Business System Improvements Through Recognition of Process Variability

by

Michael P. Miller

BS Chemical Engineering, University of Florida, 1988

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

Master of Science in Management
and
Master of Science in Chemical Engineering

at the
Massachusetts Institute of Technology
June 1997

Signature of Author ______________________________
Sloan School of Management
Department of Chemical Engineering
May 15, 1997

Certified by ______________________________
Stephen C. Graves, Professor
MIT Sloan School of Management

Certified by ______________________________
Gregory J. McRae, Bayer Professor
Department of Chemical Engineering

Accepted by ______________________________
Robert E. Cohen, St. Laurent Professor of Chemical Engineering
Chairman, Committee on Graduate Students

Accepted by ______________________________
Larry Abeln, Director of Master's Program
Sloan School of Management

Business System Improvements Through Recognition of Process Variability

by

Michael P. Miller

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

ABSTRACT

Production planning and scheduling systems that do not recognize true process variability will incur significant schedule disruption and require substantial inventories to maintain customer service. When variability is misunderstood or ignored, significant differences will exist between planned and actual utilization. This thesis analyzes the various forms of process variability affecting the supply of usable wide roll from the Commercial Film Flow sensitizing operation at Eastman Kodak Company. It evaluates the existing policies used by this operation to accommodate these sources of variability. Then, through statistical analysis, it provides improved methods for planning and scheduling production and for determining inventory safety stock levels to reduce the impact of these sources of variability. This work shows that by segmenting the sources of process variability into three forms (common cause process, uncommon cause process, and test release), one can design and implement planning, scheduling, and inventory stocking policies specifically designed for each of these forms.

The financial benefits to the Commercial Film Flow Division and Eastman Kodak Company through the implementation thus far of the concepts developed by this thesis have been estimated by Eastman Kodak Company at the following: an approximate $7 million one-time reduction in wide roll inventory, an approximate $2 million annual savings in carrying cost associated with the inventory reduction, and an approximate $200,000 annual savings in planning resources. Additionally, it is believed there are significant financial benefits to Eastman Kodak Company in lowered raw material inventories due to reduced disruption transmitted upstream from the sensitizing schedule.

Thesis Supervisors: Stephen C. Graves, Professor of Management
Gregory J. McRae, Bayer Professor of Chemical Engineering

Acknowledgments

I would like to thank the people at Kodak who found time to provide me information, answer my questions, and listen to my findings. Special thanks go to my advisors: Earl Chapman and Bob Rich at Kodak, and Steve Graves and Gregory McRae at MIT for all their support and guidance. My thanks also to the many Kodak people who helped me in my research including Jake Vankouwenberg, Debbie Spratt, Jan Voglesong, Margie Mountain, Laurie Stefanski, Dave Swann, Tom Page and many others too numerous to name. A particular thanks to the Kodak Park LFM alumni (especially Charlie DeWitt, Tao Ye, and Mark Kurz) who made sure I had the resources I needed and that I was "being taken care of."

I am thankful to Tom Braun and Danny Westerfelt for supporting the project and my involvement in it.

I gratefully acknowledges the support and resources made available to him through the MIT Leaders for Manufacturing program, a partnership between MIT and major U.S. manufacturing companies.

Finally, and most importantly, deepest sincere appreciation to my wife Cindy for tolerating all the moves, keeping our lives going, and raising two beautiful children as well.

TABLE OF CONTENTS

LIST OF FIGURES

1. Executive Summary

1.1 Thesis Statement

If consistent levels of high quality customer service are to be maintained in the presence of process variability, then there needs to be a focus on inventories, capacity requirements and cycle time. True variability reduction is often slow and tedious because it requires an increased scientific understanding of the products, processes, and their interaction. This work hypothesizes that the planning, scheduling, and safety stocking can be optimized to minimize the impact of process variability on the supply chain.

This thesis will determine and quantify the major sources of process and test variability in the sensitizing operation of Kodak Commercial Film Manufacturing Flow. The thesis then will seek to reduce the impact of the most significant sources of this variability by means of changes in the business system. These changes will consist of improvements in production planning, scheduling, and inventory policies; changes to the information flow; and other means that can be addressed directly. The thesis also will provide a process by which manufacturing can continue to evaluate the sources of variability to ensure that the planning, scheduling and inventory policies accommodate the most current performance data.

1.2 Problem Description

To understand the problems experienced by the Kodak Commercial Film Manufacturing Flow Division (hereafter referred to as the CFM Flow), one must have some understanding of the system they use for planning and scheduling their manufacturing activities. The CFM Flow uses a classical MRP II (Manufacturing Resources Planning) planning and scheduling process. MRP II is the successor to material requirements planning (MRP), a computer-based tool for scheduling and inventory control developed by researchers at IBM.[1] Hopp and Spearman clearly stated the fundamental insight of MRP:

> Dependent demand is different from independent demand. Production to meet dependent demand should be scheduled so as to explicitly recognize its linkage to production to meet independent demand.[2]

These authors define independent demand as any demand originating outside the system, typically demand for finished products. They define dependent demand as demand for the components making up these finished products. In an MRP system, each finished product (and some intermediate products) has a bill of material (BOM) which defines by quantity and type the components making up that finished product. The production schedule for finished products flows directly from the master production schedule (MPS.) The master production schedule determines net requirements for production by subtracting current inventory and scheduled receipts from the gross demand.[3] The MRP system uses the BOM for each finished product as well as the lead times for materials acquisition and individual manufacturing steps to specify component orders and manufacturing starts. MRP II is an extension of MRP that takes into account some of the problems of MRP such as schedule infeasibility due to both capacity constraints and stochastic lead times.[4]

In the case of the CFM Flow, the schedule for sensitizing support with light-sensitive materials (known as sensitizing) comes directly from the master production schedule. The material components required for the operation are determined by bill of material and scheduled by standard lead times. (The reason for making the sensitizing schedule flow directly from the master production schedule instead of an activity scheduled by bill of material will be explained shortly.) This product flow is subject to several sources of

---

[1] Hopp, Wallace J., and Spearman, Mark L. Factory Physics- Foundations of Manufacturing Management. Irwin Publishing, Chicago (1996), pp. 105.

[2] ibid., page 106.

[3] ibid., page 108.

[4] ibid., page 130.

variability including supply, process, test, and demand variability in their common and uncommon cause forms.[5] Even so, in the interest of minimizing unit manufacturing costs (UMC), the CFM Flow has sought high utilization (>90%) for the sensitizing process and scheduled production runs accordingly. Unfortunately, the nature and magnitude of the variability is such that the actual realized capacity of the process has been below the anticipated capacity. This creates frequent schedule changes to ensure the products most in need are being produced first. The CFM Flow has not had a well-devised planning process for dealing with uncommon cause and common cause yield loss as determined at the sensitizing machine or through follow-up testing. The lack of a statistically-based planning process has caused frequent schedule changes in the near-term fixed production schedule (known as the freeze zone), excessive planning and replanning out beyond the near-term fixed production schedule, and appropriate safety stock levels of sensitized wide roll. Individuals within the CFM Flow familiar with the problem and its impact have estimated that a improved planning and scheduling policy with a statistical basis could save from $2 million - $20 million /year depending on the degree of implementation.

1.3 Thesis Structure

This work accomplishes the following:

- an understanding of the nature of the three forms of process variability (common cause process, uncommon cause process, and test release) that impact availability of sensitized wide roll (Chapter 3.3 and 3.4)
- an understanding of the planning and scheduling phenomena being experienced by the CFM Flow (Chapter 3.1)

---

[5] As explained earlier in the thesis, common cause refers to the day-to-day variation of an in-control process whereas uncommon cause refers to variation with a special cause, occurring at a low frequency.

- a plan for dealing with special cause shortfall in yield of sensitized material. The plan allocates undedicated machine time within the near-term fixed production period of the sensitizing schedule just beyond the expedited lead time for remanufacture of the components necessary to remake the sensitized material in question. (Chapter 4.1)
- a statistically-based, and much simplified determination of safety stocks to accommodate common cause yield variation incurred by all products being sensitized. (Chapter 4.2)
- a statistically-based method for determining and accommodating wide roll test release variation (time and quantity) in safety stock levels. (Chapter 4.3)
- a means of combining the various forms of variability to determine appropriate safety stock levels. (Chapter 4.4)
- a method for combining these forms of variability with demand variability to set wide roll safety stock levels and for freezing larger portions of the wide roll production schedule to allow for reductions in upstream raw material inventory (Chapter 4.4)

1.4 Specific Contributions of this Thesis

The following are actual realized benefits of this work to Eastman Kodak Company:

- a reduction in sensitized wide roll safety stocks (implemented: estimated to be a one-time reduction of $7 million and an annual savings in carrying cost on this inventory of $2 million.)
- a reduction in planning and scheduling resources due to the machine time allocated for rerunning products suffering significant yield loss (implemented: estimated to be an annual savings of $200,000.)

In addition, there is the potential for major reductions in raw material inventory levels resulting from the freedom to enlarge the fixed portion of the sensitizing schedule.

Finally, since the impact of manufacturing process variability is universal, the understanding and methodologies presented in this thesis can provide benefit to other manufacturing operations as well.

2. Kodak's Existing Manufacturing and Scheduling Process

2.1 Introduction

Kodak's largest film sensitizing facility is Kodak Park in Rochester, NY. Kodak Park's film sensitizing business has two broad product classifications: consumer film and commercial film. There has been an attempt to focus products in each of these two businesses on specific equipment in the interest of matching product complexity with process capability and maximizing overall equipment utilization. Even so, there is some overlap in that any one machine produces a disproportionate mix of products from the two classifications.

Both consumer and commercial film are produced by similar process flow. As Figure 1 shows, chemicals are synthesized at the initial steps of the process. Some of these chemicals are produced internally (SynChem) while others are purchased from the outside. These chemicals are combined with others in various formulas in an emulsion manufacturing step to create emulsion. Support upon which the light-sensitive material will be placed is also being produced in the early stages utilizing either cellulose acetate (acetate) or ESTAR material.

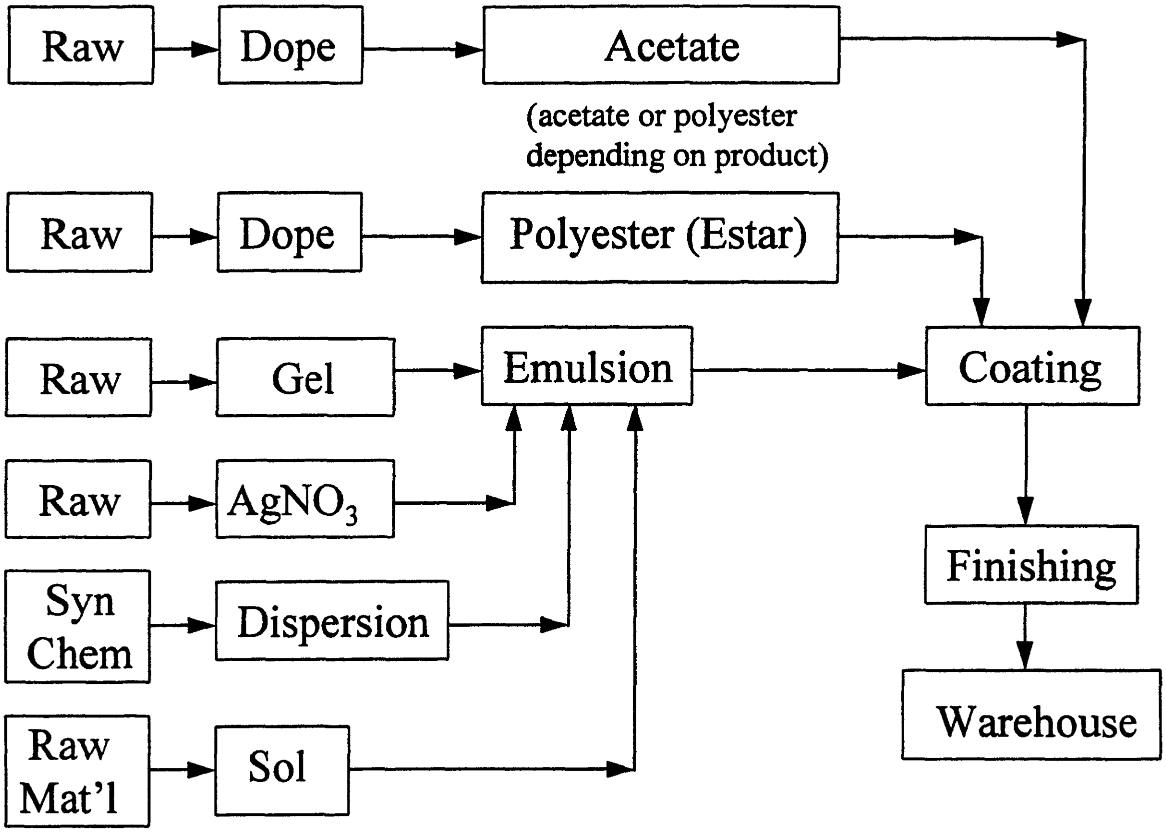


Figure 1: Simplified film production process flow

Photosensitive emulsion is sensitized onto roll support in the sensitizing step to produce sensitized wide roll. Wide rolls are manufactured in a variety of sizes depending on the specific equipment and product characteristics. These wide rolls are then "finished" or cut and packaged in a multitude of finished product formats.

As mentioned previously, the classical MRP system schedules finished products independently and sets the requirements for components up the entire process flow based on the finished product schedule. In Kodak Park's case, the wide roll sensitizing schedule comes directly from the master schedule rather than being treated as a component of finished product and being set by bill of material and standard lead time. Chemicals, emulsion and roll support are produced according to the wide roll production schedule and sensitized wide roll is finished in a "finish-to-order" or "final assembly schedule" fashion based on actual orders and some amount of in-month production load leveling. The reasons for making wide roll sensitizing process the focal point for the master schedule will be discussed in Chapter 2.3.

2.2 Description of the Manufacturing Process for Commercial Film

Commercial film manufacturing differs from other categories primarily in the complexity of the products manufactured and the length of production runs. A good measure for the complexity or manufacturing difficulty of a particular product is the number of individual layers of material that must be applied to the support. As the number of layers increases, the potential for a host of problems increases dramatically as well. These problems include undesirable layer interactions as well as reliable delivery of any one layer. Individuals on the engineering staff of the CFM Flow developed a metric "Increasing degree of difficulty" in an attempt to quantify product manufacturing difficulty. This metric incorporates number of layers as well as other individual user specifications, and contains a factor for product manufacturability. As Figure 2 shows, Commercial film (B*) involves the manufacture of the most complicated products while the manufacture of film in other product sectors (A*) is relatively simple.

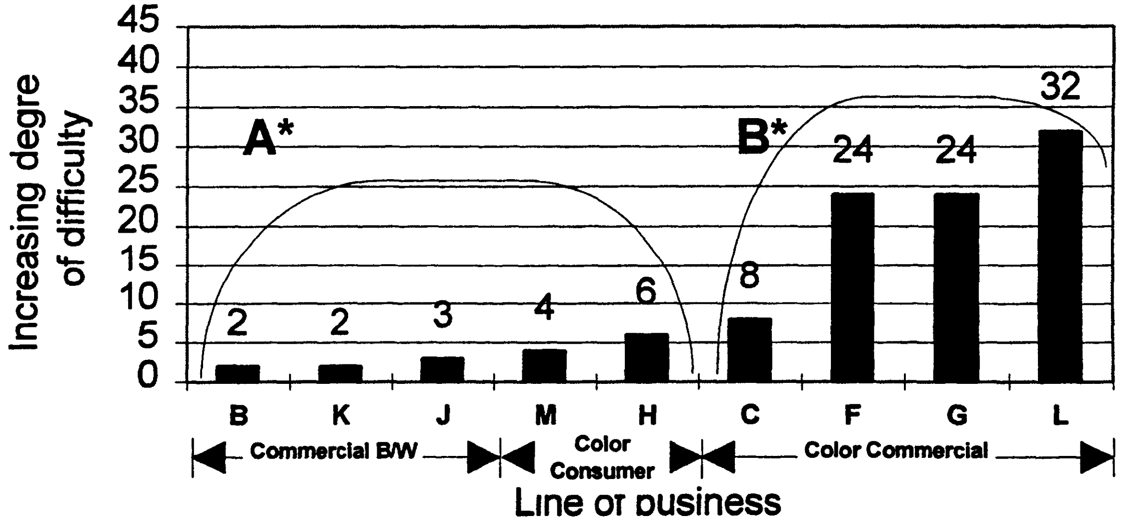


Figure 2: Manufacturability by product category

Differences in the value of this metric correlate with differences in machine efficiency, product yield, unit cost and many other important measures.

2.3 Current planning and scheduling policies used by the Kodak CFM Flow

A fairly detailed treatment the Kodak MRP II systems architecture is provided by Kristopher L. Homsi in his thesis Information Flow and Demand Forecasting Issues in a Complex Supply Chain.[6] It is necessary here to understand how the wide roll sensitizing operation is planned and scheduled and how this translates to production upstream.

Figure 3 is a graphical depiction of how sensitizing, finishing, and sensitizing components are scheduled as described in Chapter 2.1. As the figure shows, the forecasted demand signal drives the sensitizing production plan which is then "assimilated" with projected finishing rates and adjusted to meet actual finishing usage.

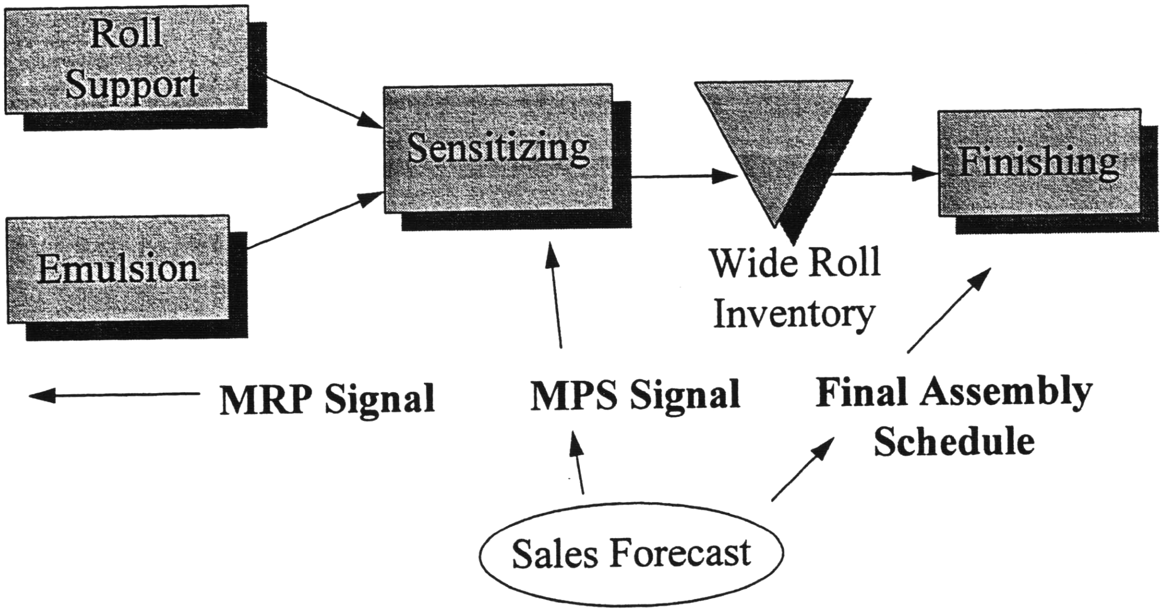


Figure 3: Planning and Scheduling of Kodak Commercial Film Manufacturing

There are three major reasons for having the sensitizing schedule flow directly from the sales forecast through the master production schedule. The most important reason is that

---

[6] Homsi, Kristopher. LFM Masters Thesis: Information Flow and Demand Forecasting Issues in a Complex Supply Chain. MIT Sloan School of Management, MIT Department of Chemical Engineering, (1995), pp. 19 - 22.

the number of different items produced by sensitizing is significantly smaller than the number of finished good items. A single sensitized wide roll product can be finished into numerous final formats, consequently master scheduling the finished format would require substantial wide roll product inventories. Driving sensitizing operations purely from actual finishing needs would require larger safety stocks of wide roll or significantly more sensitizing capacity in order to maintain service levels to finishing. Wilson, in his LFM masters thesis Determination of Optimal Safety Stock Levels for Components in an Instant Film Assembly System, demonstrated the following: "For product line demands which are not perfectly correlated, a reduction in inventory stock can be achieved by holding the inventory in a form that 'pools' the product line demands into a single family."[7] Statistically, consider finished products A, B, C, and D that each come from a single wide roll and that are not perfectly correlated in demand. The following is true about the standard deviation (σ) of the demand for that wide roll and the σ's of each individual finished product: $\sigma_{tot} < \sigma_A + \sigma_B + \sigma_C + \sigma_D$.[8] Since safety stock inventory is driven directly by σ, the same relationship holds true for safety stock inventory.

The second reason is the relative speed and reliability of the sensitizing and finishing operations. Whereas the sensitizing operation requires considerable lead-time (due to component requirements and high utilization) and is somewhat unreliable in actual product yield, finishing is relatively quick and much more reliable. Since reliable component lead times and relatively unconstrained capacity of component-manufacturing equipment are requirements for a well-functioning MRP system, treating sensitizing as a component supplier and scheduling it by bill of material would cause significant disruption. Related to this is the fact that sensitizing equipment is much more capital intensive than finishing equipment. Since the component suppliers in an MRP system

---

[7] Wilson, John J. LFM Masters Thesis: Determination of Optimal Safety Stock Levels for Components in an Instant Film Assembly System. MIT Sloan School of Management, MIT Department of Chemical Engineering, (1996), page 39.

[8] ibid., page 38.

need to be less constrained in capacity than the operations they are supporting, it makes financial sense that sensitizing is not scheduled as an MRP component supplier to finishing through the bill of material.

