policies prevent schedule movement.

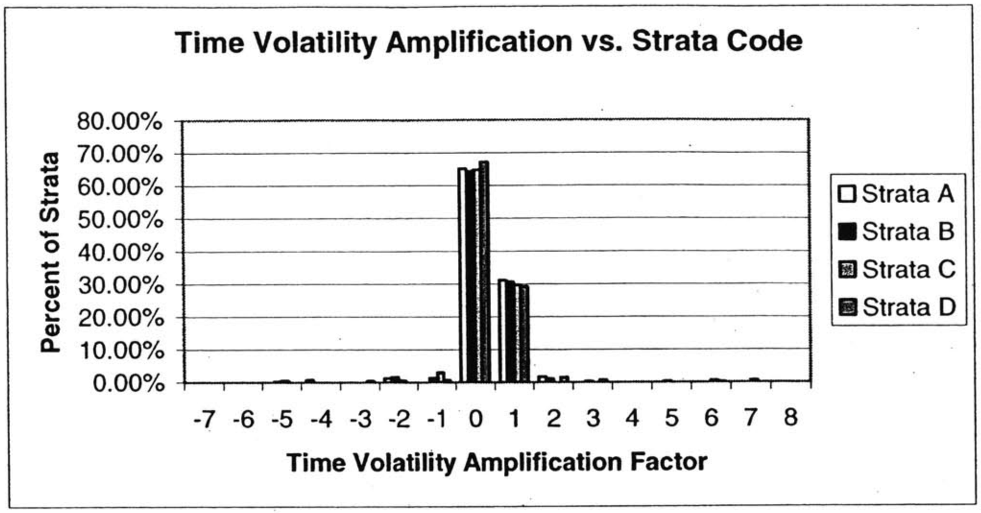


Figure 5.2: Time Volatility Amplification versus Part Strata

5.3 Summary

It is clear that the supplier schedules show frequent changes, and that the magnitude of the quantity change is amplified by the lotting policies. A further analysis of the effect of lotting policies on schedule volatility suggests that time volatility is not amplified in the same manner, and that in this case lotting policies are useful in dampening the volatility in the MRP schedule.

6. Proposals for Reducing Schedule Volatility

We have shown how lotting policies amplify the magnitude of schedule changes. Although the purchase part schedule used internally (discrete demand) shows average magnitude changes equal to approximately six weeks of average demand, the schedule that the suppliers work to shows magnitude changes 3.5 times larger. The suppliers, lacking any other information, naturally assume that Hamilton Sundstrand is making large, frequent schedule changes.

This section will suggest several methods for reducing the effects of MRP volatility amplification by discussing alternate methods of communicating requirements to suppliers as well as alternate methods of planning and ordering parts. The effect of alternate planning and ordering methods on supply chain inventory will also be discussed.

6.1 Supplier Communication

One of the primary reasons that two different schedules exist for purchased parts is a desire to reduce the work load on internal buyers. Traditionally, buyers had to issue purchase orders for every demand. They would take the recommendation from the MRP system and manually issue a PO to the proper supplier for each part. This effort could be considered a set-up time. For inexpensive parts, the cost of this "set-up" time was large compared to the cost of the parts, and therefore it made sense to issue POs for large quantities of inexpensive parts. In essence, a large batch size is required to justify the set-up cost. This logic led to the creation of strata policies to automatically determine the economical lot size for a given cost part.

As computing power grew, it became economical to automate the task of producing purchase orders. Suppliers signed long-term agreements to ship parts at specific prices over an extended period of time, and were issued requirements schedules automatically by EDI or, more recently, over the internet. This significantly reduced the work load on the buyers. In the process, the manual review which occurred before the PO was issued was replaced by an automatic lotting logic within the MRP system. A side-effect of this change was the fact that suppliers now see very large levels of schedule volatility, as the computer now makes changes based on mathematical principles, without the benefit of a manual review. Whereas a buyer might choose not to make a change to a supplier's schedule because of a small change in discrete demand, tacitly recognizing that the change is not worth the confusion it might cause, the computer now makes the change automatically. One way to reduce the impact of this side-effect is to change the way schedules are communicated to suppliers.

6.1.1 Discrete Demand

Under the current system, the only information a supplier receives regarding future demand comes from the supplier schedule. Due to the effects of MRP amplification, this schedule is subject to very large changes in quantities from week to week. In addition, this schedule does not accurately reflect the actual timing of demand for the part. Although the lotting policies were created as a recognition of high **internal** "set-up" costs associated with purchasing parts, such as buyers preparing and sending purchase orders, the receiving department manually unloading, entering, and stocking shipments, and the business office manually sending invoices, the majority of these processes have been automated. Although there are production and transportation economies of scale for the supplier, the need for Hamilton Sundstrand to place orders in large lots is very small.

Unfortunately, by sending suppliers a schedule with a lotting policy applied, Hamilton Sundstrand is in fact partially dictating a batch size for the supplier. The lotted schedule may call for 1700 parts every 17 weeks, leading the supplier to produce a batch of 1700 parts schedule for completion just prior to the expected need date. If the date and quantity suddenly change, it may be very difficult for the supplier to adjust their production schedule.

Consider an alternative where the supplier receives the discrete demand schedule for planning purposes, but is given the option to ship up to a 17 week lot size of parts. In this case, the schedule may call for 100 parts each week. The supplier determines his own internal economic batch size and chooses to make batches of 500. Since the batch size is not too large, he is more willing to hold the parts in inventory, recognizing that the likelihood is very high that all 500 pieces will be consumed. He therefore produces the parts ahead of schedule to assure he can handle the inevitable change. When the time comes to ship the first 100 pieces, the supplier sees that he is permitted to ship 1700 pieces. He sends the 500 pieces he produced, recognizing that this will erase all scheduled requirements for the next 5 weeks, and that the next schedule he will receive should reflect this change. Based on this, he plans the next production of 500 pieces. If for some reason, the schedule changes, he may elect to still complete the lot of 500 pieces, confident that when he does need to ship the parts, he will be able to ship both lots based on a maximum permissible shipment of 17 weeks worth of demand

In essence, we are giving the supplier access to a less volatile schedule that more closely reflects the actual demand for the part, allowing him to make his own decisions regarding what batch sizes are most economic for him to produce and ship. In addition, since both schedules are currently created, there is relatively little effort required to implement this proposal.

6.1.2 Customer Demand

Although this thesis focuses mainly on lotting policies applied to the purchased part schedules, in reality lotting is applied at every level of the bill of materials and to transfers of parts between plants within Hamilton Sundstrand. Therefore, it is reasonable to expect that providing suppliers with schedules of actual customer demand would provide similar benefits to that obtained by switching from the lotted supplier schedule to the discrete demand schedule.

Attractive as this suggestion may seem, in reality it may be very difficult to implement. There are many factors used to generate a schedule for purchased parts from the corresponding customer demand. These factors may include the number of parts per end assembly from the BOM, maufacturing lead-times, demand for subassemblies and purchased parts from spares customers in addition to end item demand from OEM customers, impact of loss and scrap, and many other factors. Many of these parameters are dynamically changing, making it difficult to simply provide a schedule of customer demand to suppliers for planning purposes. In addition, internal lotting for batch processes can cause a mismatch in the timing of shipments from suppliers and customer demand. Take for example an item with constand customer demand of one/week. If a subassembly requires a batch process with lot size of ten, all ten parts must be received from the supplier simultaneously to cover the next ten weeks of customer demand.

Although we might expect that linking suppliers to end item demand is desirable in reducing schedule volatility, there is no mechanism in MRP which allows such a linkage to easily be provided. However, it is worth mentioning that very successful pull systems actually link production of the lowest levels in the BOM to end item demand. Although we will not discuss the design of pull systems in create detail in this thesis, two pull systems that have been discussed at length in the academic literature that do link end item demand to the early manufacturing operations include CONstant Work In Process (CONWIP) systems and Hybrid systems.

A CONWIP system is one in which the total inventory (including work in process and finished goods) is maintained at a constant level by sending a signal to the first operation to start producing a part immediately after a part is removed from finished goods inventory. This part is then "pushed" through subsequent manufacturing steps. A hybrid system usually combines a CONWIP system with individual pull signals from the various manufacturing steps in the process to the previous operations. In this case, inventory is maintained at a constant level and parts are "pulled" from one operation to the next. The next section will suggest how such production systems may be used to reduce schedule volatility.

6.2 Alternate Order Policies

Throughout the duration of this research, Hamilton Sundstrand was considering alternate ordering policies to reduce the schedule volatility problem and reduce inventory levels. The methods under consideration included using production planners to manually create fixed, level loaded schedules for suppliers, and implementing a pull system. The pull system could be implemented either just at the purchased part level, using MRP to simulate a two bin system and automatically send a Kanban card to the supplier when one bin went empty, or it could be integrated throughout the manufacturing process so that the purchased part demand was driven by end customer demand. In addition, we will discuss how ordering parts in smaller lot sizes may be used to decrease schedule volatility.

This section discusses the advantages and disadvantages to each alternative approach in the areas of quantity and time volatility and the amount of manual intervention required. The next section will discuss some theoretical aspects regarding inventory under each of these systems.

6.2.1 Reduced Lot Sizes

Historically, Hamilton Sundstrand used large lot sizes for ordering inexpensive parts due to the many fixed costs associated with handling each order. Although automated processes have replaced many of the manual processes which led to these high fixed costs, the lotting policies remain essentially unchanged. Actually, Strata policy specified weekly ordering for Strata A parts, monthly for Strata B parts, semi-annually for Strata C, and annually for Strata D. About three years ago, Hamilton reduced the lot sizes to their current values in order to reduce inventory in the plant.

Even with the decrease in lot sizes, replacing manual order placement with MRP lotting logic led to amplification of schedule volatility from the point of view of suppliers. This amplification increases with increased lot size. For these reasons, it might make sense to reduce the lot sizes even further. With no changes to the current system, reducing lot sizes should improve the amplification factor and thereby reduce the magnitude of the quantity volatility seen by suppliers. However, even with smaller lot sizes, suppliers will be exposed to volatility both in the magnitude and the required date of shipments.

6.2.2 Fixed, Level Loaded Schedule

During the period this research was conducted, there was tremendous pressure to improve supplier delivery performance. Since suppliers felt that schedule volatility was the largest factor affecting their on-time delivery metrics, the suggestion was made to provide suppliers with a fixed schedule, preferably for a fixed quantity per time period. The idea was to take parts that were primarily used in OEM customer parts (for example the Boeing 777 is a relatively new aircraft and is almost entirely OEM demand, with very few spare parts requirements), have a planner determine a fixed schedule for the parts, and communicate this schedule to the suppliers. For example, even if the demand from Boeing was not entirely level, the planner would determine the total demand over a long period, and have the supplier produce x parts per month.

The advantages to such a proposal are: Suppliers get an absolutely fixed schedule with no time or quantity volatility – unless the planner did not account for any of a number of unforeseen events. Not only would such a policy only work on a percentage of all purchased parts (those used primarily in OEM parts), but it would require a huge effort on the part of the planners. The MRP system was implemented to prevent this effort! In addition, if demand grows over and above the schedule initially provided to suppliers (due to scrap, loss, change in customer demand, etc.), it may be very difficult to get additional parts. The supplier, believing he is working to an absolutely fixed schedule, may have no additional raw material on hand to support the new demand. This may be especially problematic if the raw material includes long lead-time items like castings or forgings. This problem can only be avoided by increased effort in planning or by increased safety stock. Both may be very expensive and Hamilton, by removing all volatility from the suppliers, would in essence be carrying all of the cost and risk associated with the reduction in schedule volatility.

6.2.3 Pull System

An ongoing subject of discussion at Hamilton Sundstrand deals with the practicality of using a pull system. The opposition to such a system centers around the general high product variety, low quantity production of aerospace parts in general, and the high unpredictability of spares demand in particular. Many people within the company believe that a pull system will only lead to increased inventory of purchased parts in the plant, due to the large number of partially filled bins scattered throughout the factory.

Sundstrand began using pull systems with their suppliers many years ago, apparently with good success. After the merger with Hamilton, and the subsequent need to standardize and replace the Sundstrand legacy computer systems with the J.D. Edwards system used at Hamilton, functionality within the MRP system was added to duplicate the pull system used by Sundstrand. It is interesting to note that overall, Sundstrand has considerably higher on-time delivery performance from their pull system suppliers, but in general has more on-hand inventory than Hamilton.

In most cases, Sundstrand uses a two bin system with an automatically generated pull system. This means that a bin size is defined, and if the on-hand inventory level falls below this bin size, the computer automatically sends out an email to the supplier to send a bin size worth of parts. The bin size is generally agreed upon with the supplier and based on a production quantity that is economical for them to produce and ship.

Opponents to the pull system maintain that this system just replaces the current lotting policy with a different, fixed quantity lotting policy. In fact, this change alone has a big impact on schedule volatility. Steele (1975) suggests that using a fixed order quantity as opposed to periods of supply can reduce volatility.

In addition, there may be some benefit to using a pull system in the area of smaller lot sizes, since one might generally expect the bin sizes to be smaller than 8 or 17 weeks of average demand.