There is a significant difference in the forecast-based/order-based scheduling balance for sensitizing and finishing. Due to its minimal lead-time and higher reliability, finishing has depended less on forecast than sensitizing and therefore been affected less by demand variability. Finishing strives to maintain a final-assembly schedule system which recognizes the financial benefits of producing from as short a demand horizon as forecast accuracy and internal cost will allow. These financial benefits flow from the consideration of safety stock inventory due to demand variability and waste resulting from product changeovers.

Within the 18 month OPAL (Operational Planning at the Aggregate Level) horizon, there is a 12 week planning horizon for wide roll requirements which equates to a master production schedule. The aggregate in OPAL refers to monthly sales expectations by product emulsion family and finishing format.[9] A planning horizon of 12 weeks is used since this is the period over which a weekly, item level schedule is considered necessary to ensure all required products will be sensitized as scheduled. Outside of this 12 weeks, the system automatically plans and updates monthly production based on forecasts. Inside of this 12 weeks, all planning changes require manual intervention by wide roll planners. Manual intervention is considered necessary due to the need to consider multiple uncertainties that the OPAL system is not designed to incorporate such as the actual rate of wide roll test release. Primarily, wide roll planners compare the updated finishing demand forecast for each individual wide roll product to its existing wide roll inventory level. At the point where the forward weeks of supply drops below a designed minimum level of projected inventory, a wide roll planner will schedule a wide roll sensitizing "event" or production batch. Since these changes are considered outside the

---

[9] ibid., page 37.

lead time of the component suppliers, they are believed to cause minimal disruption to production. The appropriateness of this belief will be explored later in Chapter 3.2.

Inside the 12 week planning horizon, the first five weeks (current + four) are considered fixed. When a particular week of planned production passes within this "frozen" zone, changes can no longer be made by wide roll planners "arbitrarily" since they would require action within the average lead times of the component suppliers. Changing the component supply schedule within the manufacturing lead time of the components causes significant disruption and cost due to overtime due to expedited production, excessive waste due to sub-optimal lot sizing, and poor capacity utilization due to inadequate load leveling. If a change is necessary to prevent a wide roll stockout or customer service impact, the wide roll planner will circulate a form requesting a change in the fixed zone which must be signed by the manager of the sensitizing unit, among others.

2.4 Sources of Variability in Fit-for-Use Wide Roll

A number of factors are seen as causes which necessarily precipitate changes to the wide roll sensitizing production schedule. These factors can be divided into the following four categories: component supply variability, sensitizing process variability, wide roll test variability, and demand forecast variability. Although this thesis focuses on the analysis and treatment of process and test variability, an explanation of each category of variation is helpful in understanding the operation.

A "sawtooth" diagram provides a good frame for describing the macro sources of variability. As depicted in Figure 4 the left-hand vertical side of any individual "tooth" represents a sensitizing event and the target footage for that event. At a constant finishing rate, wide roll inventory represents a specific amount of footage. The right-hand sloped side of the "tooth" represents depletion of the wide roll inventory by the downstream finishing operation. Ideally with no variation in production or usage (and 0 test time,) the new sensitizing event would occur at the exact moment that the available footage reached zero. However, the existence of variation requires that some safety stock be maintained to avoid stockouts.

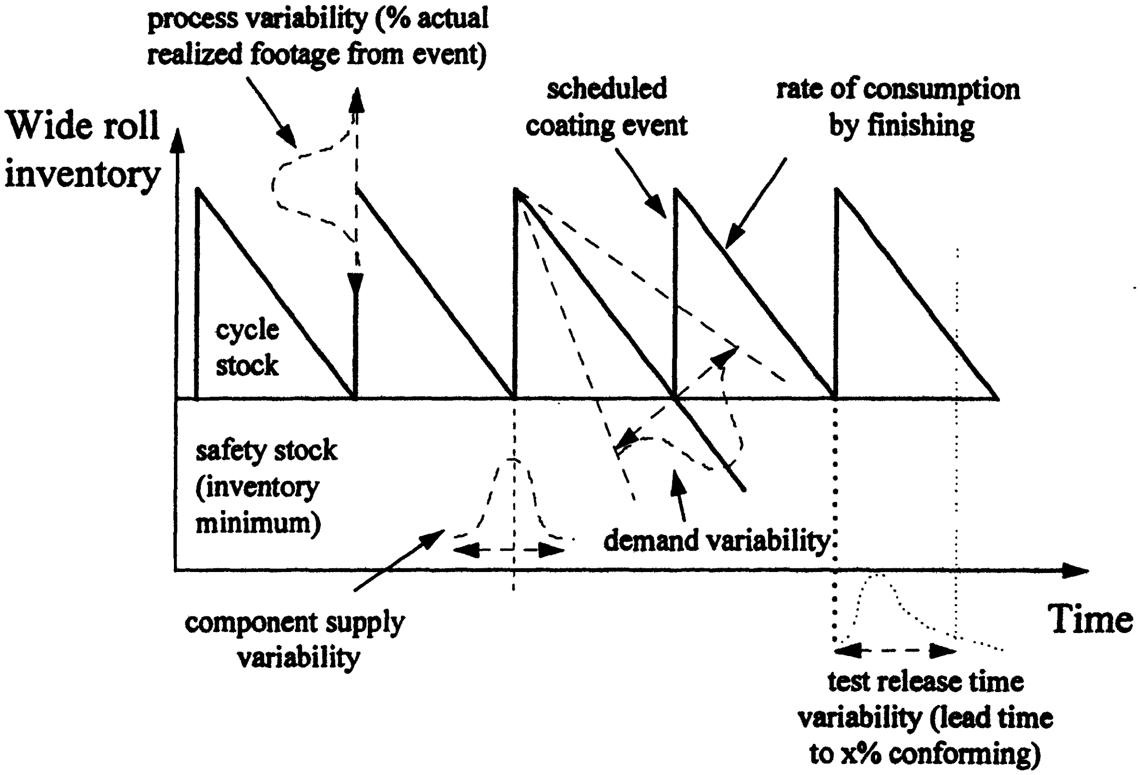


Figure 4: Sources of variability in fit-for-use sensitized wide roll quantity

Two sources of variability were not analyzed in this work: supply and demand variability. Component supply variability refers to uncertainty in the availability of fit-for-use emulsion and roll support for the sensitizing operation. Although not studied in this thesis, this is a source of change to the sensitizing schedule due to the relatively high utilization of the component manufacturing equipment. Demand forecast variability refers not to variation in demand specifically, but uncertainty in the accurate prediction of fluctuating demand. The sensitizing operation is scheduled based on a finishing forecast and inaccuracies in this forecast require safety stocks for buffering. Of these two sources of variability, demand variability is by far more significant in terms of disruption to the sensitizing schedule.

The source of variation studied most thoroughly in this thesis is sensitizing process variability. This can take the form of day-to-day common-cause yield variation but can also occur as significant, uncommon-cause yield loss. The latter is the result of what Kodak refers to as an incident failure during a sensitizing event. An incident failure situation refers to an infrequent incident at the sensitizing operation which requires the run to be aborted or significant emulsion and support to be wasted as a result. In either case, the end result is a significant shortfall in footage that cannot be characterized as part of the normal distribution of outcomes.

From the limited analysis conducted by the author into the magnitude and impact of demand variability, it would appear that this source is more disruptive to the sensitizing schedule than process variability. This is in part a result not only of demand's higher standard deviation but the fact that demand can vary both in quantity and time. Process variability manifests primarily in quantity, whereas the start time of an event does not vary as significantly from when it was originally scheduled. Knowing when a sensitizing event will occur, a wide roll planner can be reasonably confident that some good product will result from the event. Even if there is a shortfall in footage from the event, that which is produced to specification can be used to satisfy demand until an adjustment to the future sensitizing schedule can be made.

Although demand variability causes more disruption to the sensitizing schedule than process variability, Kodak directed the author to focus on process variability. This was due primarily to the fact that most felt there was more opportunity for understanding and improving the response to process variability than for demand variability. Demand variability comes from outside the CFM Flow, and therefore individuals inside the CFM Flow have limited control over it.

With regard to incident failures, the planning system implicitly plans as if these don't occur, even though they occur at a striking frequency. Data to support this supposition will be provided in Chapters 3 and 4. Because products are scheduled when they are needed, an incident failure creates an unplanned situation. When an incident failure is discovered either at the machine or after testing, the planning team must create room in the near-term schedule in order to fit the rescheduled event. Not only is the timing for this typically less than the lead time of the components but it creates a "domino" scheduling effect on other products that must be rescheduled to make way for the new event. These new events many times must occur within the fixed zone of the schedule, discussed in detail in Chapter 3.2. There is definite cost to this practice and it, at the least, keeps the flow from making significant reductions in upstream inventories due to the unreliability of the schedule. The near-term schedule disruption caused by incident failures is similar to that created by non-standard downtime[10] (NSDT) on the machine in that each creates an immediate unexpected situation. The usual effect is that the time to produce a certain product is longer than what the safety factors allow. Undedicated capacity in each week's schedule can accommodate a considerable amount of these extended runtimes, but when it is extreme, it can cause one week's schedule to spill into the next week. This then creates the need to reprioritize the scheduling of many events.

In the case of common cause yield variation, there is the temptation to make changes in the plan out beyond the fixed zone as a result of each event's outcome whether in control or not. This practice also limits the extent to which uncertainty passed upstream to raw material suppliers can be dampened by inventory management. Part of the policy proposed by this thesis will address when changes should and should not be made and what safety stock levels are necessary to allow the planning team this confidence.

---

[10] The sensitizing schedule includes some undedicated capacity to allow for standard downtime on the machine such as would be required standard product changeovers and standard quality checks at the beginning of sensitizing events. Non-standard downtime refers to that downtime on the machine which is the result of unexpected occurrences such as significant quality problems or an excessively long product changeover. This non-standard downtime shifts the timing of all subsequent scheduled events and therefore requires the schedule to be updated.

Test time and test yield variation (referred to collectively as test variability) are the other sources of variability which have a significant impact on the sensitizing schedule. The product staff tries to qualify just-sensitized wide roll promptly for use by finishing. However, this work must be coordinated with the other priorities of the product staff such as work on new products, improvements on existing products, and trial runs. The disconnect in the scheduling process is that the sensitizing of wide roll is planned and scheduled but it is fit-for-use wide roll that is needed by finishing. Due to the wide variability in test time and yield, wide roll planners at times feel compelled to reschedule new events for products that have not made it out of testing in a timely fashion. Test variability will be discussed in detail in Chapter 4.3. This thesis will also respond to the need for statistically-based decision tools around when events should be rescheduled and when safety lead time and safety stock should be adjusted to minimize the need for unnecessary rescheduling and unreasonable wide roll inventories.

3. General Findings and Analysis

3.1 The schedule loading disparity or "scheduling bow wave"

The term "scheduling bow wave" and the concept it represents were new to the author when he arrived at Kodak for the internship and do not seem to pervade planning and scheduling culture as a whole. (The scheduling bow wave refers to a machine production schedule with a higher planned utilization in the near future than in the distant future. A further description for and the causes of this phenomena for the Kodak CFM Flow will be given in the remainder of this chapter.) The author found no other reference to this term or phenomenon in any published literature and only one reference in unpublished company internal literature. An instruction program entitled "Supply Chain Analysis- Managing Uncertainty" created by Greg Kruger of Hewlett Packard (HP), Colorado Springs, CO was the only non-Kodak source describing a "perpetual near-term wave" and "problems associated with running a bow wave."[11] Through correspondence with Mr. Kruger, the author learned that HP's bow wave was caused by their

> "planning organization intentionally loading their systems with build plans higher than their real expectations for customer demand. The reason planing did this was to create a buffer of extra inventory to handle the inevitable uncertainty of what demand would be." [12]

As mentioned, the author found no reference to the scheduling concept implied by the term bow wave. However, from this point forward, the thesis author will use the term "schedule loading disparity" (or just "disparity" when close in reference to "schedule loading disparity") to describe the bow wave. Although this new term is not fully descriptive of the bow wave phenomena, the reader is asked to associate this term with what the bow wave term represents.

The HP schedule loading disparity differs from that experienced by the Kodak CFM Flow in one major aspect: the HP planning organization uses the disparity intentionally,

---

[11] Kruger, Greg. "Supply Chain Analysis- Managing Uncertainty." Hewlett-Packard publication, 7/17/96.

[12] Kruger, Greg. Electronic mail sent to author on 3/31/97.

whereas the Kodak disparity is a result of not understanding and properly accommodating the variability that impacts the sensitizing operation. This will be explained in further detail in Chapter 3.1. However, whether it exists intentionally or unintentionally, a schedule loading disparity causes problems to the organization. In his instruction program, Mr. Kruger lists distrust between planning & procurement and suboptimal inventory levels as the most significant problems created by their schedule loading disparity. They have realized the inadequacy of this policy and have moved to a statistically-based scheduling policy, similar to what is being used by Kodak CFM Flow, and what this thesis intends to improve.

Figure 5 provides a qualitative representation of Kodak's schedule loading disparity. The shape of the curve implies the continual heavy front loading in a schedule which decreases over future time.

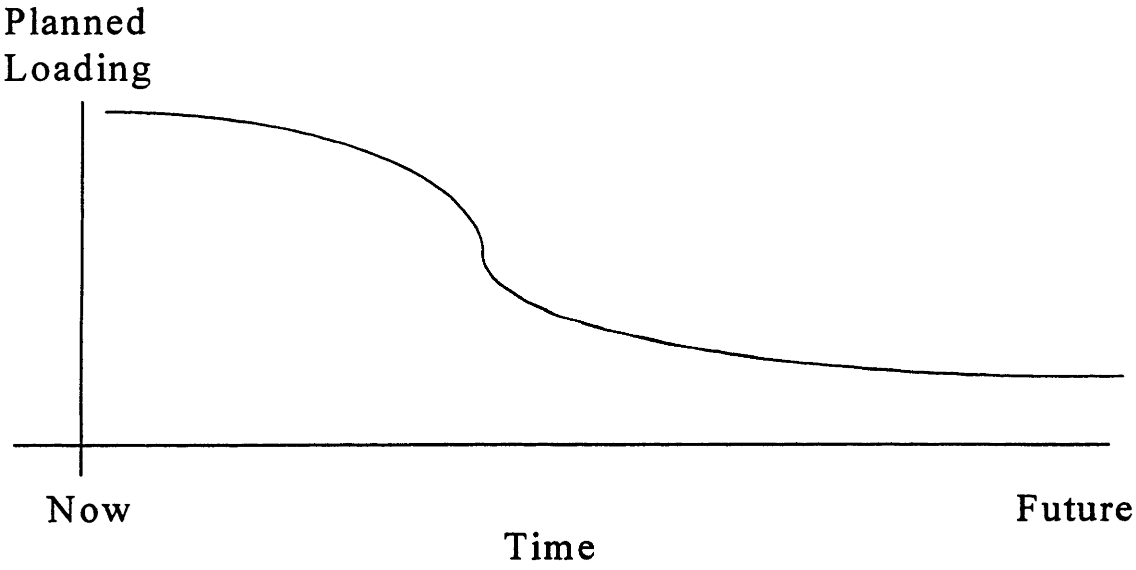


Figure 5: Schedule loading disparity or "scheduling bow wave"

For the purposes here, the author will only deal with the schedule loading disparity as it relates to manufacturing planning and scheduling, but the concepts are transferable to any set of planned and scheduled activities.

The fundamental root cause for a schedule loading disparity as described is the difference between what an entity predicts it will accomplish and how long it will take, and, what it actually does accomplish and how long it actually does take. This description is at the heart of the need to understand the true performance variability and bias in any plan or schedule. The projected plan determines resource allocation, short-term capital decisions, maintenance schedules, and a host of other activities. Disrupting these after an intention or commitment to execute is costly and frankly demotivating to those involved. Future plans should reflect past performance accurately and should not be an unrealistic representation of anticipated learning or assume variability that is lower than what actually exists. An understanding of the nature of the difference between anticipated and demonstrated performance is critical to making plans that are both feasible and cost-effective.[13] One study of rationality in expected performance for production stated:

> The management of the firms have both preference for and are personally committed to a higher production...In their attempt to predict the future production, the management will assume normal operating conditions and does not take account of unusual conditions such as machine breakdown, delivery delays...which lower future production...The "over optimism" bias is furthermore hypothesized to increase with the uncertainty of production measured by its variance.[14]

The last sentence above seems appropriate to the CFM Flow given the relatively high frequency of incident failures and the significant common cause variability. In classical capacity planning, one does not make allowances for "all or nothing" yield loss and usually underestimates the inherent variability. As production continues, it seems natural that expectations for successful production will be overly optimistic and result in a bow wave.

---

[13] An example of the lack of understanding by an organization experiencing a scheduling bow wave is the tendency to conclude that although the plan may seem infeasible over the next x number of time periods, once the organization gets beyond this, the plan should be feasible. Without fixing the root causes of the bow wave though, this improvement in schedule feasibility will not occur.

[14] Madsen, Jakob Brochner. "Test of rationality versus an 'over optimist' bias." Journal of Economic Psychology, 15 (1994) 587-599.

3.1.1 Root causes of the schedule loading disparity

In a discussion early in the internship with a material supply manager about the drivers of the schedule loading disparity, the manager mentioned four root causes:

1. Product variation- occurs when at least one of the components, usually an emulsion layer, is not performing well upon sensitizing. This problem is discovered through testing during the initial stages of the production run and usually results in an aborted run (i.e. little or no yield.)
2. Process variation- this can take the form of minor variation as in subtle variations in pump speed or significant variation as in air entrainment in a liquid delivery system depositing bubbles onto the wide roll. The latter most likely results in an unplanned stop of the sensitizing machine to allow liquid lines to be purged of air. The act of shutting down and starting up the machine consumes a fair amount of emulsion and support which would otherwise be transformed into sensitized wide roll.
3. Wide rolls found by testing to be unusable- this quantity, referred to as shrink, is wide roll that was not scrapped at the sensitizing machine but has failed post-production qualification.
4. Timing of disposition of wide roll, the quality of which is uncertain- this is variation in the testing time for determining the ultimate disposition of sensitized wide roll.

This thesis combines product and process variation since their existence isn't discovered until sensitizing begins and since they have the same effect of causing a shortfall in yield for a sensitizing event. Wide rolls found by testing to be unusable and timing of wide roll disposition have also been combined into test variation. The difficulties of dealing with uncertainty in both quantity and time will be addressed later in the thesis. Although not mentioned during the interview with the supply manager, there are also other causes of the schedule loading disparity:

5. Demand variability- as mentioned earlier, this is essentially forecast accuracy. It must be included as a root cause since it can result in unanticipated volume being placed in the near-term sensitizing schedule.
6. Sensitizing bias- this represents the difference between the quantity of wide roll that is intended to result from a certain quantity of components with no variation and the quantity of wide roll that actually does result. If the CFM Flow runs a continual negative bias, then it will forever be needing to make up the difference between the target footage and the actual long-term mean footage.
7. Demand bias- analogous to sensitizing bias in that it represents the long-run average difference between the predicted demand and the actual demand. A continual negative demand bias will also require near-term "overdrive."

3.1.2 The schedule loading disparity confirmed with data

Although sensitizing capacity plans developed by the capacity planner appeared to show a schedule loading disparity over the future 12 weeks, the author sought to determine the extent of its presence in weekly schedules. A technique developed by the thesis author used the weekly twelve-week sensitizing production schedules from 2/28/96 to 10/10/96 as inputs. Week 20 through week 35 had complete data for each of the twelve weeks, while the twelve weeks immediately prior to week 20 and the six weeks immediately after week 35 had partial data. Figure 6 is a subset of the entire data set showing how the data was handled.

Week of Schedule Creation	Date of Schedule Creation	Week in future for which production is scheduled											
		20	21	22	23	24	25	26	27	28	29	30	31
9	2/28	74											
10	3/5	51	112										
11	3/14	129	113	114									
12	3/21	100	91	114	123								
13	3/28	84	101	113	103	73							
14	4/4	96	101	116	124	99	104						
15	4/11	117	116	113	142	125	107	107					
16	4/18	113	107	116	151	145	89	133	67				
17	4/25	113	100	115	149	146	89	125	71	110			
18	5/2	118	140	119	157	147	88	137	70	134	78		
19	5/9	145	95	119	124	143	88	135	71	137	99	96	
20	5/16	145	102	118	122	147	89	134	73	134	126	82	117

Each value represents the planned weekly machine hours created on the day shown in left-hand column for the production weeks shown along the row heading above

Figure 6: Weekly production hours planned

For example, at the start of production week 20 (the week of 5/16), there was an estimate for each of the twelve future production weeks including week 20 (outlined row.) Also in each of the previous eleven weeks there was an estimate of the production requirements for production week 20 (outlined column.) Taking the average of upper-left to lower-right diagonal across the entire set of twelve-week data yields average planned loading by week in the future. For example, for the data set shown in Figure 6, the mean of the values making up the top diagonal (74, 112, 114, 123, 73, 104, 107, 67, 110, 78, 96, 117) yields the mean planned loading for week 12 of the schedule. The plot of the mean planned loading for each of the twelve weeks scheduled in shown as Figure 7.