Furthermore, the fact that the MRP system is not attempting to maintain inventory at zero by planning orders to arrive when inventory drops to nothing, but instead places an order when on-hand inventory falls below one bin, represents a form of safety stock. Many authors including Kropp (1979), suggest that safety stock can be used to dampen schedule volatility.

Finally, there is a benefit to the supplier in that there is only time volatility and no quantity volatility. If the bin size (or lot size) is 50 pieces, than the requirement will always be for 50 pieces (or 100 pieces if both bins are emptied simultaneously). Therefore, the only variability in the schedule is the timing. As we have demonstrated, there is no time volatility ampflication within the MRP system, and the average time volatility is two weeks. This means that on average, the 50 pieces will be required within a period two weeks sooner or two weeks later than originally expected. Based on this knowledge, a supplier would need only produce the 50 pieces two or three weeks earlier than expected, and still be able to meet most schedule changes.

A disadvantage to the pull system lies in the increased effort needed to maintain this system. Bin sizes must be manually sized, and periodically reviewed. If demand for a part decreases, due to a reduction in customer demand, or an engineering change which renders the part obsolete, this may need to be manually accounted for, so that Hamilton Sundstrand is not left holding two bins of unusable inventory.

6.2.4 Pull System linked to Customer Demand

In section 6.2.3., we assumed a pull system in which the MRP system is used to plan all work orders, and then automatically plans and places orders for purchased parts with suppliers as necessary to maintain the on-hand inventory. This means that the purchased part demand alone drives the orders to suppliers. Consider the example in section 4.1.1. in which customer demand for the end item "abc" was perfectly level at two units a week, but the purchased part "xyz" was consumed in groups of twelve due to lotting policies within the MRP system for higher assemblies. Although an economical lot size for the supplier might be less than twelve units, he would be constrained to deliver at least twelve each delivery. If he wished to produce in lots of eight pieces, he would need to deliver at least two lots to satisfy the demand. In essence, the MRP system's internal lotting policies create a practical limit to how small the lot sizes can go before they are no longer effective in reducing schedule volatility.

In fact, an examination of the discrete demand schedule suggests that the maximum demand in one week is approximately eight to twelve times the average weekly demand for the part, suggesting that MRP lotting policies "lump" purchase part demand into lots of two to three months before any lotting policy is applied to the supplier schedule. The results of the discrete demand schedule analysis, which demonstrate that the average magnitude change represents four to six weeks of average usage further substantiates this idea.

If we accept that the work order lotting policies used by the MRP system are valid, can we develop a system which still allows suppliers to ship smaller lots on a more regular basis? For example, if suppliers could make weekly shipments of small, fixed lots, we would expect this to eliminate quantity volatility (through the use of fixed lot sizes), and also reduce time volatility from the current level of approximately plus or minus two weeks.

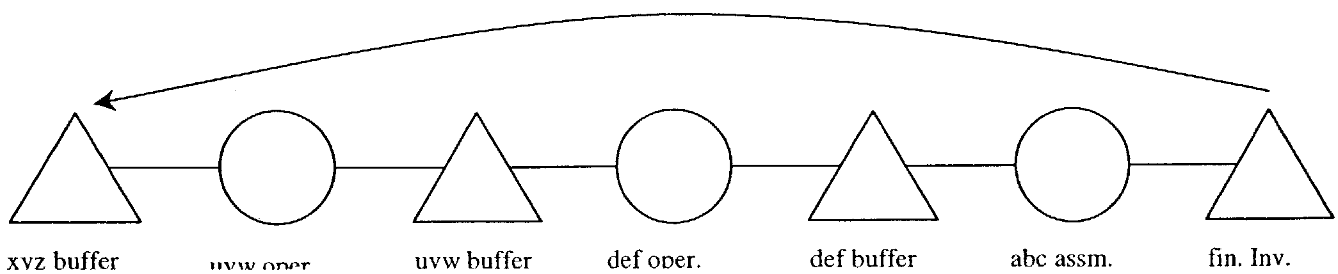


Figure 6. 1 CONWIP Manufacturing System

Consider a CONWIP (CONstant Work In Process) manufacturing system used with the example from 4.1.1. Such a manufacturing system is diagrammed in Figure 6.1. The circles represent assembly or manufacturing operations and the triangles represent buffer inventory. When one end item is taken from the finished goods inventory buffer, a signal is sent to the supplier to deliver a part. Since assembly "uvw" is produced in lots of twelve, the buffer in front of this operation is allowed to accumulate parts so that when the operation is ready to be performed, twelve parts are in the buffer. Consider the schedule for purchased part "xyz" under the original system, with constant demand for "abc" of two per week, and a fixed lot size of 12 pieces for "uvw". Also consider the schedule for part "xyz" under the CONWIP system:

Table 6.1

	Overdue	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8
Item "abc"	2	2	2	2	2	2	2	2	2
Ass. "uvw"	12	0	0	0	0	12	0	0	0
"xyz" with MRP	12	0	0	0	0	12	0	0	0
"xyz" with CONWIP	2	2	2	2	2	2	2	2	2

By linking the purchased part demand with the demand for the end item, we would expect a reduction in MRP generated quantity volatility amplification. In addition, the supplier is now able to further reduce his lot sizes.

A problem with this system, in addition to the need to manually plan and track bin sizes, is the difficulty in aggregating demand. Since a purchased part may be used in multiple end items, may be required to satisfy replacement part demand for a subassembly, or may be needed to replace scrapped parts, it is difficult to ensure all demand has been communicated to the supplier. It may be desirable to separate spares and OEM demand for a given purchased part and implement an additional pull signal for scrapped parts.

6.3 Inventory Considerations

Throughout section 6.2, several alternate planning and ordering policies were suggested to reduce schedule volatility. Since the MRP system generates volatility due to the manner in which it attempts to exactly plan orders and production so as to minimize inventory, we might expect these solutions to impact inventory levels within the supply chain. Since a primary concern of Hamilton Sundstrand is the reduction of inventory, the impact on inventory levels is very important. In this section, we will discuss some of the effects of these planning and ordering policies on inventory levels.

Although this analysis is not intended to be rigorous, it should give an idea of order of magnitude levels. For the sake of this discussion, we will assume that end items are produced in weekly lot sizes (approximately steady demand) and that the lowest level sub items, and therefore the purchased parts, are produced every six weeks, due to the MRP internal lotting policies.

6.3.1 Current MRP System

Purchase Part Inventory – Hamilton Sundstrand

The amount of inventory for purchased parts, assuming 100% supplier delivery, is dependent on the relative size between the shipment lot size and the demand lot sizes. Figure 6.2 shows on-hand inventory levels under two different conditions. The graph on the right assumes perfectly steady consumption, with a lot size of 17 weeks. This means that a supplier delivers 17 weeks worth of parts, which are consumed in small quantities steadily throughout the next 17 weeks. In this case, average inventory is equal to the area under the graph, or one-half of 17 weeks = 8.5 weeks.

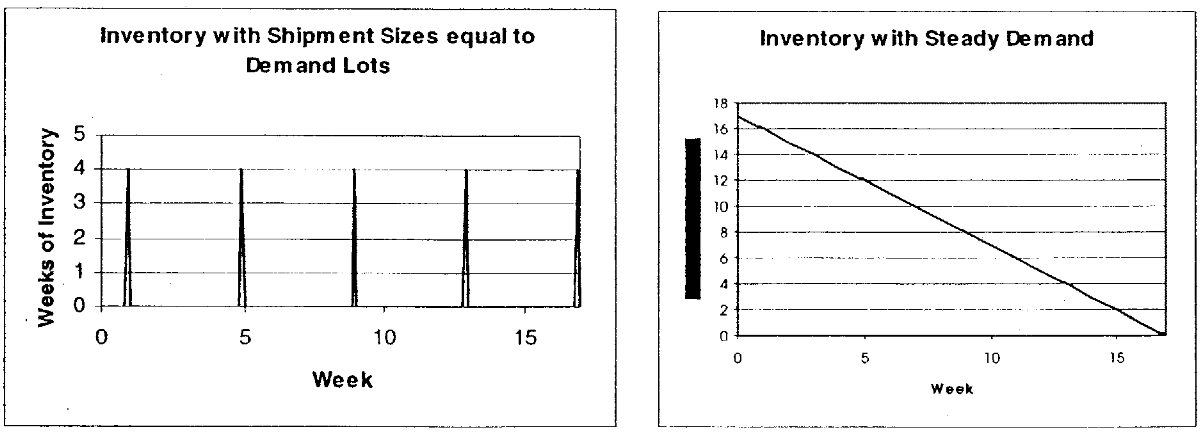


Figure 6. 2 Inventory Level with the MRP system

The graph on the left assumes that the supplier ships in lots of four weeks, and that the parts are immediately used in the lowest level assembly, which are also built in lots of four weeks. In other words, the shipment lot size = demand lot size. In this case the average on-hand inventory is very nearly zero. While these examples represent extreme cases, we see that inventory levels are constrained between zero and one-half the shipment lot size. Since Strata A and B parts currently use a period of supply lotting policy of one week, we would expect inventory of Strata A and B parts to be very close to zero. For Strata C parts, with a lot size of 8 weeks, if we assume that the lowest level assemblies are produced only once every six weeks, then inventory of Strata C parts should also be close to zero. Strata D parts, with lot sizes of 17 weeks, would have an average on-hand inventory approximately 8 weeks, however, since these parts are very low dollar value, this inventory should be negligible from a monetary standpoint.

Although Hamilton Sundstrand is able to maintain very low inventory of purchased parts under this scenario, the supplier is not as lucky. He sees a schedule characterized by frequent, large schedule changes, with an average change representing perhaps eight to twelve weeks of inventory. Faced with this environment, he can decide to carry a large amount of inventory on his shelves, or attempt to expedite orders to meet changes. If we refer to the histogram showing the distribution of magnitude changes in the supplier schedule (Figure 4.1), we see that the supplier would need to hold 30 weeks of inventory in order to meet 90% of all schedule changes. Even a 75% service level would require inventory levels of 16 weeks.

Furthermore, if the supplier, unwilling to carry such large amounts of inventory does suffer from poor delivery performance, Hamilton Sundstrand would expect to see rising levels of inventory, as WIP and purchased part inventory increase because product can not be built in a timely fashion, customer delivery performance falls, and Hamilton Sundstrand reacts by increasing system lead-times and safety stock levels. In fact, this is exactly what is happening.

6.3.2 Fixed, Level Loaded Schedule

In this case, the MRP system has been replaced with a human planner, who examines the schedule and communicates a fixed, preferably constant demand schedule to the supplier. This relieves the supplier of any uncertainty in demand, and he responds by reducing his inventory of finished goods to essentially zero, as he attempts to complete parts exactly when they are needed by Hamilton Sundstrand, and only carries the parts in inventory if he completes them sooner than expected.

Having a person plan the deliveries of purchased parts, however, does nothing to address the causes or amplification of schedule volatility, and therefore, Hamilton Sundstrand must carry a large safety stock of inventory to deal with schedule changes. The discrete demand schedule has magnitude changes on average equal to six weeks of inventory. However, since the supplier may have very limited ability to react to changes, Hamilton may need to use a buffer larger than 6 weeks. In fact, if Hamilton Sundstrand wanted to size the buffer to handle 90% of all changes, the buffer would need to be set at 8 weeks of inventory. At 95%, a buffer of 15 weeks of inventory would be needed.

Finally, a potential mismatch in timing of supplier delivery and actual consumption may exist. For example, Hamilton Sundstrand might need 50 pieces at the end of May, but the supplier is scheduled to deliver parts at the beginning of every month, causing the parts to sit in inventory for the entire month. Also, if the schedule is not examined on a regular basis, a situation may occur where decreasing demand for a part is not matched by decreasing shipments from the supplier, further increasing inventory levels.

Although this analysis is not intended to be rigorous, it is reasonable to assume that there is a trade-off between manual planning effort and inventory level in this system. One reason that MRP systems were created is because such manual planning efforts are very difficult, and often result in poor service levels and high inventory levels. Although the advantage to the suppliers is clear, in the long-run, it seems likely that such a manual system would be abandoned for MRP planning once again.

6.3.3 Pull System

A significant source of resistance to the implementation of a pull system manufacturing process revolves around the concern that such a system will dramatically increase the inventory levels as compared to the current MRP system. In order to answer this concern, let us consider two ideal cases. For the first case, assume that the time required by the supplier to refill an empty bin (replenishment time) is small compared to the consumption of parts. For example, assume that the lowest level assembly is produced