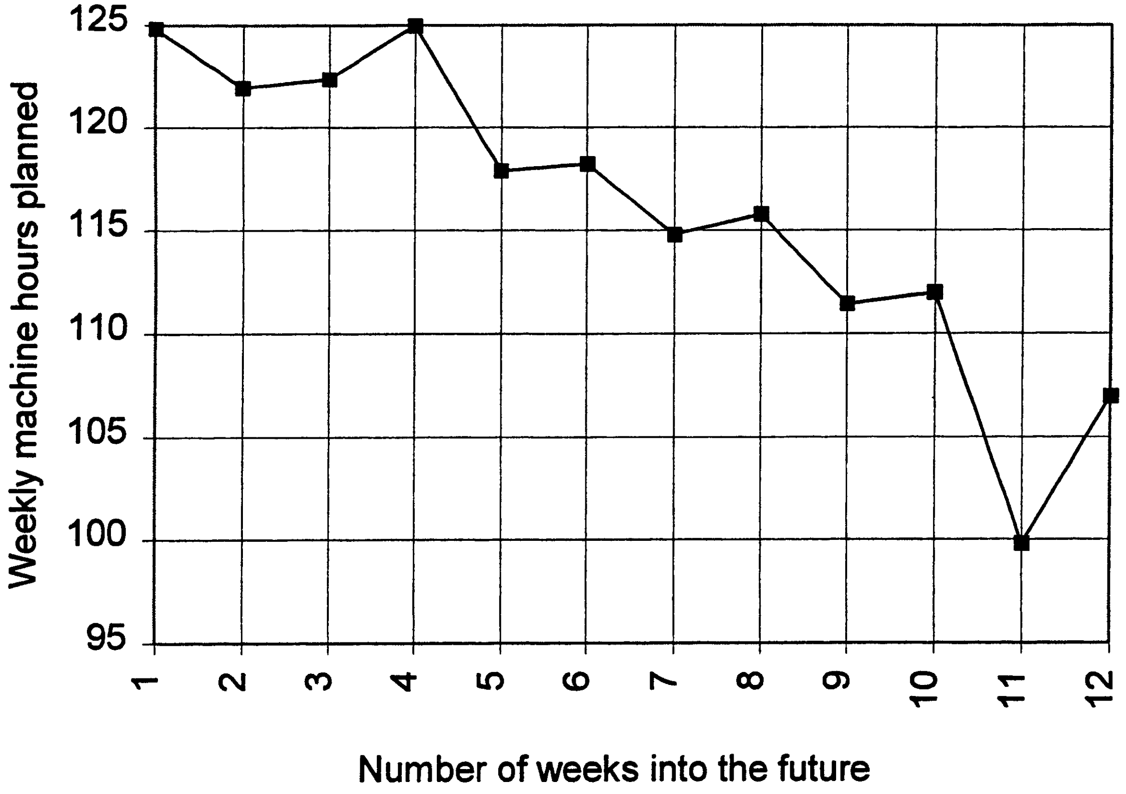


Figure 7: Average of sensitizing machine weekly hours planned vs. number of weeks into the future (2/96 - 9/96)

This can be compared to what might be considered a perfect schedule shown as Figure 8.

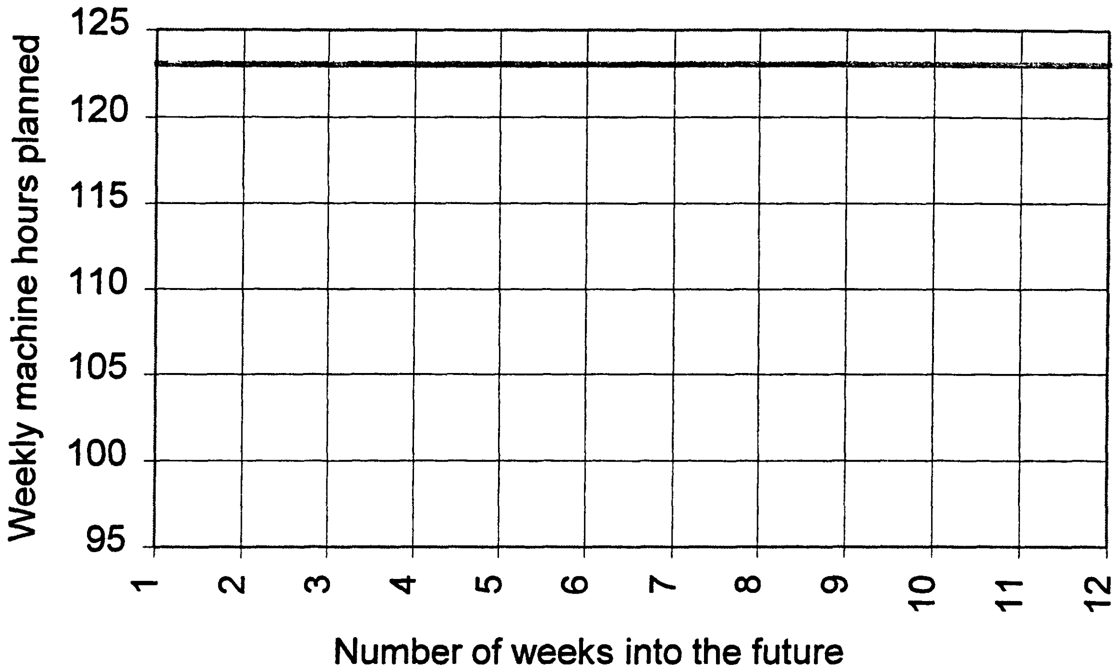


Figure 8: Perfect schedule for sensitizing machine average weekly hours planned vs. number of weeks into the future

Here the schedule appears as a horizontal line between 120 and 125 machine hours planned per week. This is perfect due to the lack of a schedule loading disparity between the near-term and the long-term. In the perfect case, planners have made necessary and sufficient accommodation for all sources of variability in their estimates for downtime, event duration, and overtime. Knowing that their assessment of actual future requirements is correct, the organization can make a low-cost allocation of resources significantly ahead of when these resources will be needed. The thesis author placed the line at the level of 123 hours since this is the mean of the hours planned for weeks one through four in Figure 7, the mostly likely representation of the true hours spent on the machine.

Returning to Figure 7, one sees a progression in weekly machine hours planned from about 100 - 105 in week 12 to roughly 120 - 125 in week 1. So this would indicate that over the period this data represents, each production week was increased on average almost a full day of production as it moved across the 12 week horizon. To further substantiate the existence of the bow wave, the author calculated that approximately 75% of the individual production weeks had negative slopes in hours/week when considered from week 1 to week 12 of the schedule.

The increase in the average weekly hours planned from 11 to 12 weeks in the future seems not to agree with what is actually occurring. If one looks at the actual data used to generate the curve, removing a 188 hour 12th week projection for week 21 reduces the planned hours estimate for week 12 from 107 to 103. This seems reasonable since there are only 168 hours in the calendar week. Removing a 146 hour 12th week projection for week 24 reduces the planned hours estimate for week 12 further from 103 to 101. It is not uncommon for planners to designate excessive and unreasonable production in the far end of the schedule if for no other reason than to tag the suspected need for sensitizing events on particular products. The planners' intend to make the timing more reasonable as the actual production date approaches. Although these unreasonable production plans may be outside the lead time of the component suppliers, it is unacceptable in that it makes resource and capacity allocation decisions suboptimal.

Further evidence of this practice of making an unreasonable schedule in the far weeks of the 12 week sensitizing schedule is provided by Figure 9. Here the standard deviation of planned machine hours is shown by number of weeks in the future. Each data point is the standard deviation of the set of differences between the planned production of the future week indicated and the production for that week as seen one week earlier.

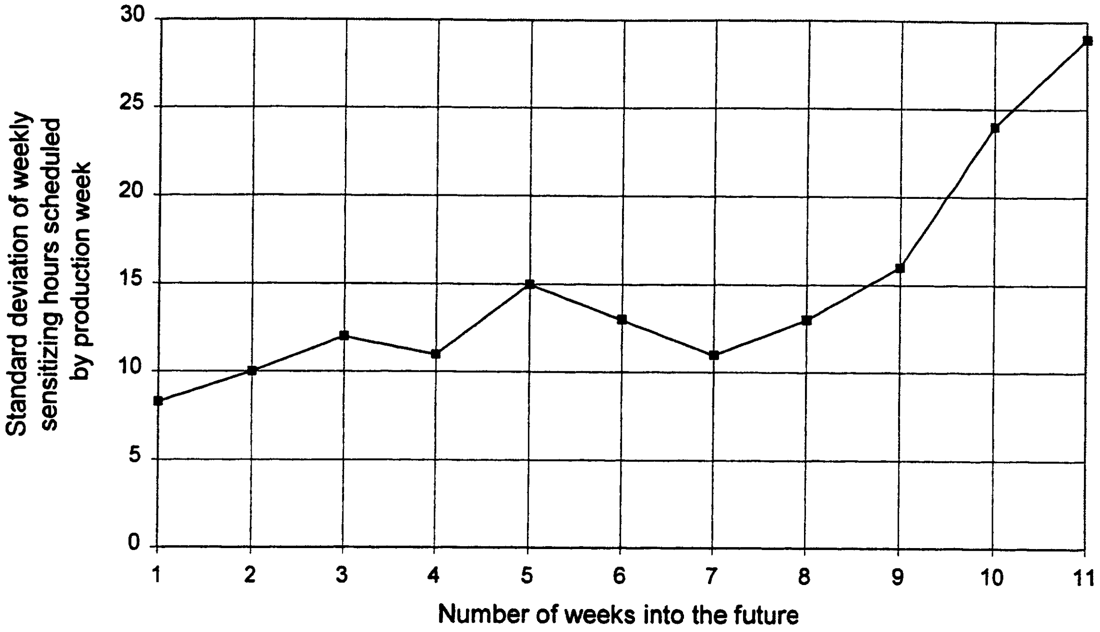


Figure 9: Standard deviation of weekly sensitizing hours scheduled by production week vs. number of weeks into the future

For example, from Figure 6, one sees that for production week 20, the difference between the 12 weeks out and 11 weeks out schedule is 23 machine hours (74 - 51.) Taking the standard deviation of set of 12 - 11 week differences for all production weeks yields a value of 29, shown for week 11 in Figure 9.

Three characteristics of this plot are noteworthy.[15] First, there is significant variation (as defined in the previous paragraph) out beyond nine weeks in the future. This reinforces the earlier suggestion that unreasonable production is planned frequently at the outer limit of the 12 week planning horizon, and corrected in later weeks. Second, there is a local maximum in the standard deviation at a point five weeks into the future, the outer limit of the fixed zone. This indicates a spike in planning activity at that point as planners attempt to resolve final scheduling problems before the schedule is fixed and they must

---

[15] Note that the author did not perform analysis on this data to determine which of these points were statistically different.

leave it as designed. (The schedule is fixed at this point so as to minimize the scheduling disruption to emulsion and roll support suppliers. The scheduling and production lead time of these suppliers is roughly five weeks, so changes to the sensitizing schedule would cause changes in activities already set in motion. The fixed zone will be explained in further detail in Chapter 3.2.) Third, the standard deviation continues to decrease as one moves from the point five weeks out towards the production week one week in the future. This indicates that even within the fixed zone, some changes are necessary. However, there is recognition of the increase in cost as those changes are made closer and closer to the actual production date as estimated by financial analysts within the CFM Flow and shown in Figure 10.

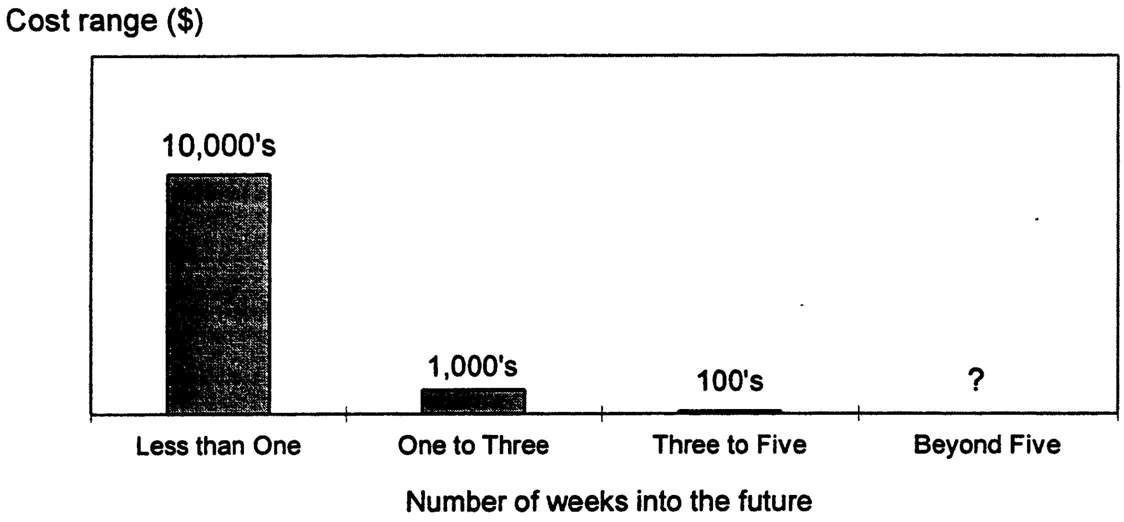


Figure 10: Cost Range ($) for schedule changes vs. Number of weeks into the future

These are costs within the CFM Flow and include such requirements as simple replanning for changes at outer limit of the fixed zone to expediting new emulsion batches for changes one to two weeks before the scheduled sensitizing date. The cost range is uncertain for changes beyond five weeks in the future since this would impact suppliers to emulsion and roll support. Reducing the schedule changes that impact raw material suppliers is seen as a opportunity by the CFM Flow for reducing total supply chain cost.

Reducing the number of requirement changes affecting suppliers by enlarging the sensitizing fixed zone will be discussed further in Chapter 3.2.

When initially confronted with the schedule loading disparity, the thesis author was intrigued but uncertain as to the reason for deep concern. As one supply manager roughly stated, the capacity and inventory planners know they have to do a lot of replanning and additional loading of the near-term schedule, but they still manage to get the products manufactured and meet the customer requirements. However, there are several concerns with adopting this sense of security. The most critical of these is the degree to which overtime on weekends was used to complete production scheduled for the five-day week. As a planned production date approaches the real date, rework and incremental volume are added to the schedule. Provided this extra production did not require more time than was available with weekends and some lighter production weeks, products would be assured of making it through the process at a reliable rate. One must remember that the performance of the sensitizing machine is a distribution such that scheduled production is completed some weeks and runs over in other weeks. Provided there is available capacity, the probability of successfully completing any scheduled production run within for instance one month from the initial production date is very high. As the available capacity is reduced, the probability of successful completion within a particular timeframe drops and the timeframe necessary to ensure successful completion of scheduled production increases. A concern with this is that the sensitizing machine went from five-day to seven-day schedule in late 1996 with the intention of adding more volume to the schedule. If adequate weighting is not given to demonstrated performance in assessing future production capabilities, then customer service could suffer due to the loss of unscheduled weekend time for work overflow.

Another flaw with the confidence in demonstrated schedule completion at some aggregated timeframe is the continued push for reduced cycle time and unit cost in production. Reduced cycle time will require reducing the inventory that serves to dampen the impact of unsuccessful sensitizing on the finishing operation. It will be less and less allowable to push some products back to provide machine time to rerun products that suffered low yield. Cost reduction initiatives will continue to make "excess" capacity unattractive, thus greatly eliminating discretionary machine time for rework.

The leaders of the CFM Flow realize that the planning and scheduling methods currently employed are costly and have been taking steps to improve these methods. One step taken has been simply to reduce the resources dedicated to scheduling sensitizing. The CFM Flow enacted this change in 1996, independent of the work of this thesis, and found there was no discernible impact to customer service, inventory, or unit cost. This result emphasizes the point that many of the schedule changes being made had added no value. Another step being taken is the addition of emulsion capacity which when in place will reduce emulsion lead-time and the impact of emulsion supply variability on the sensitizing schedule. Other steps are being taken to make sensitizing data more accessible and manageable so that performance in capacity planning and product scheduling can be tracked more easily and policy adjustments made as necessary.

Another very significant change undertaken by the CFM Flow reflects their understanding of the desirability of a flat utilization schedule. In late 1996, the capacity manager made significant adjustments to the sensitizing capacity plan to provide undedicated capacity as necessary to meet wide roll requirements with less schedule changes. The impact of these adjustments on schedule loading disparity will be shown in Chapter 4.4.

3.2 Master production schedule stability

3.2.1 Measurement of master production schedule stability in the CFM Flow

It might not be evident why an overly optimistic expectation would lead to a schedule loading disparity. A stable loading disparity (one that does not grow in size indefinitely) requires there to be some undedicated capacity on the operation being scheduled. The period studied by the author did in fact have this capacity in the form of initially-unscheduled weekends. As initially-unscheduled weekends "approached" the present, there was increasing likelihood that they would be needed for production in order to maintain customer service. At the point where this capacity was consumed in producing to meet new demand or remaking low-yield product, a "domino effect" of shuffling production began. Prioritization had to be made across the multiple products sharing the machine to determine the sequence of running that minimized cost and jeopardy of stockout. When an unforeseen addition had to be made to the near-term schedule and there was no remaining capacity, machine time had to be created by shifting out other scheduled products. These could not be placed simply on the end of the schedule and therefore, in many cases, needed to take the place of other scheduled products. When capacity was highly utilized, these perturbations rippled across products and across time to a point that the root causes of subsequent schedule changes were not easily traceable.

Although the continual rescheduling of schedules was considered by most involved to be suboptimal, changing this practice lacked strong support. This seemed due primarily to poor understanding of the relative impact of the various forms of variability and the costs of rescheduling. It became evident to the author early in the bow wave study that a "schedule disruption metric" would be very valuable in showing which schedule changes were most disruptive and in verifying that process variability was a significant driver of change.

The simplest disruption metric one might create is the pure number of master production schedule (MPS) changes per week. Building on this, one might include the size of the change in quantity of material or machine time affected, whether the product is being shifted in or out in time, and how far in the future the change is occurring. In regards to when the change is occurring, a factor which reflects changes within its cumulative lead time (CLT) freeze zone (identical to fixed zone, defined earlier) different than changes outside this freeze zone would aid in its accuracy. It would also be helpful to include a measure of overall machine utilization associated with the change since this largely will determine the magnitude of the resulting "domino effect." This need may not be that great though since one would expect a significant shift into a highly utilized week to force other changes which would also be recorded. Although one can see easily the directional impact of these various change characteristics, arriving at magnitudes which reflect the overall disruption of the change is much more difficult.

The author searched literature on schedule disruption and found only one reference to a quantitative measure of disruption. Sridharan, Berry, and Udayabhanu [16] developed a measure for schedule instability in the interest of comparing three important decision variables for MPS management in a rolling-horizon framework: the MPS freeze method, the MPS freeze fraction, and the MPS planning horizon length.

Their equation takes into account the following three variables: the number of weeks into the future that the change is occurring, the size of the change (how many units are being added or subtracted), and a weighting factor "that applies decreasing weights to schedule changes in periods of increasing distance in the future."

Although Sridharan, Berry, and Udayabhanu do not supply a derivation with their paper, the thesis author will create a derivation adapted to the CFM Flow planning system, using Figure 11 as an aid.

---

[16] Sridharan, V., Berry, W.L., & Udayabhanu, V. "Measuring master production schedule stability under rolling planning horizons." Decision Sciences, 19, no. 1 (1988): 147-166.

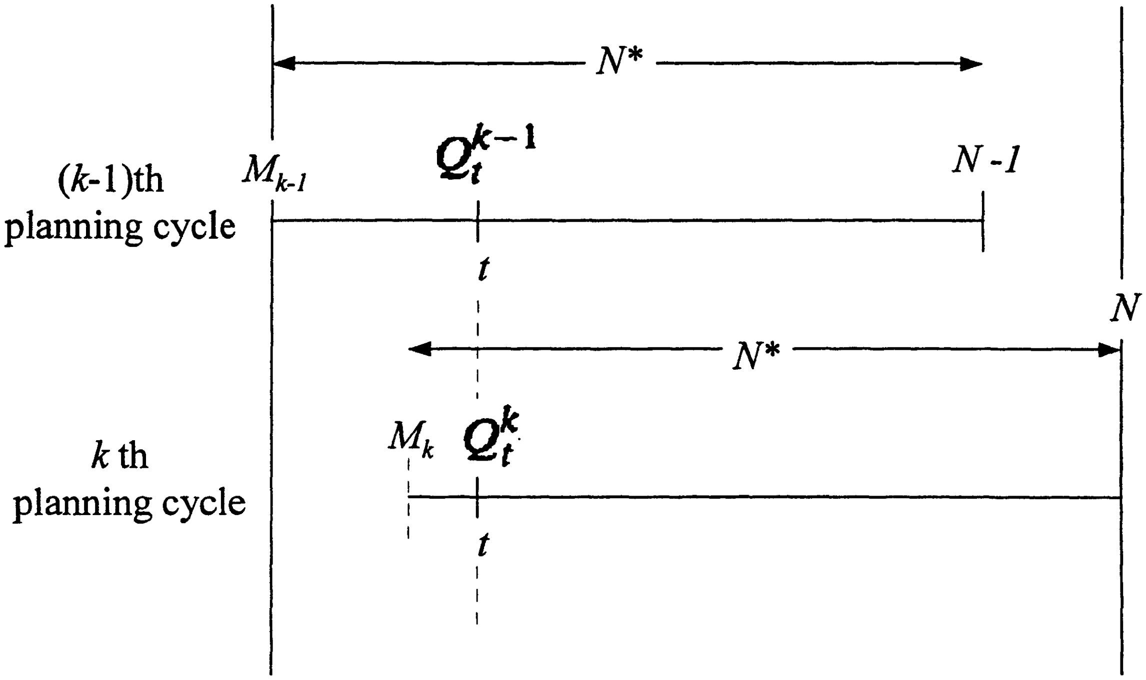


Figure 11: Depiction of multiple planning cycles in a rolling production schedule

The end result should be a relationship that quantifies system disruption created by changes to the production schedule. One can define a production schedule change simply as any alteration in quantity or timing in any period of a previously-established schedule. The Flow uses a planning cycle frequency of once per week and a master production schedule length N* = 12 weeks. The variable k will designate the specific planning cycle in question, and M_k the first period of planning cycle k. The variable t will be defined as the specific time period of the quantity change in question such that a quantity change x weeks from the current week will be designated as occurring in time period t = x. Let Q_t^k be the quantity of a specific product scheduled to be run in time period t and planning cycle k. A weighting parameter α ($0 < \alpha < 1$) will be used in combination with the quantity $t - M_k$ to weight quantity changes in the near future more heavily than quantity changes in the distant future. Using the quantity $t - M_k$ as an exponent on α such that it will have a nonlinear effect. (A linear relationship would make schedule changes x/2 weeks in the future twice as disruptive as changes x weeks in the future. In reality, changes become more disruptive and costly in an nonlinear fashion as they are made nearer to the present, and the derived expression must reflect this.)