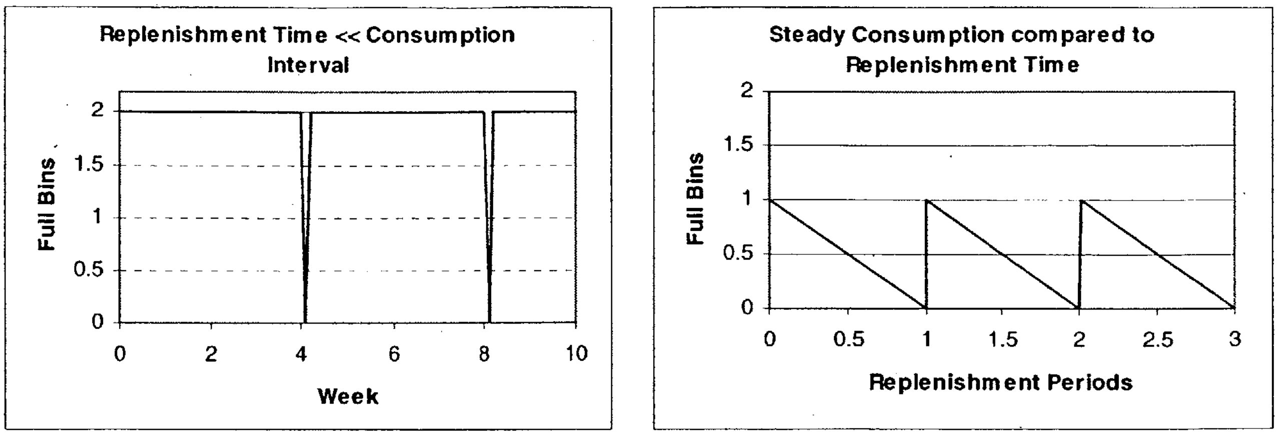


Figure 6. 3 On-Hand Inventory in a Pull System

monthly, and that the supplier can refill the bins immediately. Also assume that when the consumption occurs, a quantity greater than one bin but less than or equal to two bins is used, thereby triggering a signal to refill the bins. For the second case, assume that consumption is perfectly steady, and the bin size is set exactly equal to the consumption during the replenishment time. Figure 6.3. shows the inventory levels under both of these perfect scenarios.

In the first case, average on-hand inventory is very nearly equal to two full bins. In the second case, the average on-hand inventory is equal to half of a bin. Since these two cases represent opposite, ideal situations, we would expect to find that inventory levels are somewhere in between these cases. In addition, since many of the suppliers that Hamilton Sundstrand uses are within several hours of the plant, and since demand for lower level items occurs only every few weeks (partly due to internal MRP lotting policies), we would expect inventory levels to more closely approximate the first case.

Typically, Hamilton Sundstrand uses the logic that the bin size should be set equal to the largest demand within the replenishment time. Therefore, if the replenishment time is one week, the largest single week of demand would be used to size the bin. For this analysis, we are assuming that the low level items are consumed all at once in a quantity equal to six weeks of demand, and therefore the bin size would be set equal to six weeks for any replenishment time of six weeks or less (replenishment time would almost always be less than two weeks, except for very distant suppliers). Therefore, we would expect average on-hand inventory under a pull system to be approximately two bins of six weeks each, or twelve weeks of inventory.

In addition, the supplier would be expected to carry inventory to account for schedule volatility. He is now no longer buffering against quantity volatility, since he is shipping fixed quantity lot sizes, and expects to receive the actual pull signal two weeks before or after originally expected. Since he receives the pull signal on average once every six weeks, he might just adopt a policy of always keeping one bin worth of parts on-hand. This amounts to an additional inventory of one bin (six weeks) over and above the twelve weeks carried by Hamilton Sundstrand.

6.3.4 Pull System linked to Customer Demand

In this scenario, we apply the same logic that we used to analyze the pull system at the purchased part level in section 6.3.3. We will assume that most suppliers are located in the general geographic area of the plant, and therefore replenishment time is generally one to two weeks. Furtheremore, we will use Hamilton Sundstrand's bin sizing logic in which the bin size is set to the largest demand during replenishment time. However, now we will assume that the purchased part pull signal is driven by end item demand.

For this analysis, we assume that end item demand is fairly steady, with very nearly the same quantity produced each week. Since purchased part demand is now driven by end item demand, the purchased part usage is fairly steady also. We might reasonably expect this scenario to more closely resemble the second case shown in Figure 6.3. In this case, on-hand inventory levels were maintained at one-half of a bin. Unfortunately, even in this case, demand is not completely steady, and is about the same order of magnitude as replenishment time. I.e., parts are consumed once a week, and the supplier takes several days to refill the bin. Therefore, it might be more reasonable to assume that on-hand inventory is approximately one bin.

Using the same logic to determine the bin size, we conclude that the bin size should be set equal to the largest demand during replenishment time, or between one and two weeks of demand. Therefore, we conclude that the on-hand inventory is approximately one bin, of one to two weeks inventory. Furthermore, the supplier also carries an extra bin on-hand to guard against schedule volatility, resulting in a total supply chain inventory level of two to four weeks of inventory.

6.4 Summary

Table 6.1. summarizes the advantages and disadvantages of each ordering policy in the area of schedule volatility (both quantity and time), manual planning effort required, and inventory levels.

Table 6.2

	Schedule Volatility		Planning Effort		Inventory Level	
	Quantity	Time	Upfront	Ongoing	Supplier	HS
Current System	High	Yes	None	Low	16-30 wks	~0 wks
Fixed Schedule	None	None	High	High	~0 wks	8-15 wks
Pull System	None	Yes	Medium	Low	6 wks	12 wks
CONWIP/Hybrid	None	Yes	Medium	Low/Med	1-2 wks	1-2 wks

From the table, we can see that there is a cost to reducing schedule volatility, either in increased manual effort, or in increased inventory levels at Hamilton Sundstrand. However, it should be noted that although the theoretical Hamilton Sundstrand inventory levels for the current system are very small, actual inventory levels are much higher. This is partially due to current efforts to combat poor supplier deliver, generally in the form of lead-time or inventory buffers. Furthermore, although any of the alternate planning methods would likely increase the inventory levels at Hamilton Sundstrand, the actual total supply chain inventory would likely decrease. Hamilton Sundstrand must therefore determine if the disadvantage to carrying the inventory on their books is outweighed by the benefit of an overall reduction costs through the reduction in overall supply chain inventory levels.

Furthermore, we should note the fact that suppliers do not carry such high levels of inventory under the current system is reflected in the poor supplier delivery performance, and therefore we would expect any of the alternate proposals to improve delivery performance. In fact, former Sundstrand sites that use Pull Systems do have generally higher levels of inventory, but also have vastly better supplier deliver performance.

7. Recommendations and Conclusions

The analysis of schedule volatility has shown that supplier schedules are characterized by frequent, large magnitude changes. Although these changes are driven by changes in customer demand, as well as changes made within Hamilton Sundstrand at all levels of the MRP system, these changes are amplified in magnitude by period of supply lotting policies used to create the Supplier Schedule. A supplier wishing to achieve a 90% service level in this environment without constantly adjusting his production plan would need to carry 30 weeks of inventory for each part to insure he could accommodate the changes.

The fact that suppliers may be unwilling or unable to carry such large amounts of inventory is evidenced by their poor on-time delivery performance and the high level of WIP inventory at Hamilton Sundstrand that cannot be completed until remaining parts arrive from suppliers.

There are several ways in which schedule volatility can be reduced, including reducing changes at their source. Unfortunately, these efforts have historically proven difficult and ineffective. The amplifying effect of the MRP system can be reduced in a number of ways, including reducing lot sizes, changing the way schedules are communicated to suppliers, or by adopting fixed lot sizes, preferably in the form of a pull system.

Recognizing that many of these recommendations take time to implement, and understanding that the problem needs to be addressed immediately in some manner, we have divided these recommendations into three groups, based on implementation time.

7.1 Reduce Lot Sizes, Use Fix Lot Sizes and Work to Discrete Demand

The easiest and quickest solution is to reduce lot sizes and/or switch to a fixed lot size policy. Reducing lot sizes while maintaining a period of supply policy will help reduce the amplifying effect of the MRP system, thereby decreasing the magnitude of schedule changes that the supplier sees. Although this change will in general increase the number of changes a supplier sees each week, he will be able to accommodate schedule changes with lower inventory levels. In other words, he may see more schedule changes each week, but will be more likely to be have parts in inventory when a change occurs, thus increasing his on-time delivery performance.

Many suppliers have minimum order size requirements, however, these should not be impacted by reducing the lot sizes. The MRP system already contains logic that places orders based on the larger of either the minimum order size or the lotted order size. For suppliers who have not traditionally specified a minimum order size, and now find themselves sending parts more frequently than is economical, minimum order sizes can be entered at any time, and the planned orders will be adjusted accordingly.

Furthermore, recognizing that the use of fixed lot size ordering itself will reduce schedule volatility, it may be desirable to work with individual suppliers to identify economical order sizes. These lot sizes should generally be less than or equal to the average order size under the current period of supply lotting system to prevent an increase in inventory levels at Hamilton Sundstrand. The supplier will now expect orders in multiples of this fixed lot size, and can plan his production accordingly.

Although the fixed lot size is very effective in reducing schedule volatility, the possibility exists that Hamilton Sundstrand will occassionaly purchase more parts than are really needed to meet future demand. For example, if the fixed lot size was 10 pieces, and Hamilton Sundstrand had a requirement for 1 piece, with nothing else in the future, the MRP system would place an order for 10 pieces, leaving the plant with 9 unneeded parts. To eliminate this problem, Hamilton Sundstrand can reduce schedule volatility without changing lotting policies simply by communicating the discrete demand schedule to suppliers, while still allowing them to ship any quantity less than or equal to the lotted value. The supplier will work to a less volatile schedule that more closely matches the actual demand for parts. In order to avoid confusion, the manner in which the discrete demand schedule and the maximum allowable shipment quantity (based on the lotting policy) are communicated should be discussed with suppliers.

7.2 Pull System Manufacturing

Sundstrand, before their merger with Hamilton Standard, began using pull system manufacturing. The result of this implementation was a marked increase in supplier delivery performance. The smaller, fixed lot size ordering which characterizes this system provides a much lower level of schedule volatility, resulting in lower required supplier inventory and thereby improved service levels. The partially filled bins within the plant serve as safety stock and also help to reduce schedule volatility by absorbing schedule changes.

Purchased part inventory levels at Hamilton Sundstrand with a pull system are certainly larger as compared to a perfectly functioning MRP system. However, poor supplier delivery has led to high levels of partially completed WIP inventory and an increase in lead-time and safety stock buffers, therefore, such a direct comparison of total inventory in the plant is invalid. Furthermore, the resulting schedule stability allows suppliers to significantly reduce inventory levels, and total supply chain inventory for the purchased parts actually decreases under the pull system. Since Hamilton Sundstrand eventually absorbs the supplier's inventory holding costs in the form of higher direct material purchased cost, a pull system results in a net benefit.

In order to facilitate the introduction of the MRP system used at Hamilton in the former Sundstrand facilities, functionality has been created in the system to work with a pull system. Therefore, this functionality can be used to order parts from suppliers on a pull system, without significant changes within the factory. However, since placing parts on a pull system requires that suppliers produce additional parts over and above the current scheduled demand in order to intially fill the bins, this process should be discussed with each supplier individually, and a schedule created to place parts on the system.

7.3 Pull System with CONWIP or Hybrid Control

Once suppliers begin working to a pull system, Hamilton Sundstrand should begin working to reduce bin sizes, and thereby reduce the amount of inventory in the plant. Although the ideal goal of single piece flow (lot sizes of one piece) may be uneconomical for supplier deliveries, the process of reducing bin sizes is still worthwhile. Many suppliers deliver a wide range of part numbers, and Hamilton Sundstrand continues to rationalize and reduce their supply base. Therefore, it may be possible for suppliers to economically ship small lot sizes, since they are shipping many parts simultaneously.

Unfortunately, bin size is currently driven by demand lot size. There is little use in having two bins, each with one piece, when the assembly that uses the part is always built in lots of eight. Even with fairly even, steady customer demand at the end item level, lotting policies at lower levels in the bill of materials force the purchased parts to be consumed in larger lots than might otherwise be acceptable. However, by linking purchase part pull signals to consumption of the end items, this aspect of the MRP system can be circumvented. By placing a buffer in front of the batch operation, small lot sizes can be ordered, while simultaneously allow processes which require batch operation to run economically. In essence, the lower levels of the bill of materials have been decoupled from the higher levels in a manner which is impossible to achieve with an MRP system.

Hamilton Sundstrand has already begun considering pull systems which link all the processes in the manufacturing of an end item to the demand of the end item. Termed Supply Chain Integration, or SCI, such a system requires considerable work to design and implement, but holds the promise of greatly reduced inventory levels and a simultaneous decrease in schedule volatility.

7.4 Future Research

Considerable work has been done to demonstrate how quality improvments can be obtained and inventory can be reduce through the use of pull system manufacturing. We believe that such a system also presents considerable advantages in the area of schedule stability. The fact that a formal schedule typically only exists for forecasting purposes in traditional pull systems makes it difficult to actually measure schedule stability. However, as companies try to adopt their MRP system to a pull system methodology, the opportunity exists to study schedule stability improvements. Furthermore, modeling and simulation can be used to compare schedule stability under many scenarios. Researchers including Blackburn (1986) and Ho (1989) have carried out such studies using different lotting policies to understand the impact on schedule volatility. Such an analysis should be expanded to study the performance of various types of pull systems.

7.5 Conclusions

Lotting policies in the MRP system can amplify schedule volatility in modern MRP systems, so that even small changes in the master schedule can lead to very large requirement changes in the supplier schedules. Such changes may make it difficult for suppliers to meet shipment schedules, eventually disrupting the downstream manufacturing processes.