From Figure 11, one can see an example of comparing a change in quantity Q in period t between planning cycle k and planning cycle $(k - 1)$. The extent of this disruption will be the product of the absolute value of the difference in quantity Q and the weight parameter expressed as $(1 - \alpha)\alpha$, with the second α raised to the exponent $t - M_k$.. In going from planning cycle k to planning cycle $(k - 1)$, the expression will sum these products across all schedule changes (from $t = M_k$ to $M_{k-1} + N - 1$.) As seen in Figure 11, these are the summation limits because the expression only considers the time frame between the first period of the current planning cycle M_k and the remaining part of the current schedule that was part of the schedule in the previous planning cycle k, which is $M_{k-1} + N - 1$. The expression then sums this summation across all planning cycles under consideration. Dividing this value by S = the total number of orders across all planning allows for normalization with respect to the total number of changes and total number of planning cycles. This will yield a single disruption or instability value I which can then be used to track the success of scheduling policy changes in reducing schedule instability.

Combining these as described yields Equation 1, provided by Sridharan, Berry, and Udayabhanu.[17]

$$\textbf{Instability } (I) = \sum_{\forall k>1} \sum_{t=M_k}^{M_{k-1}+N-1} |Q_t^k - Q_t^{k-1}|(1-\alpha)\alpha^{t-M_k}]/S$$

Equation 1: MPS Stability Measure

In this equation, the variables are defined once again as follows:

t = time period of schedule change
Q_t^k= scheduled order quantity for period t during planning cycle k
M_k = beginning period of planning cycle k
N = planning-horizon length
α = weight parameter ($0 < \alpha < 1$)

---

[17] ibid., page 149.

S = total number of orders over all planning cycles
k = number of the planning cycle under consideration

As an example of the use of this expression, suppose a quantity $Q = 100$ of a particular product is scheduled to run in time period $t = 6$ of planning cycle $k = 4$, with the first period of the planning cycle $M_k = 3$. Suppose in the following planning cycle $k = 5$, one finds the scheduled run quantity of this specific product has been reduced to $Q = 50$, still in $t = 6$, with $M_k = 4$. Using a weight parameter $\alpha = 0.5$, one finds that value of instability I to be $\{|50 - 100| * (1 - 0.5)\, 0.5^{(6-4)}\}/1 = 6.25$. Considered in isolation, the value is meaningless, but when compared across different time frames, it provides a relative measure of change in disruption.

In the thesis author's opinion, this instability measure lacks completeness in that it does not force a substantial enough difference in severity based on when the change occurs. The weight parameter α does not create a step change in severity at the edge of the fixed or freeze zone where a step change needs to be to agree with the component lead time restrictions for the CFM Flow.

Given there were no other established instability measures available in published literature, the thesis author proceeded with this measure. In order to have a baseline sample of weekly schedule changes for the sensitizing machine, the author compared weekly sensitizing schedules that listed scheduled production for every week of the 12 week planning horizon. He then recorded all changes in quantity and/or timing. Unfortunately the author did not begin this comparison until production Week 37 of 1996 and only continued it until Week 44. Although recording the changes was relatively simple, determining the apparent reasons for these changes was not. In order to determine the causes for changes, the thesis author had to contact each wide roll planner on a weekly basis to review all schedule changes within each planner's product responsibility.

To associate a measure of disruption with specific causes, the author recorded the number of changes by production week. A value of 0.5 was used for α since, in the thesis author's opinion, it yields a weighting profile that most closely matches the cost breakdown shown in Figure 10. The results of the analysis of the schedule changes for the CFM Flow are shown in Figure 12. By visual inspection, there appears to be little if any correlation between the number of changes and the schedule instability by production week. Some changes are definitely more damaging than others based primarily on the proximity of the affected week to the current production week.

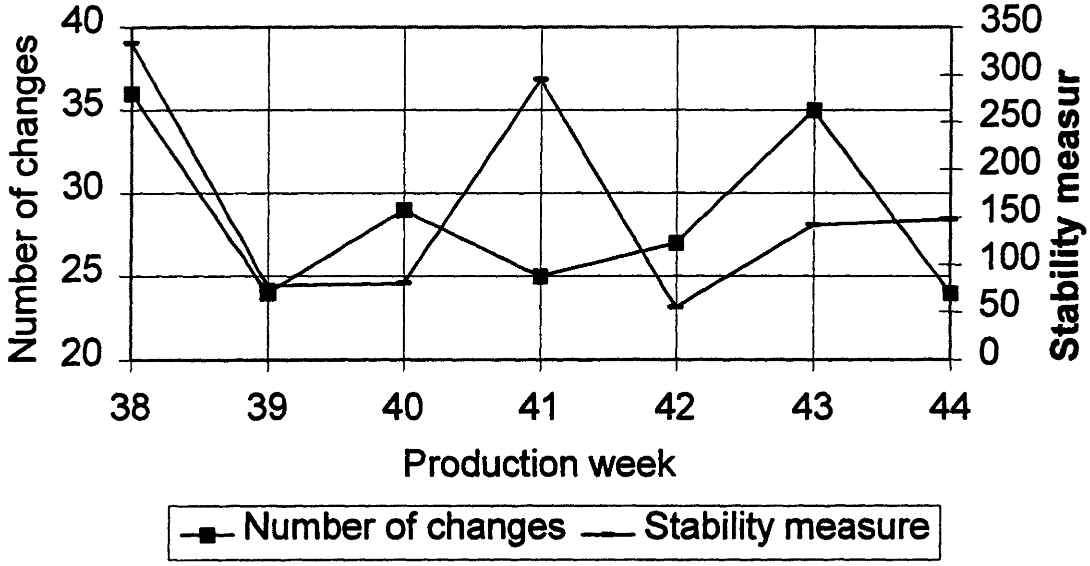


Figure 12: Number of schedule changes and stability measure vs. production week

To tie schedule disruption to the stated reason for each schedule change, the author reduced the multitude of stated reasons for changes to thirteen. Figure 13 shows this set of thirteen reasons as well as the results of the analysis. The five aborted sensitizing events, which are defined as previous sensitizing events that resulted in essentially no usable footage, were the most disruptive on a total and per change basis. Following this reason, there appears to be some correlation between the number of changes and stability measure by stated reason.

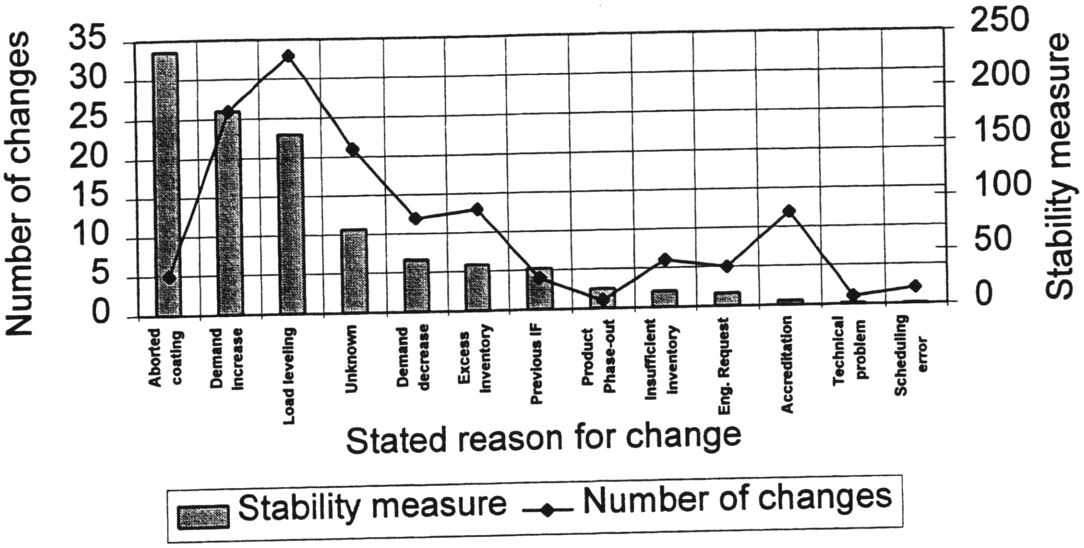


Figure 13: Number of schedule changes and stability measure vs. stated reason for change

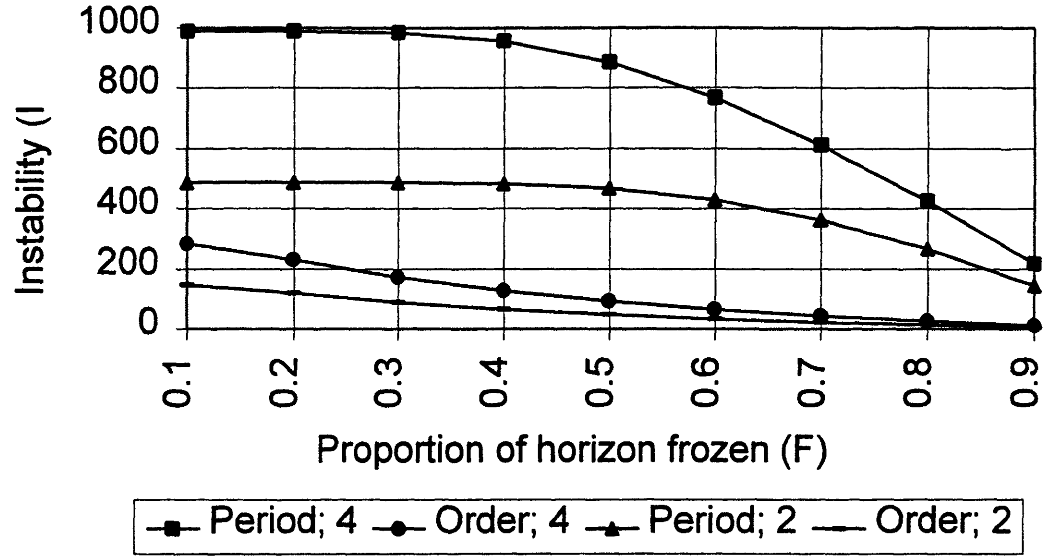
Another noteworthy part of the plot is the high number of changes driven by load leveling. In most cases, this load leveling referred to the need to shift a particular scheduled event out of an overloaded future week into another future week that had ample undedicated processing time. Used properly, schedulers should load level only when first making a schedule. Load leveling allows processes that can handle average demand but not peak demand to continue to fulfill customer requirements. Provided that adequate service can be provided to the customer and the costs associated with holding extra inventory do not exceed the cost of adding additional capacity, load leveling is a well-accepted technique. In the case of the sensitizing machine however, the need to make frequent schedule changes in the interest of load leveling is driven by a combination of poor planning and scheduling policies, very high utilization, and significant variability from multiple sources. Load leveling in this situation exacerbates the schedule loading disparity.

As stated earlier, there are obvious problems with the stability measure used to quantify the impact of the reasons for the changes. However, this provides a good example of how one might go about determining the major and minor drivers of disruption. This data could be kept in a database to evaluate how specific improvements to the scheduling system and reduction in the sources of variability are reducing schedule disruption.

3.2.2 Evaluation of the master production schedule freeze method

The freeze zone or frozen portion of a production schedule refers to that part (extending from the current week to some future week) of the schedule which is considered fixed in regard to quantity and timing of scheduled production runs. The production scheduled to be run within this zone usually can be changed only by manufacturing management approval. The CFM Flow historically has frozen a portion of the planning horizon by set period rather than by order. The five-week fixed zone has been used for all products running on the sensitizing machine without regard to the true time between orders. Sridharan, Berry, and Udayabhanu showed through simulation that period-based freezing produced far less stable schedules relative to order-based freezing. In their paper "Measuring Master Production Schedule Stability Under Rolling Planning Horizons", they compared stability of schedules by freeze method as well as by freeze proportion and planning horizon length.

Using the researchers' simulation-based regression models for instability, the author developed a comparison of period and order-based freeze methods using Kodak's 12 week planning horizon and both a two week and four week sensitizing frequency. The results of this comparison are shown as Figure 14.



The number following the freeze method in the legend of the plot defines the sensitizing frequency in number of weeks between sensitizing events.

Figure 14: Comparison of period and order-based freeze methods by resulting schedule instability

The parameter for the sensitizing frequency enters the regression model by means of a parameter for the number of sensitizing cycles in the 12 week planning horizon. Two to four weeks represents the range of frequencies for a significant number of CFM Flow products. The parameter F, proportion of horizon frozen, is defined as (number of periods frozen)/(planning horizon length) for period-based freezing and as (number of orders frozen)/(number of orders in the planning horizon) for order-based freezing. Given a five-week frozen zone within a 12 week planning horizon, Kodak's freeze proportion is about 0.4. The plot shows that over the entire range of freeze zone proportions, order-based freezing is more stable than period-based freezing. From this one can conclude that the CFM Flow could reduce schedule disruption by freezing sensitizing orders rather than by freezing a specific time period. The author will address this concept once again in the proposed planning policy later in the thesis.

3.2.3 Evaluation of buffering strategy for materials requirement planning system disruption

In addition to looking at the freezing method, the author also chose to evaluate the wide roll planners' strategy for justifying schedule changes and compare it to standard methods established in literature. Chrwan-jyh Ho[18] studied several procedures for dampening materials requirement planning (MRP) system nervousness: static dampening procedure, automatic rescheduling procedure, and cost-based dampening procedure. MRP system nervousness is a commonly-used scheduling term and refers to the disruptive changes to component schedules created by changes in the master production schedule.

In this evaluation, for the static dampening procedure he used the dampening rule "which ignores any reschedule-in message of only one week and any reschedule-out message of less than two weeks."[19] A 'no rescheduling fence' is then established around the original due date to differentiate the significant and insignificant rescheduling messages. Under the automatic rescheduling procedure, all released open orders are rescheduled automatically as the MRP system recommends with exception that no rescheduling is allowed within the minimum lead time necessary for the component suppliers to provide components. Lastly, the cost-based dampening procedure method looks at the cost trade-offs of rescheduling and requires each rescheduling message be economically justified before taking effect. Ho concluded from the experimental results that when the parameters for the 'no rescheduling fence' are selected appropriately, the static dampening procedure method results in the lowest MRP system nervousness. In comparison to the other two methods, the automatic rescheduling procedure creates a system with more disruptions and poorer performance.

---

[18] Ho, Chrwan-Jyh. "Evaluating the impact of operating environments on MRP system nervousness." International Journal of Production Research, 27 no. 7 (1989): 1115-1135.

[19] The term "reschedule-in" refers to a schedule change whereby a quantity of product to be run at a specified time in the future will now be run earlier. The term "reschedule-out" is just the opposite in that a quantity of product to be run at a specified time in the future will now be run earlier.

The Kodak method of rescheduling seems to be a hybrid of the automatic rescheduling procedure and the cost-based dampening procedure. Like the automatic rescheduling procedure, the MRP system automatically reschedules outside the twelve week firm zone. However, rescheduling within this firm zone is only accomplished by manual intervention of the wide roll planners. Like the cost-based dampening procedure, an economic disincentive to rescheduling within the fixed zone has been established so that the instigators of rescheduling are aware of the economic penalties of changes in this zone (see Figure 10.) It is obvious from the large number of one week changes that no form of the static dampening procedure was utilized for scheduling the sensitizing machine. Ho used a simple equation for quantifying MRP nervousness which consisted of taking a summation of weighted reschedule-in notices and weighted reschedule-out notices. A strong argument against this measure would be that one-week changes at the far reaches of the planning horizon cause negligible disruption to the system and therefore should be left to the desire of the wide roll planners concerned. Depending on the discipline applied by the wide roll planners in rescheduling outside the 'minimum lead time', the resulting nervousness could be similar to that created by the relatively-poor performing automatic rescheduling procedure method. One can conclude from this that sensitizing schedule disruption in the CFM Flow could probably be reduced by imposing a static dampening procedure requirement on the magnitude of a desired schedule timing change before it is allowed to occur.

3.3 Pool of Data on Actual Realized Footage to be Studied

3.3.1 Actual Realized Footage vs. Planned Footage

A robust production environment implies that the production process will make the scheduled products reliably. In the case of a film sensitizing operation, wide roll planners' plan and schedule specific lot sizes of wide roll to be sensitized. Ideally this would equate with the amount of fit-for-use wide roll that is made available for the downstream finishing operation. In the case of this operation however, the process is not completely reliable with respect to common cause yield and uncommon cause yield.

Wide roll planners look for the "planned footage" (PF) to be generated, however the "actual realized footage" (ARF) is some fraction of the planned footage. The ARF refers primarily to that amount of wide roll that is not immediately scrapped as it comes off the sensitizing machine. Although there is waste created with each production lot, the material that is wound as wide roll must still pass a testing process to qualify as fit-for-use. This testing process is described in detail in Chapter 4.3. The uncertainty about the ARF and the time to test and pass the wide roll material creates significant disruption in the sensitizing schedule.

Figure 15 shows the ARF vs. the PF for the sensitizing operation from 1/2/96 - 11/27/96. The ARF scale should be read such that 100% ARF means the PF was the actual amount wound off the sensitizing machine as sensitized wide roll. Excluding experimental sensitizing runs, each individual product sensitizing event with PF ≤ 500,000 ft over this period is represented for a total of 606 data points. Seven events > 500,000 ft PF have also been excluded from the graph to maximize visual resolution of those below 500,000 ft PF. The mean and standard deviation for the entire 613 point data set are 94.5% ARF and 24.1% ARF respectively.

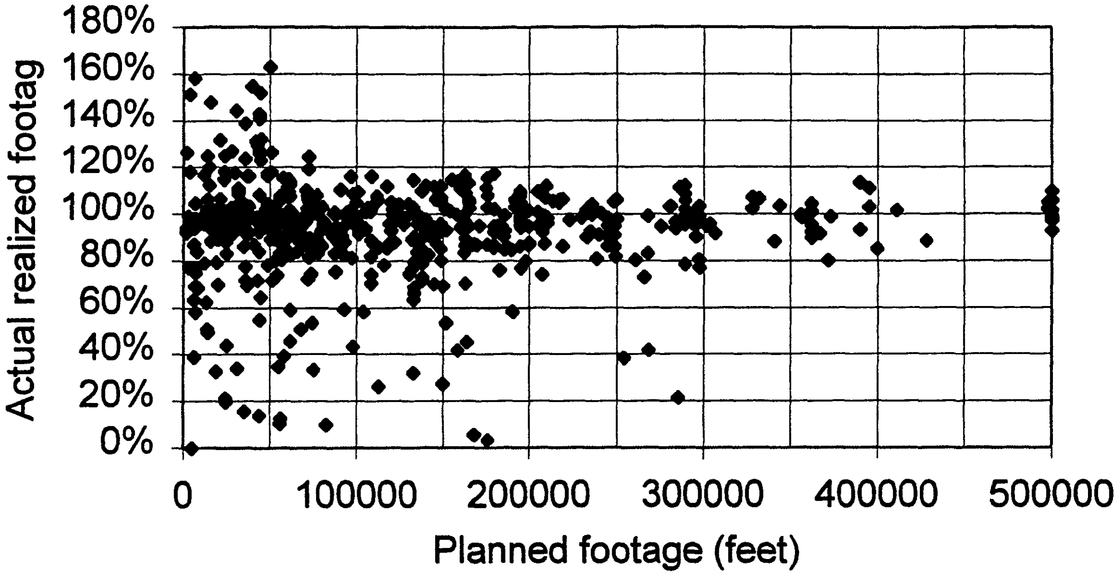


Figure 15: Actual realized footage (%) vs. planned footage for all products sensitized on machine (1/96 - 11/96)

Several interesting points can be made simply by observing the data configuration. First, there is a significant drop-off in the occurrence of ARF > 120% as the PF exceeds 50,000 ft. Second, there appears to be a relatively tight band of ARF outcomes between 80% and 120% for all PF's. Third, there is a significant continued occurrence of ARF < 80% (referred to as incident failures) at least up to a PF of 300,000 ft. The segmentation of outcomes into these three apparently distinct populations as shown in Figure 16 helps considerably in defining planning and scheduling policies for accommodating the outcomes.

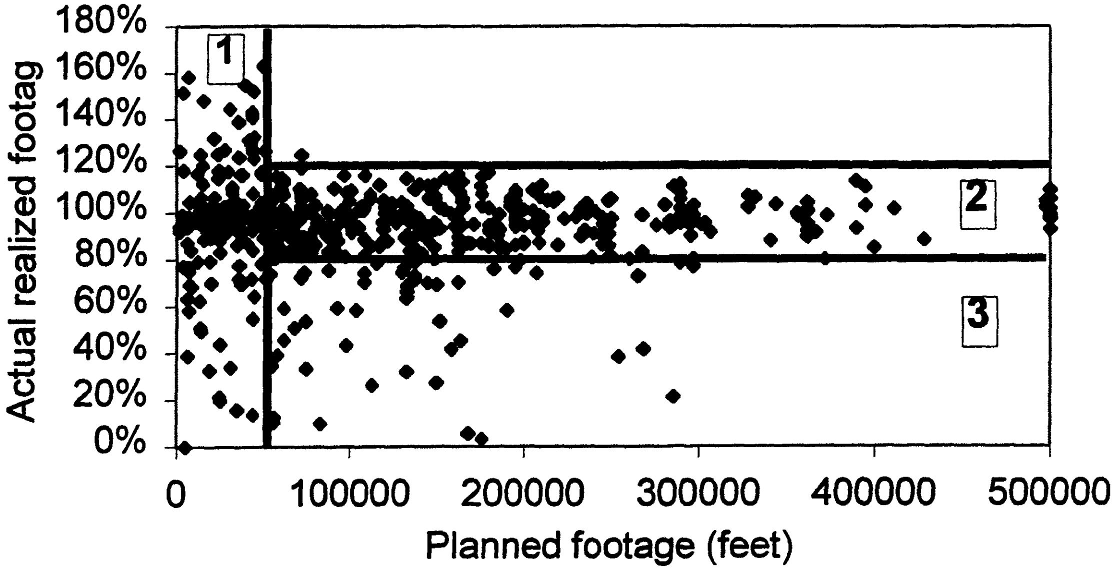


Figure 16: Segmentation of ARF vs. PF data into distinct populations

The mean and standard deviation of the three populations individually are listed in Figure 17. The total number of 603 points in the table are 10 less than the 613 due to the 7 points > 500,000 ft PF and 3 points > 50,000 ft PF which had % ARF > 120%.