Although efforts to reduce the sources of volatility in the system, namely changes made to the schedules and to MRP system parameters, and reduction of scrap and loss are certainly desirable, such efforts have usually proven unsuccessful in ultimately improving schedule volatility. However, through reduction of lot sizes, improved schedule communication using discrete demand and the use of fixed lotting policies, schedule volatility can be significantly improved.

Finally, implementation of pull system manufacturing, through the automatic use of fixed lot sizes (bin size) and inherent safety stock from inventory in bins throughout the plant, can further improve schedule stability. Unfortunately, the use of a pull system in a manufacturing environment with large product variety and low production volumes may lead to an initial internal increase in purchase part inventory. However, the improvement in schedule stability and supplier delivery performance should lead to a decrease in overall supply chain inventory levels and possibly total inventory levels in the plant. Furthermore, implementation of a CONWIP or hybrid pull system can eliminate the tendency of the MRP system to unnecessarily lot lower level items (including purchased parts) and allow further reductions in inventory.

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Appendix – Schedule Volatility Analysis Methods

The MRP system is run every Sunday. Therefore a new schedule is created only once a week. For simplicity's sake, we limit our investigation of schedule volatility to all requirements within an eight-week period from the date the schedule was created. Generally speaking, volatility within this time frame is most disruptive to a supplier. The suppliers typically have determined their production requirements and ordered raw material and therefore changes within this time frame require some type of expediting.

By limiting the investigation to an eight week period, we mean that we consider only those requirements on any given weekly schedule that occur within a period starting on the date the schedule was created, through the next eight weeks. We then compare that schedule to a schedule created one week later, and compare that schedule to the following weeks schedule, and so forth. Any parts that are received during the week are netted off the current schedule, from the earliest requirement date (starting with overdue requirements), and this adjusted schedule is then compared to the following week's schedule. In essence, we are comparing what a supplier would reasonably expect to see, with what they actually see each week.

Counting Schedule Changes

Consider a typical schedule for a single part number:

Table 1

	Overdue	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8
Schedule 1	0	0	0	10	0	15	0	24	0

The schedule shows the quantity required in each week for the next eight weeks. Since the schedule was created Sunday, Wk 1 represents the need for parts from that Monday until the end of the week and so on. The schedule also shows that there are no parts that are overdue. If no changes occur which effect the schedule, the supplier would expect the schedule on the following week to look like:

Table 2

	Overdue	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8
Schedule 1	0	0	0	10	0	15	0	24	0
Schedule 2	0	0	10	0	15	0	24	0	6

If the supplier were to deliver 8 pieces during the week, they would expect the schedule to become:

Table 3

	Overdue	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8
Schedule 1	0	0	0	10	0	15	0	24	0
Schedule 2	0	0	10	0	15	0	24	0	6
Schedule 3	0	2	0	15	0	24	0	6	9

If the supplier makes no subsequent deliveries, the following week, 2 parts would be overdue, as shown in the following schedule:

Table 4

	Overdue	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8
Schedule 1	0	0	0	10	0	15	0	24	0
Schedule 2	0	0	10	0	15	0	24	0	6
Schedule 3	0	2	0	15	0	24	0	6	9
Schedule 4	2	0	15	0	24	0	6	9	0

So far the schedule has been absolutely stable, with no signs of volatility. However, suppose the supplier made no shipments, and the schedule next week looked like:

Table 5

	Overdue	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8
Schedule 1	0	0	0	10	0	15	0	24	0
Schedule 2	0	0	10	0	15	0	24	0	6
Schedule 3	0	2	0	15	0	24	0	6	9
Schedule 4	2	0	15	0	24	0	6	9	0
Schedule 5	2	15	5	24	0	6	9	0	23

The schedule now shows an additional requirement for five pieces. If the supplier now delivers 20 pieces, he would expect the following schedule to appear the following week:

Table 6

Expected	0	2	24	0	6	9	0	23	0

This shows that the 20 pieces have been netted out from the earliest to the latest, so that the two overdue pieces, the 15 pieces in week 1, and 3 of the 5 pieces in week 2 have been satisfied. Suppose the schedule that week actually looked like this:

Table 7

Expected	0	2	24	0	6	9	0	23	0
Actual	0	**4**	24	0	6	9	0	23	0

The supplier expected a requirement of two pieces based on having shipped 20, but there is now an open requirement for 4 pieces, an increase of two from what was expected.

It is worth noting that a pull-in of a requirement (i.e. an existing quantity is needed earlier than originally scheduled) may be considered a single change by a human observer, but would be counted as two changes - an increase in one weekly quantity, and a decrease in a different week. For example:

Table 8

Schedule 1	0	0	0	0	20	0	0	0	0
Schedule 2	0	**20**	0	0	0	0	0	0	0

In the second week schedule, the requirement for 20 pieces is not shown in the expected position one week sooner, but is instead need two weeks earlier. This is a pull-in, and would be considered two changes in the schedule. The week in which 20 pieces were required now has no requirement (-20 pieces) and the week that now has a 20-piece requirement originally had no requirement at all (+20 pieces).

Measurement of Change Magnitude

In order to compare schedule changes in parts with different usage levels, it is necessary to understand the relative scale the change represents. For example, we recognize that a schedule changed by 20 pieces may be significant if the part has an average annual usage of 30 or 40 pieces, but may be insignificant if the part has an average usage of 10,000 parts / year. Certainly this relative scale is important to a supplier when reacting to a change. Therefore, in order to adequately measure and compare change magnitude, we must normalize the values. Normalization is done by dividing the actual change by the average weekly usage of that part.

For example, consider a part that has an average weekly usage of 10 pieces. The requirement for a given week was 15 but then changed to 25 pieces. Therefore, the magnitude of the change would be:

(new qty – old qty) / average weekly usage = (25 pcs –15 pcs) / 10 pcs/week = 1 week

In essence, we are measuring the size of the change in terms of weeks of average demand. Therefore a magnitude change of 4 would mean that the change represented a difference of 4 weeks of average demand, or about a one-month supply of parts. Using this measurement allows changes to be compared across parts with widely varying demands.

Determination of Average Weekly Usage

Although the above calculation is very simple, the calculation of average weekly usage is more difficult. Until now, we have relied solely on the supplier schedules to determine volatility. Consider a schedule:

Table 9

	Overdue	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8
Schedule 1	0	0	0	0	0	16	0	24	0

We could simply add the schedule for each week together, and divide by the total number of weeks, in this case (16 + 24)/8, and declare the average weekly usage to be 5 pieces/ week. Unfortunately, the schedule tells us nothing about the on-hand inventory. If inventory exists, this is obviously being consumed during the first four weeks, and the actual average weekly usage is greater than 5 pieces. In addition, the schedules may show excessive volatility week to week, making an accurate calculation of average weekly usage difficult. Therefore, a more accurate method is needed.