Data population	Data set boundaries	Number of points	Mean (% ARF)	Standard deviation (% ARF)
1	≤ 50,000 PF, all % ARF	179	98.9	34.2
2	50,000 ≤ PF ≤ 500,000; 80% ≤ % ARF ≤ 120%	371	97.6	8.5
3	50,000 ≤ PF ≤ 500,000; % ARF ≤ 80%	53	56.1	22.6

Figure 17: Statistical summary of three population data sets

Statistically, there is greater than 99% confidence that data population 1 and 2 are different. Data population 3 is also different from 1 and 2 with better than 99% confidence, however a strict statistical test does not make sense in comparing 3 to 1 and 2 since 3 is fundamentally a different type of distribution.

The most significant of the three populations in terms of schedule disruption is the population # 3, events with PF ≥ 50,000 ft, and % ARF ≤ 80%. Kodak refers to a sensitizing yield result in this category as an incident failure (IF.) Yield loss of this size is very difficult to accommodate, particularly when the sensitizing and component suppliers equipment is highly utilized and when there is pressure to drive down safety stocks of wide roll. This paper will address later the plan for minimizing the impact of these incident failures on the schedule and safety stocks.

The population of ARF's >120% are very interesting but not significant in terms of the impact on the chain. Since they occur on products with very short PF (< 50,000 ft), the magnitude of the excess wide roll created is kept small. It is also noteworthy that excess production causes one to postpone future production runs of the same product. A schedule is disrupted much more significantly when production runs are moved up in time (sooner than previously planned) than when they are moved out in time (later than previously planned.) Products with short PF's tend to sensitize infrequently compared to products with long PF's. Consequently, a significant overrun (ARF % > 120%) or shortfall (ARF % < 80%) on an event can be accommodated with a schedule shift for the next event far out in the schedule or by keeping very minimal safety stock inventory.

There is also good understanding as to what causes these sometimes very significant overruns. Uncommon cause yield is driven primarily by the number of unplanned stops on the machine. To anticipate some probability of an unplanned stop and to ensure that a significant amount of a product will be sensitized properly, product engineers size emulsion batches to allow for some number of stops on the machine. If a stop occurs and one stop was predicted, the ARF should fall roughly in line with the PF. If more stops than predicted occur, the outcome would classify as an incident failure. If however, fewer stops than predicted occur and the PF is small (~ < 50,000 ft), then a significant overrun will occur. The amount of extra component material kitted (withdrawn from storage and collected in preparation for a sensitizing event) for the sensitizing event can be 50% of the amount necessary to reach PF with no waste.

A very fascinating part of this plot is the asymmetrical nature of the ARF beyond PF of 50,000 ft. When, the PF exceeds 50,000 ft, there is adequate production time to feed back information on sensitizing performance to the kitting[20] operation such that preparation of excess components can be avoided. However, if there is a high number of machine stops due to machine problems, component problems or some other cause, extra component material to make up the difference is probably not available. And since the lead times for the components is on the order of weeks, remaking components to resupply the sensitizing machine and continue the run is not an option. The operation could keep extra emulsion in stock to guard against these incidents, but the cost would be

---

[20] Kitting refers to the act of pulling from inventory and consolidating the components required for an upcoming sensitizing event so they will be ready to run when the event start time is reached.

tremendous due to the large number of different liquid ingredients, their limited shelf life and the lack of excess emulsion-making capacity. Therefore, there is no production tool to prevent shortfalls in output when there are production problems. Given the multitude of emulsion components, the emulsion manufacturing lead time and its shelf life, this is an economically prudent decision. Downstream inventory in sensitized wide roll and finished product allow sensitizing to avoid additional component inventory.

3.3.2 Actual Realized Footage vs. Time

Figure 18 shows % ARF tracked over most of 1996. Once again, there is a relatively tight band of outcomes between about 80% and 120% ARF. Focusing below this band though, one can see that the number of production runs resulting in yields of ≤ 80% ARF did not decrease as the year proceeded.

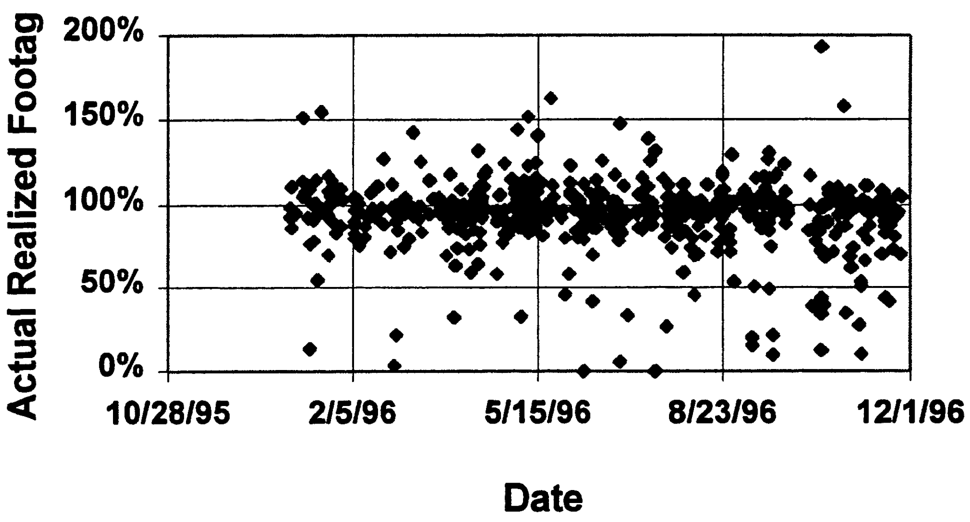


Figure 18: Actual realized footage (%) vs. date for all products sensitized on machine (1/96 - 11/96)

In fact it appears, as shown in Figure 19, that the number of significant yield shortfalls appear to be increasing in frequency as the year goes on. Consequently, the problem with incident failures was not isolated in time and the need to address it in the planning and scheduling systems increased as the internship progressed.

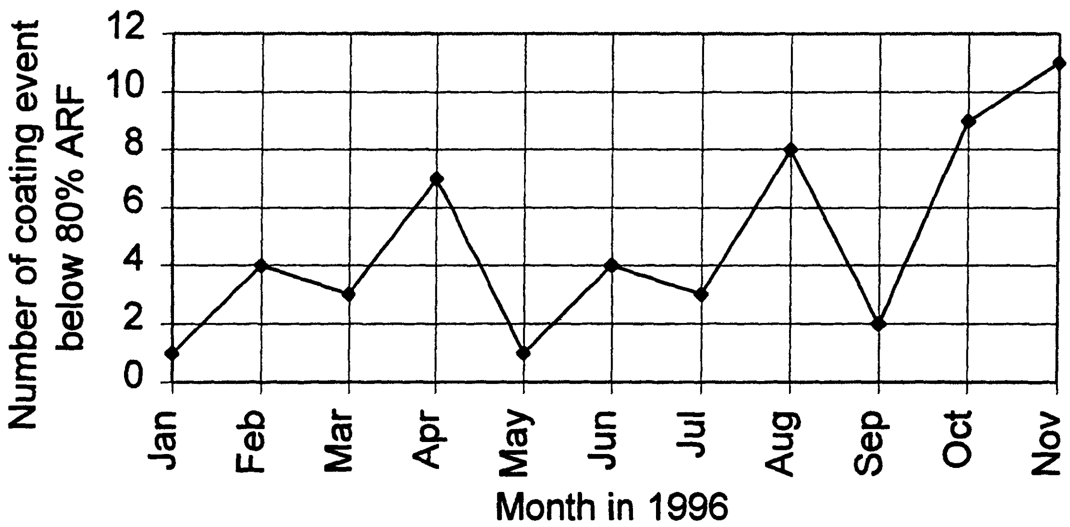


Figure 19: Number of sensitizing events below 80% ARF vs. month in 1996

From the analysis in this chapter, one can conclude that there are three distinct populations in terms of sensitizing yield. Since these populations are so different in statistical attributes and the nature of their occurrence (frequency of occurrence and relationship to runlength), it seems prudent that an analysis focused on each population will provide further insight.

3.4 Statistical analysis of event yield data

3.4.1 Comparison of yield data to normal expectation

The analysis of the incident failures began with determining the frequency and severity of their occurrence. Classical Deming training instructs us to determine the root cause when uncommon cause variation occurs and eliminate the root cause so that source of variation will not occur again. This approach works well when the root cause is fairly specific and when the frequency of occurrence is low. In the case of the sensitizing machine, yield results that fall outside the limits of normal variation happen at relatively high frequency. Classifying a set of outcomes occurring at high frequency outside the normal limits is not entirely inconsistent since there are two distinct populations with distinctly different causes. Further details of this will be provided in Chapters 4.1 and 4.2.

Another implicit industry standard also seems to be to tolerate uncommon cause variation unless there are significant safety, environmental, or financial consequences from this variation that could jeopardize the health of the firm. Processes would include machine design, instrumentation and controls, and even planning and scheduling systems. The mindset is that one cannot and should not anticipate and accommodate economically all possible disturbances to the process and inputs, so one should focus on eliminating these causes if they occur. Most projects would never be profitable if the designers took all steps necessary to eliminate the probability of any uncommon cause disturbances, regardless of cost. This is not to say that one should avoid evaluating the tradeoff between probability and risk, and the cost to minimize both of these.

Significant yield shortfalls for a sensitizing event are usually associated with unplanned stops of the machine. However, the reasons for the unplanned stops are complicated and it has not yet been shown that they can be eliminated by root cause analysis. In addition, new products are added continually to the product mix which forces the CFM Flow back to the bottom of the learning curve. Although an increased awareness of design for manufacturability allowed several products introduced in 1995 and 1996 to have significantly shorter rampups in production efficiency, the painful learning in the early phases of a new product's life will most likely not go away entirely. Consequently, the CFM Flow has accepted that a relatively high frequency of these incident failures is the norm until major steps are made in sensitizing capability.

In order to provide an appreciation for the separation between common and uncommon cause yield variation, the author compared actual yield data from February through July 1996 with the normal expectation of yield using the actual mean and standard deviation. The author focused only on sensitizing events with PF > 50,000 ft since incident failures in this range cannot be protected against economically with schedule shifting and safety stock inventories. In developing the histogram, the ARF of each individual event on a specific product constitutes a data point. As Figure 20 shows, there is very poor agreement between histogram for the actual point-to-point data and the normal distribution given the mean and standard deviation of the same data. Using a chi-square test on the two distributions, one is better than 99.5% confident that the two distributions are different.[21]

---

[21] The use of a chi-square test requires a reasonable assumption that the distributions under consideration are normal. One usually uses a chi-square test to compare the distributions of two different sets of data. In this case, the thesis author is comparing the data set with itself, or rather the normal expectation of itself. It is essentially a check for normality.

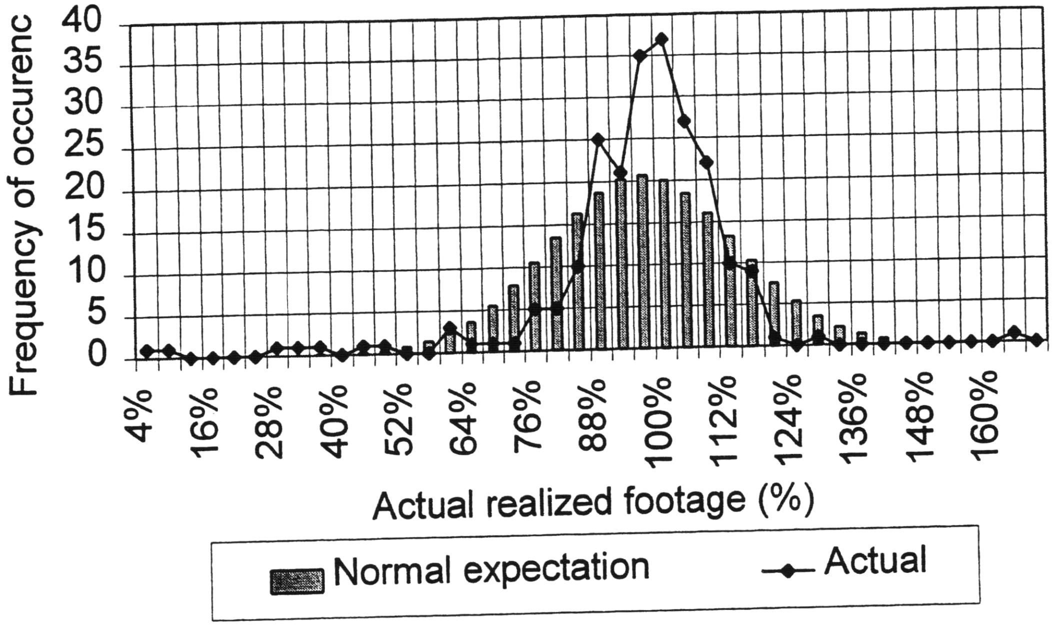


Figure 20: Frequency distribution of actual realized footage (%) for sensitizing events with planned footage exceeding 50,000 ft (2/96 - 7/96): comparison of actual with normal expectation

One can now begin removing points at the tails of the distribution of actual data and repeatedly testing for normality. In doing this, one must remove the 11 data points ≤ 64% ARF and the one data point of 164% ARF to gets the histogram of normal expectation shown in Figure 21. (Note that the 12 data points have been removed from the histogram calculation but are still shown graphically.)

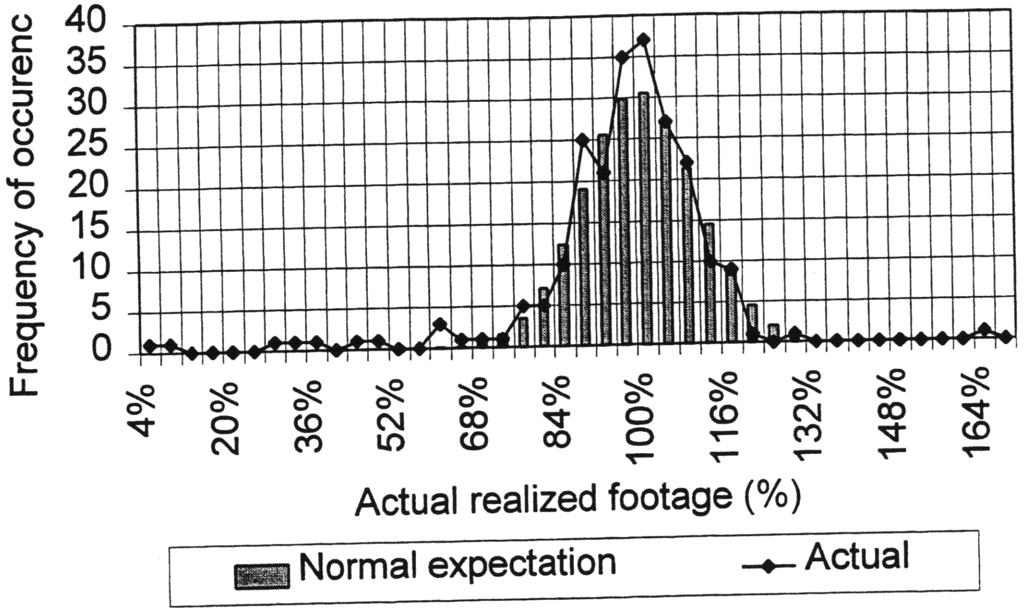


Figure 21: Frequency distribution of actual realized footage (%) for sensitizing events with planned footage exceeding 50,000 ft (2/96 - 7/96): comparison of actual with normality expectation excluding incident failures up to ARF ≤ 68%

By inspection, one can see a dramatic improvement in the agreement between the normal curve and the true data. In regards to goodness of fit, the chi-square statistic for the reduced data set is 14.04. For the number of degrees of freedom allowed, the critical chi-square value at 0.005 percentile is 28.0. Therefore since 14.04 < 28.0, one can see that the fit is extremely good. From this one can conclude that the hypothesis that the underlying yield population is normal cannot be rejected. One can also conclude that, at the least, yield results below 64% ARF (within data population 3 from Figure 17) are not part of the probably normal population.

3.4.2 Evaluation of variability vs. planned footage

Observing the data in Figure 15 of Chapter 3.31, one may be tempted to think that there is a strong correlation between variability in % ARF and PF beyond the simple break at 50,000 PF. Knowledge such as this would provide support for increasing sensitizing event lot sizes in the interest of achieving lower variability in outcome. The author tested the strength of a correlation across a multitude of PF segments in the range of 80% ≤ ARF ≤ 120% and found only one segmentation that confidently supported decreasing %ARF with increasing PF. A chi-square test revealed that there is 94% confidence in a difference in the distribution of outcomes for events with PF < 200 KLF (thousand linear feet) vs. that distribution of outcomes for events with 200 KLF < PF < 350 KLF. No other more detailed segmentation revealed a difference in variability of any significance. This result does seem to be supported by a visual inspection of the ± two standard deviation band two sigma band in Figure 22.

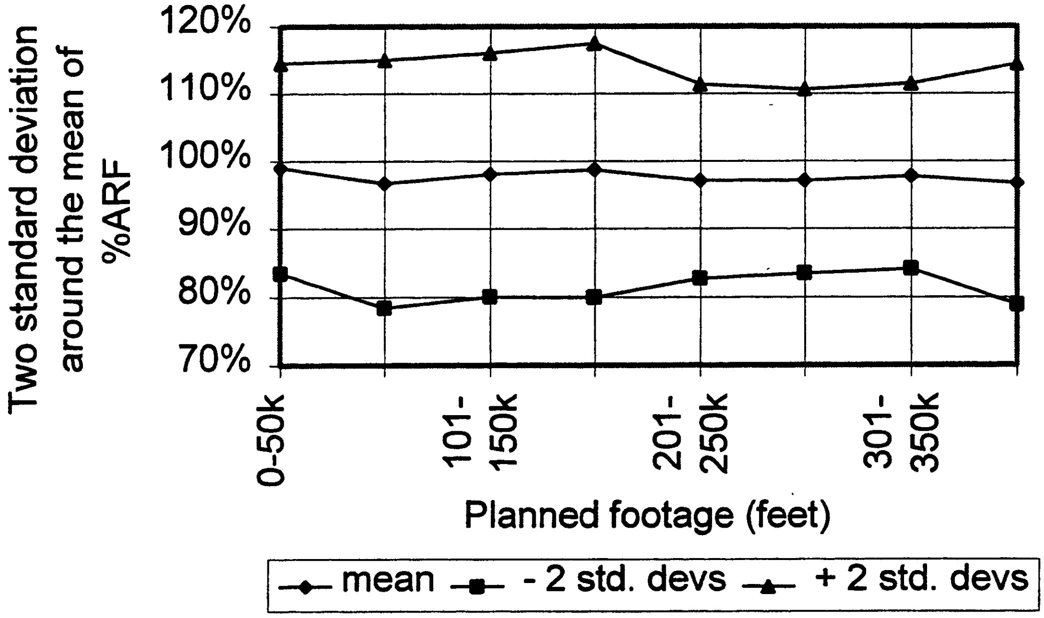


Figure 22: Two standard deviations around the mean of %ARF vs. PF based on 80% - 120% ARF on sensitizing machine (1/96 - 9/96)

One can conclude from this analysis that this single break in two populations may be helpful in adjusting some lot sizes but was not of the significance anticipated by some in the CFM Flow.

4. Source Specific Analysis & Proposed Policies

4.1 Uncommon cause process variability- incident failures

To mitigate the schedule disruption associated with the uncommon cause incident failures, the author and several members of the CFM Flow developed and implemented a plan. This section analyzes incident failures and discusses design and implementation results of the Headroom for Incident Failure Plan. This terminology will be explained shortly.

4.1.1 Analysis of uncommon cause variation

At this point it is important to discuss the reasons why the thesis author selected an incident failure ceiling of 80% ARF. The most compelling reason is that the limit of positive yield results (> 100% ARF) is 120% ARF. Having shown that the underlying common cause variation is normal, it seems reasonable to use the expectation of symmetry and place the incident failure limit at 80% ARF. Another reason for this choice of 80% ARF is the statistical data for data population 2 given in Figure 17. For this data population set, two standard deviations below the actual mean is 80.6% ARF. The use of two standard deviations agreed with the confidence level that the CFM Flow managers felt was appropriate.

In examining the phenomena of incident failures, the author tabulated and graphed all IF's from mid-February through October 1996 by number.[22] The data revealed 37 IF's spread over 42 operating weeks, a time period which seems sufficient to represent the long-term frequency of occurrence. Figure 23 shows that 50% of the weeks have no IF's,

---

[22] In analyzing the incident failure phenomena, the thesis author did not look for correlation with specific operators, crews, days of the week, or other potential drivers. Research into the actual incident failures revealed there were a multitude of different causes, ranging from physical problems with component materials, sensitizing equipment malfunctions, and poor photographic performance of the sensitized product. Therefore, with only 53 incident failures to analyze and given the time required to gather and maintain data against which to test correlations, the thesis author concluded that the probability of a correlation did not justify the time to investigate potential correlations of this nature.

and that the remaining weeks are split roughly evenly between one and two IF's per week. Of the two remaining weeks, one incurred three IF's and one incurred five IF's. Although one might presume this distribution to be Poisson in nature, the data shows a poor fit with a Poisson distribution.

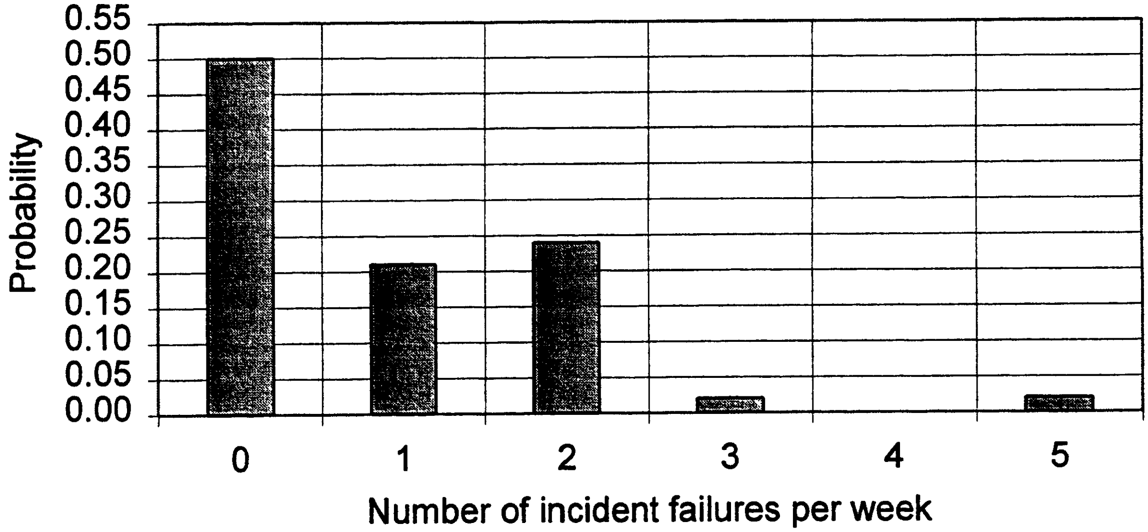


Figure 23: Probability distribution of incident failures (≤ 80% actual realized footage) on events exceeding 50,000 planned linear feet on the sensitizing machine by number per week (based on data from 1/96 - 10/96)

In regards to goodness of fit, the chi-square statistic for the data set distribution is 16.97. For four degrees of freedom allowed, the critical chi-square value at 0.995 percentile is 14.9. Therefore since 16.97 > 14.9, one can conclude with high confidence that the fit with a Poisson distribution is poor. To test the impact of the single week with five IF's, the author removed this week and recalculated the goodness of fit. The chi-square statistic for the new data set is 6.32. The new critical chi-square value at 0.9 percentile is 7.78 and at 0.75 percentile is 5.39. So the probability that the IF frequency is Poisson increased considerably, but not sufficient to say with 90% confidence that it is Poisson.

Fundamental to a Poisson distribution is independence of occurrences. It would seem that the poor fit is due to the lack of independence between IF's. When an IF occurs, there is an increased probability that another will occur due to the sensitizing machine being the fundamental driver.

4.1.2 Description of the Headroom for Incident Failure plan

The fundamental problem with incident failures is that since they are uncommon cause in nature, they can not be predicted statistically on a product level. Each product that is sensitized on the machine may experience a single incident failure every year or less frequently. Therefore, to adequately protect with inventory the supply to finishing against this occurrence, the chain would need to stock the equivalent of an entire event or more in every product, in addition to the inventory for other sources of variability. This is the reason that safety stocking for insurance against incident failure would be prohibitively expensive. In the case of incident failures, the CFM Flow has a number of options for continuing to meet customer requirements until a new sensitizing event on that product can occur. These options would include accelerating the release rate of any product still in quality testing and using the common cause safety stock inventory to maintain a supply to finishing.

The key leverage points are that the incident failures are fairly predictable in aggregate and that the products in question are being sensitized on a single machine. These support the concept that stockout insurance in the form of undedicated capacity (headroom) on the sensitizing machine is preferable to inventory.[23] Undedicated capacity or headroom is defined as that amount of sensitizing capacity reserved in the schedule that <u>will</u> be utilized, although the nature of its use is not known at the time it is placed in the schedule. Essentially, the Headroom for Incident Failure Plan involves leaving room in

---

[23] This premise was not modeled by the thesis author for validation, although a model would be useful in this respect. Those individuals in the CFM Flow connected with the problems and this concept were comfortable moving forward with a plan that utilized this concept, given the probability they might be wrong.

the future schedule just outside the minimum lead time of the component suppliers, adequate in size to allow resensitizing of the majority of products which might suffer an incident failure. This headroom would be placed at the end of the second week after the current production week, well within the standard fixed zone. Given this quick remake time, inventory is replenished much sooner than otherwise and disruption to other previously-scheduled products is minimized.

4.1.2.1 Size of Headroom Window

A fundamental initial question about the headroom for incident failure plan was the optimal size of the future headroom window. A window of insufficient size would not provide adequate time on the sensitizing machine to make a significant proportion of products. A window of excessive size would create problems in utilization if an IF did not occur. An initial rough estimate by the author yielded a size of approximately nine hours per week. However it was obvious from the simplicity of the calculation method and the comparison to planner's qualitative recognition of the majority of event durations that this timeslot would be inadequate. Therefore the author developed a cumulative distribution of the sensitizing event size for all products on the sensitizing machine, based on runrates in hours per square meter, sensitizing events per year, and anticipated volumes by product for 1997.[24] Figure 24 shows the graphical results of this calculation.

---

[24] The reader is reminded that although no model was used to substantiate this optimal window size, a model would serve well in this purpose.

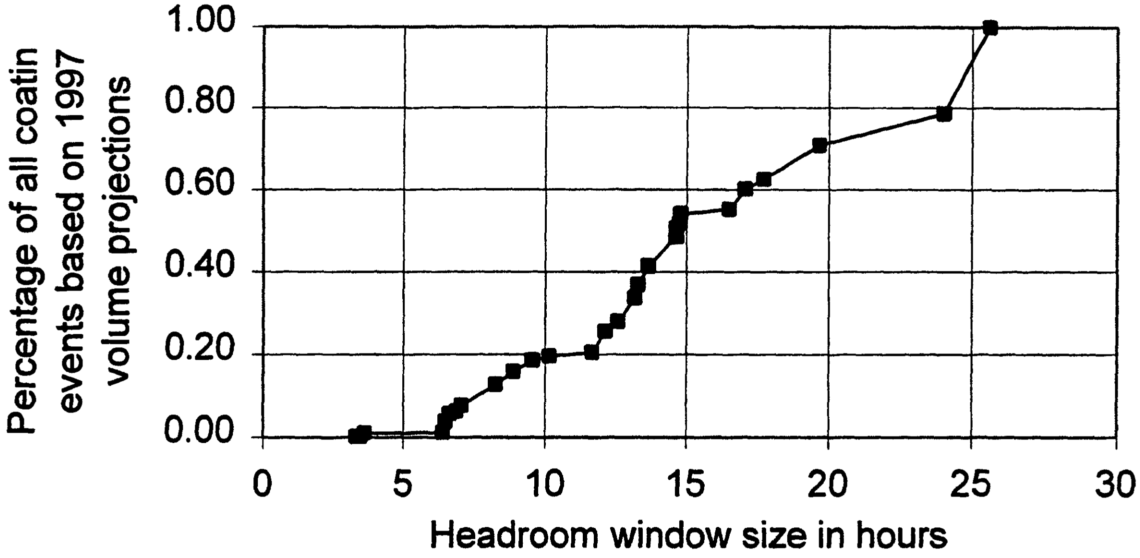


Figure 24: Cumulative percentage of all sensitizing events sized in hours based on 1997 volume projections for sensitizing machine

To determine this distribution, the thesis author used the calculation method shown in Figure 25.

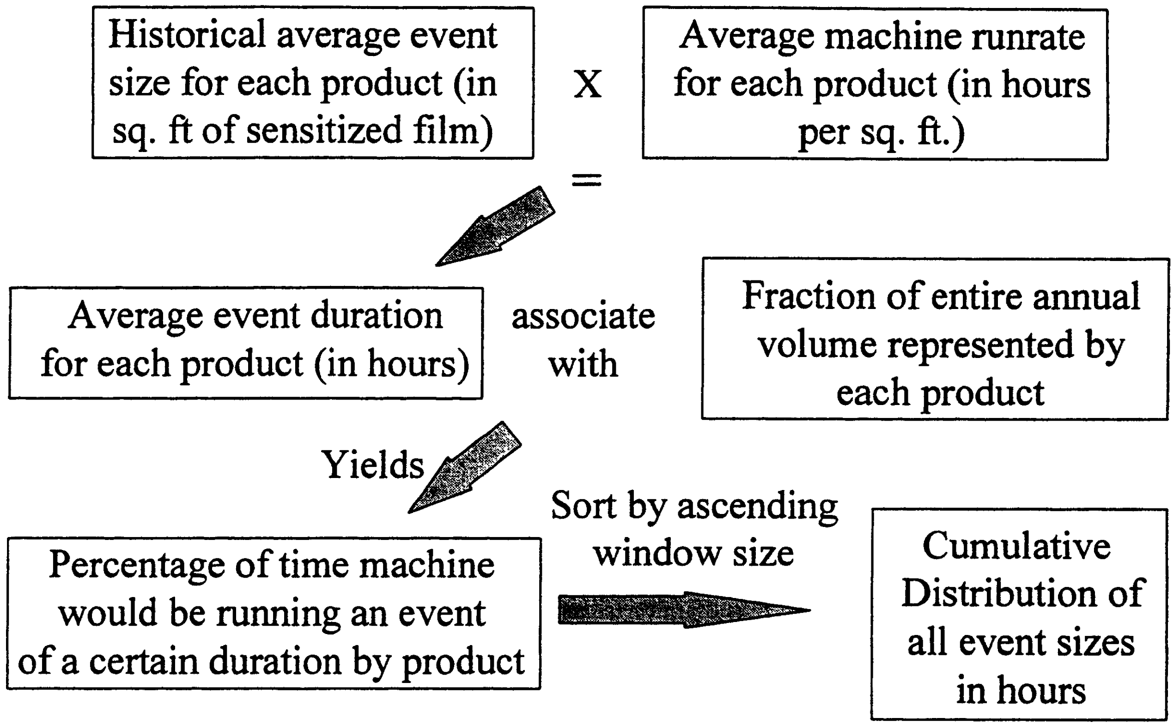


Figure 25: Flowchart for calculation method used to derive cumulative distribution of event sizes in hours

This method is particularly useful since it considers the probability that a given product running on the sensitizing machine will be of a particular event size. If incident failures are essentially random with respect to the product being sensitized, this is exactly the type of relationship one would want to use in specifying a headroom size.

It is interesting that the original size of nine hours would have been able to accommodate no more than 20% of all sensitizing events occurring on the machine in 1997. From this analysis, it seemed reasonable to use a window size of 18 hours since that would provide room for almost 70% of the events to occur. Also, given there is elasticity in the schedule two weeks out, using an additional five hours would not be unreasonable and would raise the coverage to about 80%.

4.1.2.2 Mechanics of plan

In evaluating the feasibility of an 18 hour window, the sensitizing machine capacity planner expressed concern over the schedule disruption that would result from trying to dissolve or fill the entire window in the case of no incident failures in a week. To balance the need for a window of adequate size against the need to minimize schedule disruption, a clever solution was devised. The 18 hour window two weeks out would actually be two 9 hour windows as depicted in Figure 26. A portion of undedicated capacity also would be placed in the emulsion schedule one week out (in Week B) from the current production week to allow emulsion to be remade in time to supply the new sensitizing event. Due to roll supports high utilization and shared customer base, a window of undedicated capacity may not be available. Roll support typically makes any individual type of support once every two - three weeks, so a good portion of the support will already be made. (In those cases where it was not, the wide roll planners will need to find the earliest time for a sensitizing event when roll support will be available.) Normally emulsion is being made three to four weeks ahead of when it is required in sensitizing. As Figure 26 shows, emulsion being made in Week A normally will be used in sensitizing in Week D.

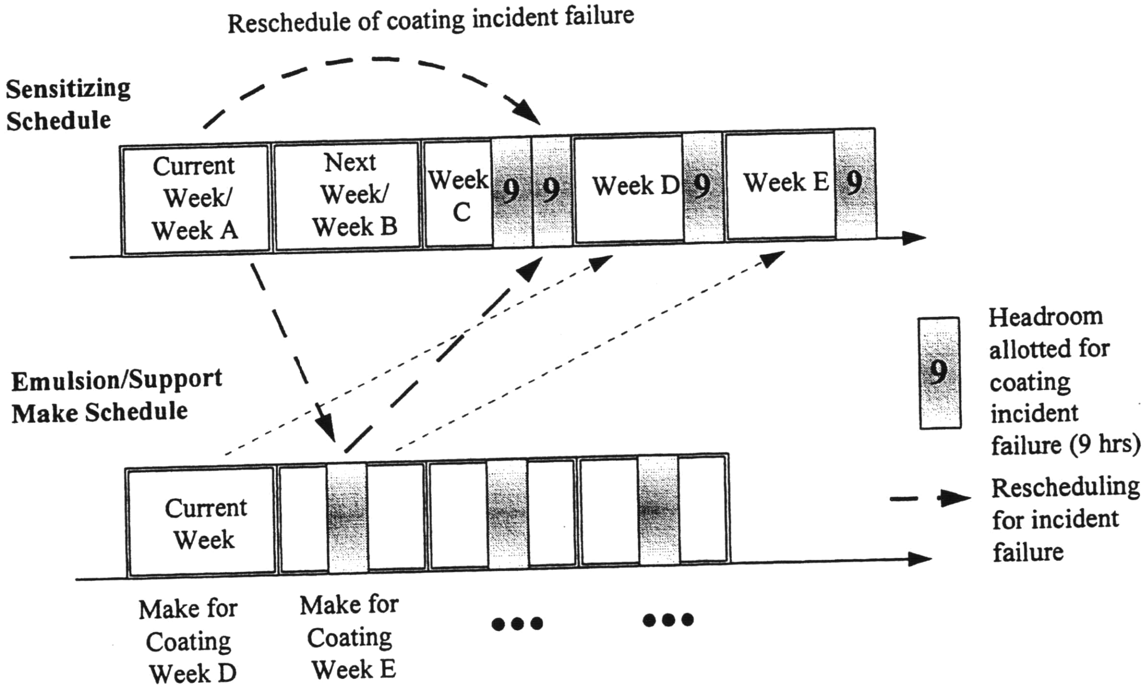


Figure 26: Use of headroom when incident failure occurs

In the event that an incident failure did occur in the current week (Week A), the entire 18 hour window would stay in the sensitizing schedule and be used for remake in Week C of the product that failed in Week A. Although this might be considered standard batch scheduling procedure, using this approach in a formalized fashion was novel to the CFM Flow.

In the case that a sensitizing incident failure did not occur in a given week, nine hours would be dissolved and nine hours would be shifted out a week. As Figure 27 shows, dissolving the nine hours would result in the entire schedule moving forward by that amount. Shifting the other nine hours would result in Week D shifting forward the entire 18 hours.

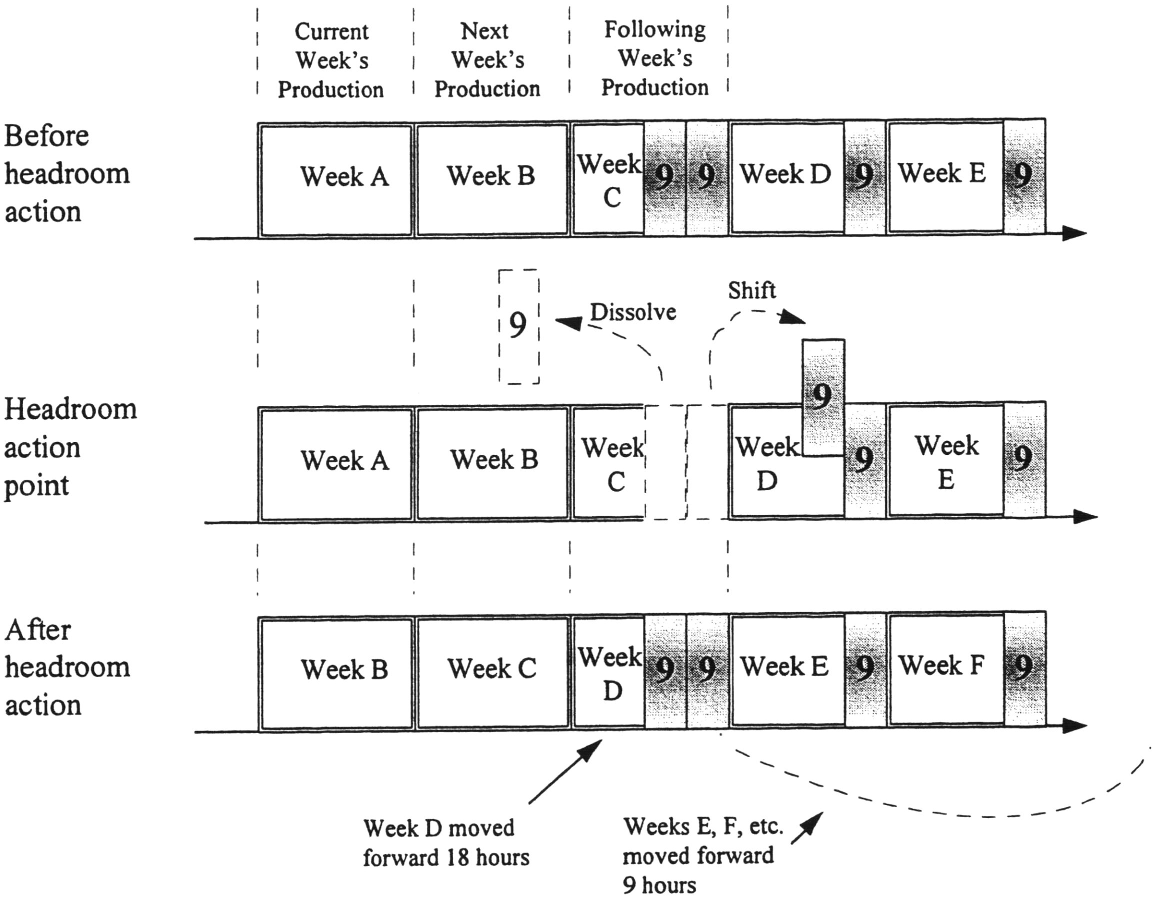


Figure 27: Headroom action when no incident failure occurs

To put this plan into place, the sensitizing machine capacity manager placed the 18 hour window in the last week (week 12) of the 12 week master production schedule for mid-September. The 18 hour headroom window transitioned through the 12 week production schedule until the second week of December when this first window was available two weeks out. Sources inside the planning organization have confirmed that at least from December through February, incident failures were occurring at roughly one per week, about as predicted. In each case, the headroom for incident failure was used for remaking the low yield product, resulting in reduced disruption to other scheduled products.

4.2 Common cause process variability

4.2.1 Analysis of common cause process variability

Prior to 1995, safety stock levels for individual sensitized wide roll products reflected little historical process variability. Training by a Kodak statistics expert throughout that year provided wide roll planners with some tools for setting safety stocks in a statistically accurate way. The original intention was that demand variability would be considered in the form of forecast error and supply variability in the form of lead-time uncertainty only. However, the variable yield nature of the sensitizing operation and the magnitude of this uncertainty led the CFM Flow to use the forecast error calculations for process variability as well.

Classical safety stocking calculations use a true standard deviation based on an assumption of normal variation. To simplify the calculation without losing too much information, the planners use the mean absolute deviation (MAD %) calculation for variability instead of the true standard deviation. This MAD % is simply a arithmetic average of actual footage/planned footage in percent for each individual sensitizing event. (Using a set of special MAD safety factors for customer service level minimizes the difference from the true standard deviation result.) The general formula used is the following:

Safety stock for = MAD % * 5 Weeks Lead-time * Safety factor for
desired process variability customer service level
(forward weeks
of supply)

The point should be made here that this is not a safety stock for process variability in the traditional sense. Sensitizing event outcomes are analogous to supply variability wherein an event is like a receipt of material from a supplier. If the quantity of material received from a supplier is less than that specified by the recipient, this represents supply variability. The recipient operation must carry enough safety stock in produced goods to insure against stockout of parts to the next operation until the next scheduled shipment arrives. Since the CFM Flow uses a fixed zone as described earlier, it cannot respond to common cause process variation by placing a new sensitizing event in these first five weeks of the schedule. All the process uncertainty is a result of the sensitizing event itself. Therefore, the MAD calculation determines how much material in forward weeks of supply must be carried to cover against the process variability that acts like supply variability.

As an example of how this calculation works, consider the following table of fictitious sensitizing event outcomes. The author has arranged the once-monthly yield outcomes in order that the true mean centers on 100% planned footage. The insufficiency of the data set will be ignored for the purposes of the example.

Month	*% Actual realized footage*	*Absolute deviation from 100%*
1	86	14
2	104	4
3	96	4
4	97	3
5	112	12
6	104	4
7	99	1
8	107	7
9	87	13
10	108	8
MAD	**NA**	7

Figure 28: Example table for MAD safety stock calculation

The mean absolute deviation for this product that sensitizes once a month is 7%. For a desired service level of 98%, the Table of Safety Factors distributed to the planners gives a MAD safety factor value of 2.56. The above equation then yields:

Safety stock for process variability = 7% * 5 weeks * 2.56 = 0.9 forward weeks of sensitized wide roll supply

This would be the inventory level necessary to ensure that 98% of the time, adequate wide roll would be available to finishing in regards to sensitizing process variability.

Therefore, with a set of yield results from previous events, a planner can calculate what the safety stock for a particular product should be to prevent stockout due to process variability at some confidence level.

However, this formula makes several assumptions that should be questioned. The first concern that might be raised is in regard to the appropriateness of using forward weeks of supply as the safety stock unit. In his 1993 LFM Masters thesis[25], Bill Hetzel describes how the use of FWS can lead to the "springboard effect" (a common industry term,) an ongoing situation wherein noise in demand and forecast is amplified as the information is transmitted up the chain. His statement that "forecast changes cause safety stock changes" assumes that a forecast change is closely followed by actual production to adjust the safety stock. In the case of two production areas in series, the upstream wide roll production operation produces to meet its own safety stock requirements in forward weeks of supply as well as the safety stock requirements for the downstream operation.