A better estimation of usage can be found using the change in inventory over a period of time. For example, if starting inventory was 20 pieces, and the inventory at the end of a given period of time was 5 pieces, the usage was at least 15 pieces. If we then include the fact that 10 parts were received during this period, we would conclude that 25 pieces were consumed. If the period was 5 weeks long, then the average usage must have been 5 parts/week. This calculation alone would be sufficient if parts were always on time.

Consider the following example:

There were zero parts in inventory at the beginning of the period and at the end of the period, and no parts were delivered. However, the number of parts overdue changed from zero to 20. This means that the factory actual wanted to use 20 pieces, but they were not available. In this case the actual usage (desired) was 20. Therefore, the calculation for average weekly usage looks like:

Average Usage = (Receipts + Change in Overdue – Change in On-Hand Inventory) / Weeks in Period

Symbolically, let:

I_i =	Initial On-Hand Inventory
I_e =	Ending On-Hand Inventory
O_i =	Initial Overdue
O_e =	Ending Overdue
R =	Receipts throughout period
U =	Average Weekly Usage
w =	weeks in the period

Then:

$$U = (R + (O_e - O_i) - (I_e - I_i)) / w$$

Accuracy of Average Weekly Usage calculation

The calculation of average weekly usage can only be as accurate as the data from the MRP system. Unfortunately, this data is subject to various sources of uncertainty. Generally speaking, MRP systems are very good at recording anything entering or leaving the plant, in this case, receipts or shipments. We can therefore consider R to be very accurate. Since we also know the exact dates of the data we use to determine the starting and ending points, we know w exactly. This leaves the calculation of I and O open to uncertainty.

We have already determined that schedules change drastically for unknown reasons. Since overdue is actually one of the quantities in our weekly schedules, there is definitely some uncertainty in the value of O. On average, approximately one thousand parts are overdue in any given week, out of approximately 30,000 active parts. This means that we would expect approximately 1000 parts to be overdue at the beginning of a period, and approximately 1000 parts to be overdue at the end of the period (although these parts are not necessarily the same). Therefore, at most 2000/30000 or about 7% of all parts should be affected by uncertainty in the overdue schedule.

Probably the single largest source of uncertainty in the calculation of average weekly usage is the value for on-hand inventory. There are many sources of inaccuracy that may affect the value in the computer for on-hand inventory. Loss or scrap is certainly one source. Binstock, a category of parts at Hamilton Sundstrand, is treated in such a way that the computer only includes the quantity in the storeroom but ignores all stock at the assembly stations throughout the plant. Scrap and loss, as well as the problem with binstock, are most prevalent with inexpensive parts. Generally speaking, only low dollar parts are binstock and more expensive purchased parts are much less likely to be scrapped or loss without someone noticing and adjusting the value in the computer.

Finally, the inaccuracy increases inversely with the length of the period being considered. If the on-hand inventory is off by one piece, and the piece is used on average once a week, calculating average usage using on-hand inventory over a one-week period will be very inaccurate. This calculation may yield an average usage of zero or two – in essence an error of 100%. If the period being considered is longer, say 10 weeks, the inaccuracy caused by the on-hand inventory error of one reduces to 10%.

In summary, the calculation of average weekly usage is affected by various sources of uncertainty. In general, the inaccuracy is larger for less expensive parts and can be greatly reduced by calculating average usage over a must longer period of time. For this thesis, we have used a period lasting 15 weeks. Even with this length of time, approximately 10% of parts showed a negative usage during the period. Therefore, calculations of average weekly usage change magnitudes, especially for inexpensive parts (typical strata C and D parts) should be treated with caution.

Time Volatility Calculation

The previous section described the calculation of quantity volatility in the schedule. However, we also want to be able to consider time volatility in the schedule. We define time volatility as the number of weeks that a requirement moves within the eight-week schedule. For example, if 10 pieces were needed in week 6, and the new schedule suddenly shows that 10 pieces are needed in week 2, this represents a movement of 3 weeks. (Schedule 1 had 10 pieces in week 6, and Schedule 2 should have had 10 pieces in week 5, but now shows the requirement in week 2)

In order to measure time volatility, at least two weekly quantities must change from one week to the next. If there is only one change, this means that the schedule either increased or decreased – i.e. there was no apparent movement. It is certainly possible that the requirement moved into or out of the eight-week schedule, but this movement cannot be measured using our data.

If there are three or more schedule changes, it becomes difficult to determine what kind of movement occurred. Consider the following schedules with no receipts:

Table 10

	Overdue	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8

Schedule 1	0	5	5	5	5	5	5	5	5
Schedule 2	**0**	**8**	**3**	5	5	5	5	5	5

Even for a human observer, it may be difficult to determine with absolute certainty what happened in the schedule. There are three changes, the 5 pieces in week 1 should now be overdue, but no pieces are overdue. If those 5 pieces had simply moved 1 week later, we would expect 10 pieces due in week 1, but only 8 are due. In addition, two less pieces are required in week 2. In total, there are 4 fewer pieces required in the next three weeks, and two weekly periods have decreases. Which of those decreases caused the increase from 5 to 8? There is no way to determine with certainty. Whenever there are more than two changes, the exact movement is ambiguous.

Even when exactly two changes occur, one change must be positive and one change must be negative for a movement to have occurred. If there are exactly two changes, but both represent an increase, as in the following schedule, no movement has occurred:

Table 11

	Overdue	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8
Schedule 1	0	0	0	10	0	15	0	24	0
Schedule 2	0	0	**12**	0	**18**	0	24	0	6

Both the quantity of 10 and the quantity of 15 have increased. No movement of a requirement has occurred.

We can see that both an increase and a decrease must occur to measure time volatility. However, we would note that the increase and decrease must not be the same magnitude. Consider this schedule:

Table 12

	Overdue	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8
Schedule 1	0	0	0	10	0	15	0	24	0
Schedule 2	0	0	**15**	0	**8**	0	24	0	6

The requirement for 10 pieces increased by 5 pieces to 15, while the requirement for 15 pieces is now reduced by 7 to 8 pieces. An observer would most likely assume that the increase from 10 to 15 was entirely due to the decrease from 15 to 8 with some other factor accounting for the additional two-piece decrease. This would represent a movement of two weeks.

In summary, time volatility as defined in this thesis, can only be determined if the following conditions occur:

- Exactly two weekly quantities change from one schedule to the next
- One change is positive and the other is negative
- The increase and decrease can be different magnitudes