If one closely examines the planning system used by the wide roll planners, one sees that noise in forecast or demand does not trigger changes in actual production, but rather changes in the production schedule. Using essentially a reorder point system, the wide roll planners look out to see what the anticipated demand is beyond the fixed zone. Noise in the forecast will change the anticipated inventory on hand at some point in the future and therefore adjustments in production timing and quantity are made to the schedule. However, all of these changes fall outside the fixed zone, since this target inventory is composed of cycle stock and safety stock for process and demand variability.

A second assumption is that the five weeks lead-time is appropriate for all products. This five weeks flows from the five week fixed zone, the scheduled future period over which

---

[25] Hetzel, William. B. LFM Masters Thesis: Cycle Time Reduction and Strategic Inventory Placement Across a Multistage Process. MIT Sloan School of Management, MIT Department of Chemical Engineering, (1993), pp. 69 - 74.

schedule changes are to be avoided without significant reason. However, this five weeks implicitly assumes that each product sensitizes once every five weeks even though the true sensitizing frequency may be more or less than this. To work around this assumption, there must be some representation of the true average sensitizing frequency for each product. The thesis will explore this in more detail later in the section on recommended policies.

Another assumption to reconsider is the number of past events used for calculating inherent variability. Figure 29 is a copy of a typical supply safety stock page for two different products from line of business I. The top section of data is for the product designated code 1 (also referred to as product 1) and the bottom section of data is for the product designated code 2 (also referred to as product 2.)

```
                                ORD         ORD    PERF    ABS
                     CTD   CTD  QTY   ORD   QTY    ACT/    SUPP
                ORD DATE  DATE  PLAN  P/D   ACT    PLAN    VAR
 LOB  CODE      WK  PLAN  ACT   K2'S  K2'S  K2'S     %       %    LATE CODE/REASON
===== ========= === ===== ===== ===== ===== ===== ======= ======= =====================
 XXX
 GIS             33              21.8        23.4 107.34%   7.34%
 GIS  Code 1     38              10.9        14.0 128.44%  28.44%
 GIS             42              21.8        22.2 101.83%   1.83%
 GIS             45              10.9        11.2 102.75%   2.75%
 GIS              4              17.3        14.2  82.08%  17.92%
 GIS             12              31.8        32.9 103.46%   3.46%
 GIS             19              14.5        13.8  95.17%   4.83%
 GIS             24              31.8        32.5 102.20%   2.20%
 GIS             31              26.0        25.6  98.46%   1.54%
 GIS             38              23.0        24.4 106.09%   6.09%
 GIS
 GIS
 GIS
 GIS
 XXX

MEAN ABSOLUTE DEVIATION                                       7.64%
SUPPLY SAFETY STOCK=5 WEEKS LEADTIME+98% CUSTOMER SERVICE    0.98 WEEKS
SUPPLY SAFETY STOCK=5 WEEKS LEADTIME+98% CUSTOMER SERVICE    6.85 DAYS


 XXX
 GIS             33               3.6         3.4  94.44%   5.56%
 GIS  Code 2     38               9.2         8.6  93.48%   6.52%
 GIS             45               3.6         3.7 102.78%   2.78%
 GIS             52              12.8        11.5  89.84%  10.16%
 GIS             12               2.9         2.0  68.97%  31.03%
 GIS             38               5.7         2.8  49.12%  50.88%
 GIS
 GIS
 GIS
 GIS
 GIS
 GIS
 GIS
 GIS
 GIS
 XXX

MEAN ABSOLUTE DEVIATION                                      17.82%
SUPPLY SAFETY STOCK=5 WEEKS LEADTIME+98% CUSTOMER SERVICE     2.28 WEEKS
SUPPLY SAFETY STOCK=5 WEEKS LEADTIME+98% CUSTOMER SERVICE    15.97 DAYS
```

Figure 29: Supply safety stock calculations for Graphics codes

Code 1 uses ten data points representing ten sensitizing events over the previous 57 weeks, and code 2 uses six data points over the same historical period. Most statistical texts claim that a minimum of 20 points are necessary to draw any reasonably confident conclusions about a distribution.

The working of the resulting safety stock level in forward weeks supply is as follows. The wide roll planner targets new production to keep each product's inventory level above the minimum inventory level. This minimum is defined as the overall safety stock level for all forms of uncertainty and determines how far the wide roll level should be allowed to fall before a new event is ordered. If process (defined as supply in Figure 29) variability is the only source of variability for code 1, then the wide roll planner schedules a new sensitizing event at the future point when the projected inventory drops to 6.85 days of supply to finishing.

As Figure 30 shows, using only a few samples yields little information about the protection needed. With only ten data points for a product with a yield standard deviation of 10%, one must use a yield range of roughly 6% - 14% yield to be 95% confident that one has captured the true standard deviation. In the case of code 2, the methodology yields a safety stock level of roughly 16 forward days supply.

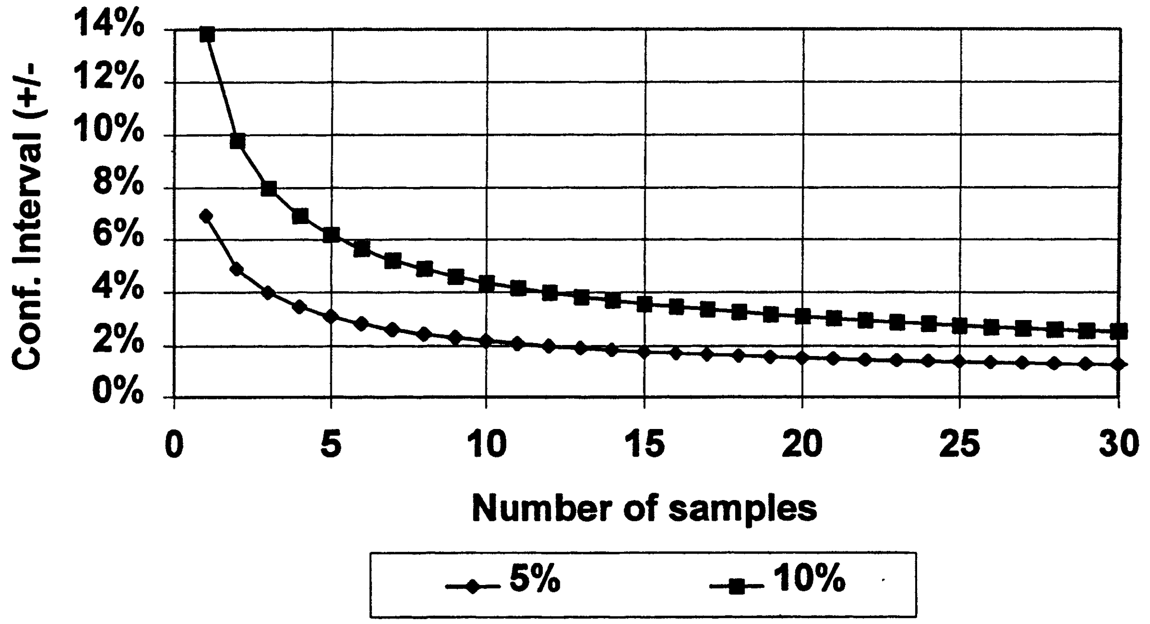


Figure 30: Confidence intervals +/- (95%) for two standard deviations of a normally distributed population vs. number of samples

Another important consideration not figured into the safety stock calculations is the sensitizing bias by line of business (see Figure 31.) The MAD calculation method assumes that the true mean of yield is 100% of the targeted footage by calculating the difference of each outcome from the targeted footage. In many cases for CFM flow products however, the true mean has proven to be more or less than the targeted footage. The correct calculation method determines the mean % yield footage from past events and then calculates the difference of each individual outcome from this true mean.

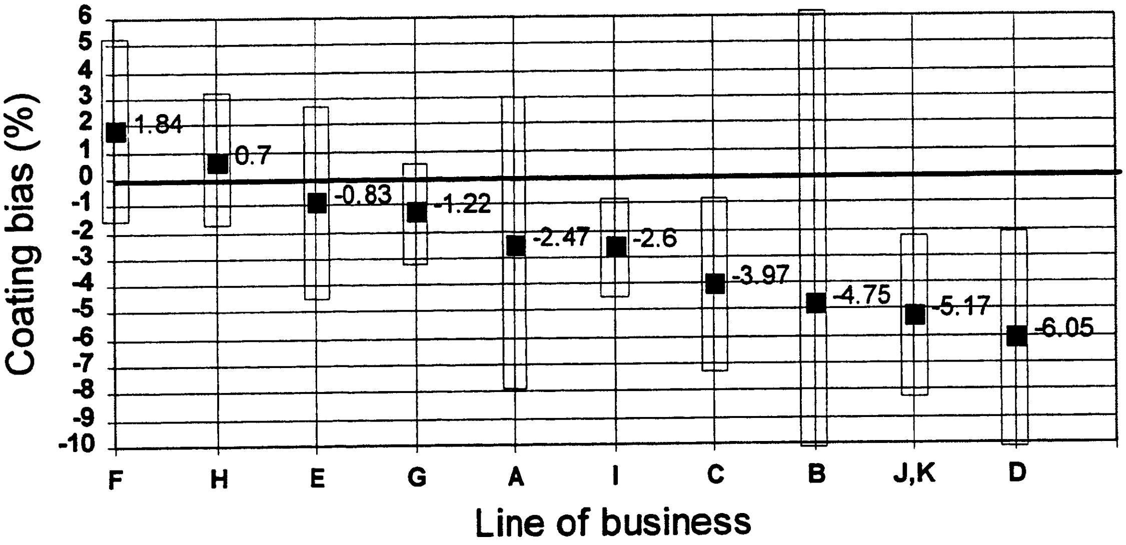


Figure 31: Sensitizing bias and 95% confidence intervals by line of business for all products and all events with target footage > 50 KLF and actual realized footage between 80% and 120% on sensitizing machine (1/96 - 11/96)

One further problem with the procedure is that it provides no rules for eliminating special cause outcomes. The methodology for dealing with incident failures varied from planner to planner but consisted mostly of individual judgment. Each planner was faced with tradeoffs such as including or excluding potential outliers and the impact of this on an already anemic sample size.

In the case of code 2 shown on the bottom half of the wide roll planner safety stock calculation sheet appearing as Figure 29, the understanding of true mean yield and sensitizing bias is critical to arriving at appropriate safety stocks. Ignoring for the moment the fact that there are too few points with which to work, one can see that two of the six event yields are less than 80% of target footage, classifying them as incident failures. It is not sufficient to use the true mean alone, one must also consider the nature of the points going into that true mean. If one includes these two "extra 20%" points in the calculation, the true mean calculates to 83%. This would classify the 69% yield event in week 12 as part of common cause variation and would almost flag the 103% yield event in week 45 as part of uncommon cause variation. Outside of the calculations, neither one of these two conclusions seems reasonable. However, if one also removes the 69% and the 49% points from the true mean calculation, the new true mean becomes 95% and the result from week 45 is only 7.7% above the mean. Granted more data points would dampen the effect of outliers on the true mean, but this example illustrates that the calculation is slightly iterative with respect to what points should be included and excluded. This is an important step in making an effective policy since the policy for common cause variation is not intended to provide protection against uncommon cause variation or incident failures.

Figure 29 also shows the lack of differentiation in safety stock calculation based on event size. Code 1 sensitizing event lengths are mostly above 50,000 ft PF whereas code 2 sensitizing event lengths are below 50,000 ft PF without exception. This thesis discussed earlier that small runners (defined as having PF < 50,000 ft) would have a safety stock policy of either holding an event worth of inventory or shifting future event timing. Another important point is that these small runners tend to be run as part of a family of related products. Sequentially, they tend to be sensitized last in the family. For a given quantity of common component material for the family, this "place in line" makes the small runners yield outcome dependent on the sensitizing performance of all other products sensitized in that family. If another product experiences some waste, it will most likely be sensitized to the planned footage, stealing support and emulsion from those family members being sensitized afterwards. Consequently, one could question the sense in trying to characterize the distribution of outcomes on a small runner, the yield of which is strongly dependent on other products.

Given the thesis author's concern about data sufficiency and the inclusion of incident failures, the author sought to determine the validity of product-by-product variability and safety stock calculations. To improve the size of the data set, the author aggregated all product yield outcomes into their respective lines of business. The thesis author chose this level of aggregation since the most fundamental differences in products are associated with the business classification the product. Products within a line of business tend to have very similar technical complexity and therefore process variability. The author developed % ARF distributions for each line of business and compared these distributions to the distribution of the entire set of yield outcomes for all products sensitized on the machine. The results of this comparison are shown as Figure 32.

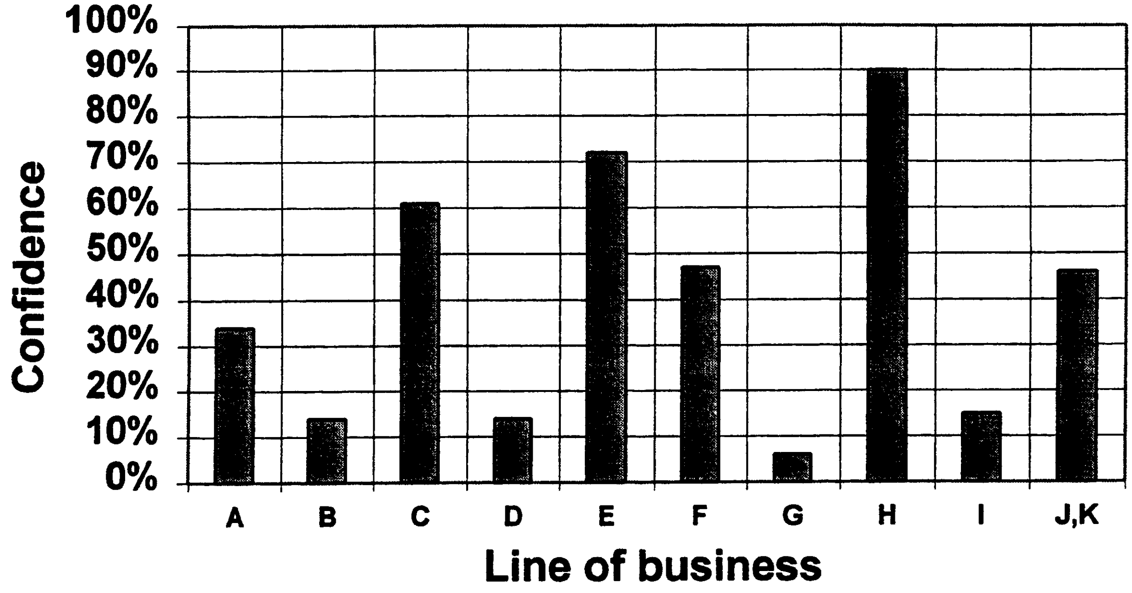


Figure 32: Confidence that distribution of actual realized footage by line of business is different than that of all events sensitized (with line of business sensitizing biases and events < 50,000 ft removed) for all products running on the sensitizing machine (1/96 - 11/96)

As the reader can see, only one line of business (H) had a distribution of outcomes which one can say with high confidence (≥ 90%) is different than the yield distribution at large. All other lines of business had varying degrees of confidence in their uniqueness, but all were below what statisticians consider to be a sound confidence level.

These results were very surprising to the managers in the CFM Flow in that they didn't agree with their intuition about the varying degrees of complexity and resulting yield uncertainty associated with products in different lines of business. There are several possible reasons for the lack of fit between intuition and statistical results. First of all, this analysis only looked at the incident failure-free common cause variation of each line of business. People in the CFM Flow tend to associate products with their incident failure history since these painful outcomes leave a strong impression. Without rigorous analysis, it is difficult to consider and draw conclusions about historical differences by line of business in common cause variability only. (In support of the analysis results, the managers did agree that products in the H line of typically had very good runs compared to the rest of the product mix.)

A second cause of the data's surprise factor may relate to the difference in sensitizing performance perception and the actual statistical recording for performance for products that sensitize in families. As mentioned earlier, a product that has long sensitizing runs and sensitizes in a family may have a poor yield but still reach target footage since it can steal material from products sensitizing later in the family sequence. Although this would hurt the yield of the smaller runners, the impact of a poor performance on the large runner that sensitizes frequently leaves a stronger impression than a poor performance of a smaller runner, the footage from which may not even be required for some time. The data may record a good outcome in terms of reaching target footage for the large runner, and an IF for the small runner (which will be excluded from calculation.) Consequently, the common cause yield data set will make the products look as if they ran better than they actually did. Even so, as long as the CFM Flow continues the practice of shorting later runners in the family to support the early runners, this should be viewed as the process variability for safety stocking purposes.

There may be other reasons the data is surprising but the key point is that outside of products in the H line of business, the wide roll planners are only justified in setting safety stocks on a sensitizing machine basis across all products based on all outcomes. They should continue to revisit this analysis over time since different products/lines of business have different learning curves and they may find that others will drop out of the aggregate distribution as being unique. The author will provide details later in the thesis of the steps to take for calculating and updating these safety stock levels.

4.2.2 Proposal for handling common cause process variability

The first step in accommodating the true common cause process variability is to remove any and all sensitizing biases. Removing sensitizing bias properly may require some iteration between calculation of the true mean yield and the determination of incident failures. Some judgment must be used since incident failures will reduce the calculated true mean such that some incident failures may not fall outside the 20% range. (For a further description, one can refer to the discussion of calculating standard deviation for product 4 following Figure 29.)

To calculate the sensitizing bias, one should use sensitizing yield data for the past 12 months and confirm the existence of a bias for each product by sensitizing family (for those products that sensitize as part of a family) and by individual product for those products that sensitize alone. Then, one should make an adjustment in expected footage from a given quantity of emulsion as specified by the calculated bias such that 100% PF is the true mean yield. Until such adjustments to the information systems are made, remove the bias from calculation by calculating the standard deviation from the calculated mean of the set of actual outcomes for sensitizing variability rather than from the target 100% PF.

The standard deviation of sensitizing process yield (sp) should be recalculated every six months. The first step is to remove all incident failures from the data set so these outcomes are not included in the calculation of common cause process variation. One should do this by searching the last 12 months of sensitizing yield data for incident failures (incident failures being defined as events having PF > 50 KLF and %ARF < 80% PF) and remove these from each product's set yield data.

Following this, one needs to check for uniqueness of yield distribution between each line of business and the set of all products sensitizing on the machine (as of 11/96, H is the only unique line of business at 90% confidence.) To do this, one should calculate a chi-square value between each line of business yield distribution and the entire product set yield distribution to test for goodness of fit. If the confidence in uniqueness exceeds 90%, one should consider that line of business distribution unique. Otherwise, one should consider it part of the sensitizing population. Then using the appropriate data set, one should calculate the standard deviation (s_p) as follows: $s_p = ((\text{sum(true mean yield - \%ARF for each event})^2)/(n-1))^{0.5}$ where n = number of events in the data set. The parameter (s_p) can be kept in units of percent or multiplied by average event size to get KLF (thousand linear feet.) This measure of common cause process variability s_p can be combined with other forms of variability (described in Chapter 4.4) to determine optimal safety stock levels and to enable a freeze policy that will reduce schedule disruption passed to component suppliers.

4.3 Wide roll testing variation

This section of the thesis does the following:

1. describes the existing process for evaluating wide roll,
2. presents the author's statistical findings for products across all lines of business,
3. discusses some alternatives for how test release variability might be captured,
4. recommends one of these approaches that can be incorporated easily into an overall variability policy described later.

4.3.1 Description of wide roll physical testing process and analysis of variation

4.3.1.1 General description of wide roll physical testing process

A major source of variability associated with Commercial film manufacturing at Kodak is the dispositioning of wide roll material when initial testing of the material signals that making an acceptability determination will be difficult. This discussion and analysis of variation only consider physical testing since this is the major driver of high variability in test time. Film is also subject to other types of testing, the release times for which tends to be less variable. The sensitizing yield data analyzed to this point is a record of the break between product that is initially-nonconforming (know right away at the sensitizing machine it is unacceptable) and product of initially-uncertain conformity (need testing to confirm that it is acceptable.) The majority of the initially-uncertain conformity product is reviewed and released within a few days after the event (outside of the aging period required for some products.) However, that product which is not released during this initial period due to suspect quality enters a detailed testing and review phase, the nature of which creates problems for planning systems.

Figure 33 provides an overview of the testing process for most Commercial sensitized wide roll. The inherent complexity of manufacturing these products becomes apparent in the types of defects encountered and the sophistication of the tools used to detect and evaluate these defects. Although scanners have been employed successfully in finding problems that might go otherwise undetected, their output requires painstaking review by sensitizing technicians and engineers. When empirical algorithms for discerning the nature of these defects fail to provide enough information for proper disposition, technical personnel request additional samples from the affected areas of the wound rolls. Time is required for mechanical removal of these samples from the rolls and for the follow-up analysis of these samples. The large number and variable duration of the steps that must occur to reach a final disposition decision for these rolls creates uncertainty in the timing and quantity of fit-for-use wide roll released from sensitizing.

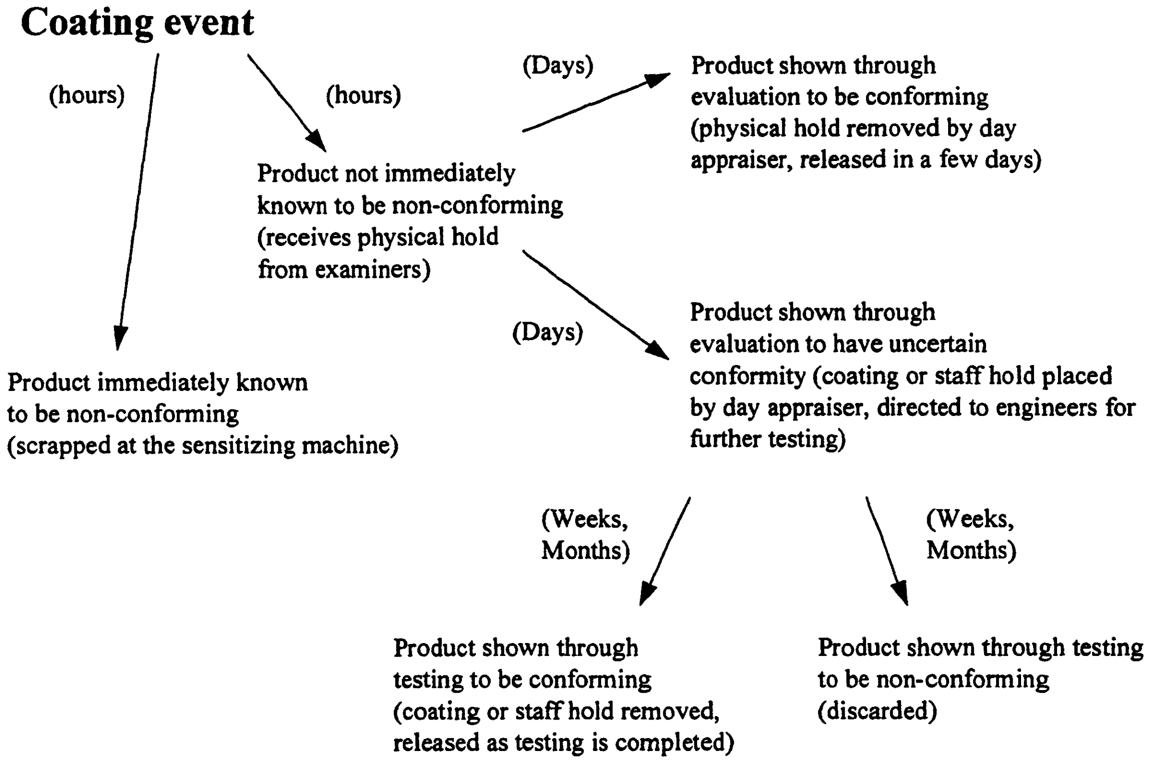


Figure 33: Sensitized wide roll physical testing tree

A fundamental problem with the current sensitized wide roll evaluation scheme is that staff personnel are releasing production product in a relatively slow fashion. This time lag creates significant problems with scheduling new production since the quality of material produced is not determined within a specific time frame. The disconnect in time and urgency between the production process and the staff evaluators prevents a tight feedback loop between the operation and inspection. Rapid inspection of output is necessary for processes with significant variability seeking to run at high utilization. There are weekly meetings between the planning staff and engineering staff for each line of business focused in large part on discussing the probable outcome of sensitized rolls held for extended evaluation. The planning systems don't do a good job of retaining information about rolls on extended hold. Past occurrences have included rolls on hold that were not labeled as such in the inventory system, and rolls that simply are no longer relied on to meet demand. Although the planners have requested upgrades to the information systems, resource availability to perform this is low and the project is not considered to be a high priority.

4.3.1.2 Analysis of wide roll testing variation

Although the quantity of rolls requiring intense testing scrutiny is considered by many to be small, the effects of this testing appear significant. Figure 34 shows the distribution of release times for 8,864 rolls that could be associated with a line of business out of a total 9,025 rolls sensitized between 1/2/96 and 9/27/96.

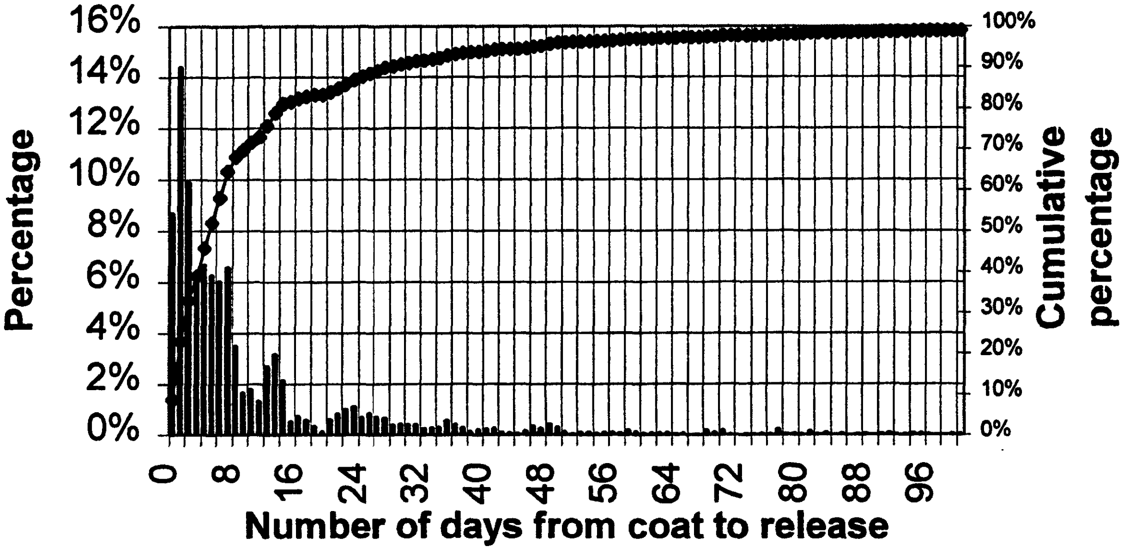


Figure 34: Distribution of days from sensitizing to release for all rolls sensitized on the machine (1/2/96 - 9/27/96)

All aging/transformation periods have been removed where applicable since these do not relate to the variability in release time, which is the focus of this test release analysis. The data shows that in aggregate, 80% of the rolls are released in 16 days or less and 90% in 32 days or less.

The wide roll release data available to the thesis author for analysis did not show what rolls that went into testing were eventually discarded due to poor quality, nor did it show what fraction of each complete roll that went into testing came out. (Sometimes, sections of a roll have quality problems. Finishing will cut out these sections and use the rest of the roll used as conforming product.) The thesis author was told by several individuals that the percentage of tested rolls that are eventually discarded is very small. The data used to generate Figure 34 show that more than 98% of the entering rolls did make it out of testing. Given this information, it seems reasonable to assume that all rolls are eventually released and that policies that use this assumption will be very close to policies that consider the material that is eventually discarded.

If one looks at the release distributions by line of business, one sees a picture consistent with the known complexity of the products being analyzed for release. Although it is a somewhat difficult plot to read, Figure 35 shows the distribution of release time aggregated by line of business.

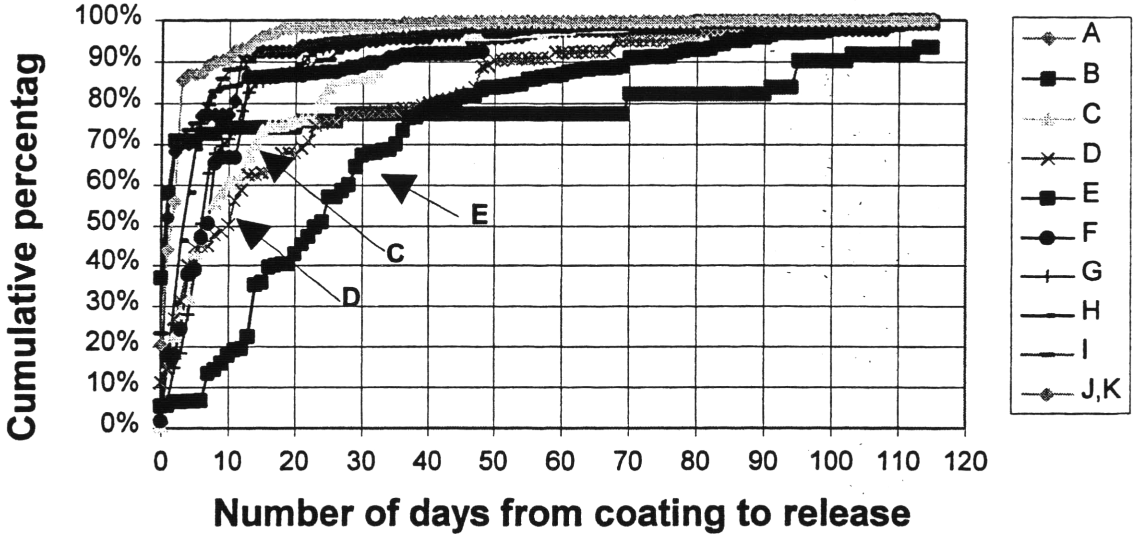


Figure 35: Cumulative percentage of all rolls released vs. number of days from sensitizing to release by line of business (1/2/96 - 9/27/96)

Except for C, D, and E, every line of business releases 70% of its rolls in 10 days or less. The release distribution of E seems to be the most interesting of those shown in that it is the only LOB that does not rise dramatically in cumulative % released inside of 10 days. Instead it follows a linear path in cumulative % released up to 80% at 40 days. This would indicate that few E rolls escape a rather torturous testing regime and there is a much broader range of quality considerations for E products that tend to spread out the data. Therefore, one can conclude that products in lines of business C, D, and E have test release times that are considerably more variable than the release times of the products in the remaining lines of business.

Figure 36 shows the same data at selected release percentages in tabular form. These values could be incorporated into a policy for capturing wide roll testing variability, the forms of which will be discussed shortly.

Line of Business	25%	50%	75%	80%	85%	90%	95%	98%
A	1	1	6	11	12	12	30	60
B	0	1	21	70	95	95	119	204
C	3	6	16	24	26	33	46	58
D	2	10	23	40	48	50	68	94
E	14	23	37	42	54	70	85	100
F	4	7	13	13	13	31	49	53
G	4	6	12	13	14	21	26	43
H	2	4	6	7	12	23	30	35
I	1	1	5	7	9	13	23	50
J,K	1	2	3	3	3	8	14	18

Figure 36: Number of days from sensitizing to release by cumulative percentage of all rolls released for each line of business (1/2/96 - 9/27/96)

Using a graphical format for two categories of release percentage, 75% and 90% released, one has a better view of the distribution of release times by line of business (see Figure 37.)

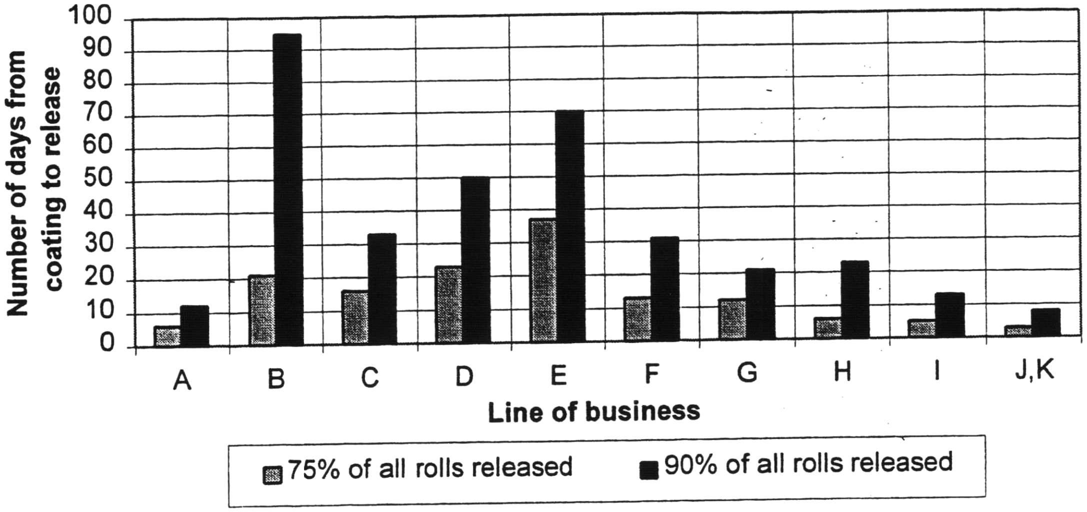


Figure 37: Number of days from coating to release for 75% and 90% rolls release by line of business

One result shown in Figure 37 that is misleading is the number of days to release 90% for line of business B. The sensitizing machine being analyzed is not used very often to produce B products; there are only 63 total rolls of B produced over this time period and only ten B rolls took longer than 95 days to be released. This is in fact a relatively easy product to produce to specification, so one should consider these facts when devising a policy to address test release time variability.

As with sensitizing process yield variability, test release time variability also presents the level of aggregation for calculation issue. For several reasons, it makes sense to consider test release variability at the line of business level. First of all, the test release staff are assigned to wide roll evaluation by line of business and develop expertise with the products for which they have accountability. Second, the wide roll release data in its current form is relatively difficult to manage and manipulate. For this reason, using the line of business level reduces the data manipulation workload considerably. Lastly, due to the wide variability in test release, the size of the data set at the product level may be inadequate to properly characterize this variability. The author uses product 3 of line of business G and product 4 of line of business D for analyzing test variability and deriving policies because these data sets are easy to manipulate.

Upon studying the release rate of wide roll on a product-by-product basis, one quickly realizes that there is a fairly repeatable distribution of sensitizing to release times. This pattern consists of a well-formed and characterizable hump shortly after the sensitizing event and then a poorly formed, non-characterizable pattern of longer release times. Figure 38 provides a classic representation of the test release process.

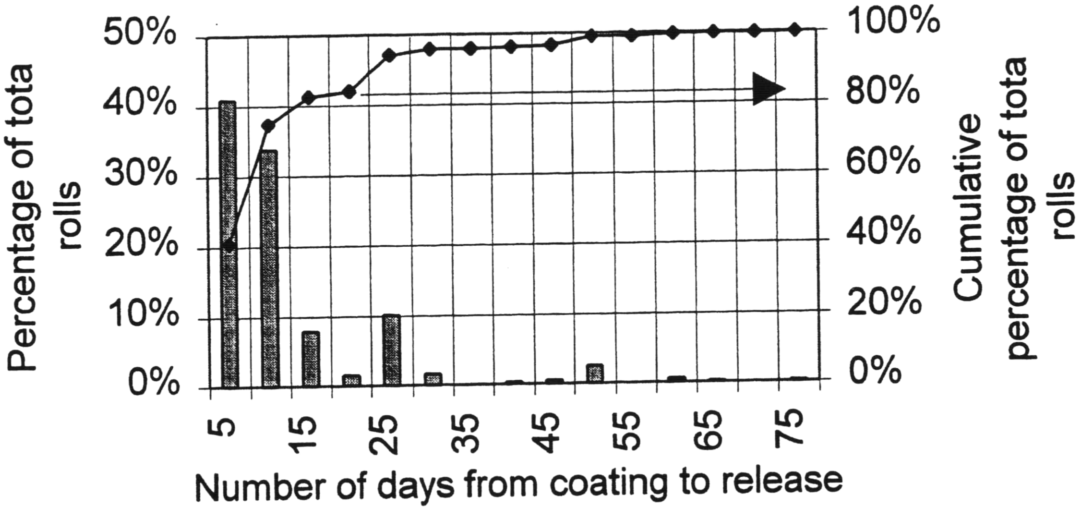


Figure 38: Distribution of days from sensitizing to release for product 3 on the sensitizing machine (2/96 - 9/96)

For product 3, the reader can see that better than 80% of the rolls are released in 20 days or less. The peak at 25 days comes from a single event that had over 40 rolls released 22 days after sensitizing. In some sense this set of outcomes is driven by the notion that things tend to go right similarly but they go wrong in different ways.

The release pattern of Product 4 displays a similar pattern. Figure 39 shows the wide roll release distribution for all sensitizing events on product 4 from 1/96 to 10/96. If one ignores the large release at day 55, each roll of which came from a single event, there appears to be a well-defined distribution up to about 40 days release time and a fairly random distribution beyond 40 days. The release rate is longest at the beginning because a significant number of rolls have such good initial quality that they can avoid the product staff evaluation altogether. (Note that the initial aging period has not been removed from this data. When attempting to capture test variability on this and other products requiring aging, this initial transformation time should be subtracted before calculating a measure of variability.)

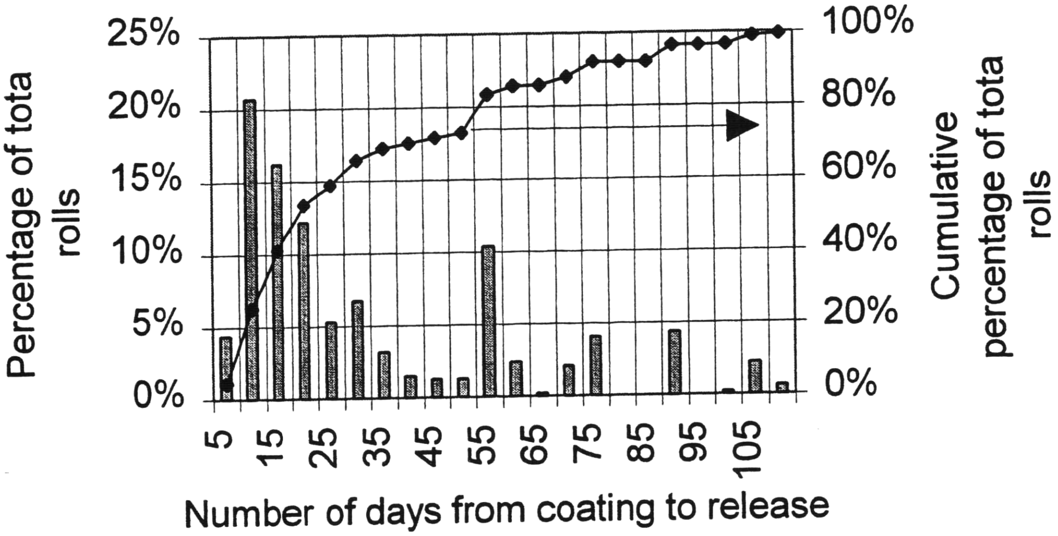


Figure 39: Distribution of days from sensitizing to release for product 4 on the sensitizing machine (1/96 - 10/96)

Obviously, the rolls of product 4 that were shown through initial evaluation to be conforming were released immediately and those rolls requiring additional testing were released some time after that.

One can conclude from this analysis that a substantial percentage of wide roll entering testing is released almost immediately and that the remaining rolls are released across a broad range of time. One can also conclude that there is considerable variability in release times by line of business. Since one has little statistical confidence in the actual release time of rolls taking a long time to be released, it seems unreasonable and costly to base new event scheduling on these rolls with long release time.

4.3.2 Alternative policies for dealing with test release variability

Because there is no way to predict the pattern of release times following the initial release phase, it seems sensible that any protection plan using statistics for test variability should focus on the initial release period only. The multitude of testing procedures, transfer steps, and sampling steps that can occur to product that is shown through evaluation to have uncertain conformity makes the second mode difficult if not impossible to characterize. Event to event, prediction about the probable release timing and quantity is unreliable at best. Therefore, one should focus on that material which is shown through evaluation to be conforming, since this is reliable and characterizable.

For rolls that aren't released as part of the initial release phase, some other simple policy should be applied. This policy could be to simply assume these rolls are bad or non-conforming and to plan future events accordingly. When a sizable number of these held rolls over multiple events do come available, they could be released as a lot, perhaps large enough to allow the elimination of an entire future event. In any case, the practice of making sensitizing production schedule timing dependent on a few held rolls appears suboptimal.

The testing release of sensitized wide roll is a significant problem for planning and scheduling systems. The yield off the sensitizing machine discussed earlier consists of a single data point per event. However the uncertainty in quantity and timing of wide roll testing release causes each event to have its own distribution. This added complexity must be taken into account setting a protection policy.

Previous attempts by wide roll planners to establish safety stock for test variability actually dealt with the mean time to release. Wide roll planners would calculate the average of all release times by product and then add this amount to safety stock. The problem with this method is that there is no accounting for variability in the release times. Taking the mean of the entire distribution, including the compressed short-term mode and the random lon-term mode, may cause the protective mechanism (in this case safety stock) to be excessive in some instances and inadequate in others.

4.3.2.1 Characterization of test release distribution as Poisson

Suppose that one wishes to incorporate test variability into a stockout protection policy. Keeping in mind the nature of the distributions observed in Figure 38 and Figure 39 (well defined initial peak in release time and a random release time thereafter,) one would choose to base a protection (safety stock or safety lead time) quantity on the well-formed part of the distribution. If one could associate a known distribution with the release data, then one could incorporate this variability easily into a safety stock policy. Based on visual inspection of Figure 38 and Figure 39, the distribution of release times appears best characterized as Poisson.

A problem with characterizing these distributions as Poisson is that rolls of a particular product are sensitized and released as separate occurrences. Consequently, a roll in one event will tend to have more in common with other rolls in the same event than with rolls in other events. As such, if one roll in an event is found to be conforming, there is strong probability that the following roll will also be conforming. However, this non-memoryless nature of wide roll quality is dampened as the size of the data set grows and a Poisson model for release time is more applicable.

Depending on the amount of data available one can either judge qualitatively where one believes the right tail of the Poisson curve ends or one might perform a chi-square on the data and find the point where one can first say confidently that it is no longer Poisson. Judging qualitatively the release time distribution for product 4 in Figure 39, it appears that the distribution ceases to be poisson-like at approximately 35 - 40 days after sensitizing, or when about 70% of the rolls from the event have been released. Since one cannot speak confidently about release times after 40 days, one would schedule a new sensitizing event based on when this 70% would be depleted by finishing. One could then include the σ (standard deviation) for the distribution in a combined safety stocking policy that accounts for all major sources of variability, discussed later. This would provide high confidence that given the event-to-event variability around this 70%, sensitizing would not stock out finishing due to test variability. Rolls released outside this distribution would be accumulated across multiple events and classified in the tracking system as released when a significant number were became available.

4.3.2.2 Comparison of release rate to finishing rate

Another approach to capturing test variability is to compare the test release rate to the finishing consumption rate. Figure 40 and Figure 41 depict such a comparison for the average test release rate and finishing rate across multiple events of product 3 and product 4 respectively.

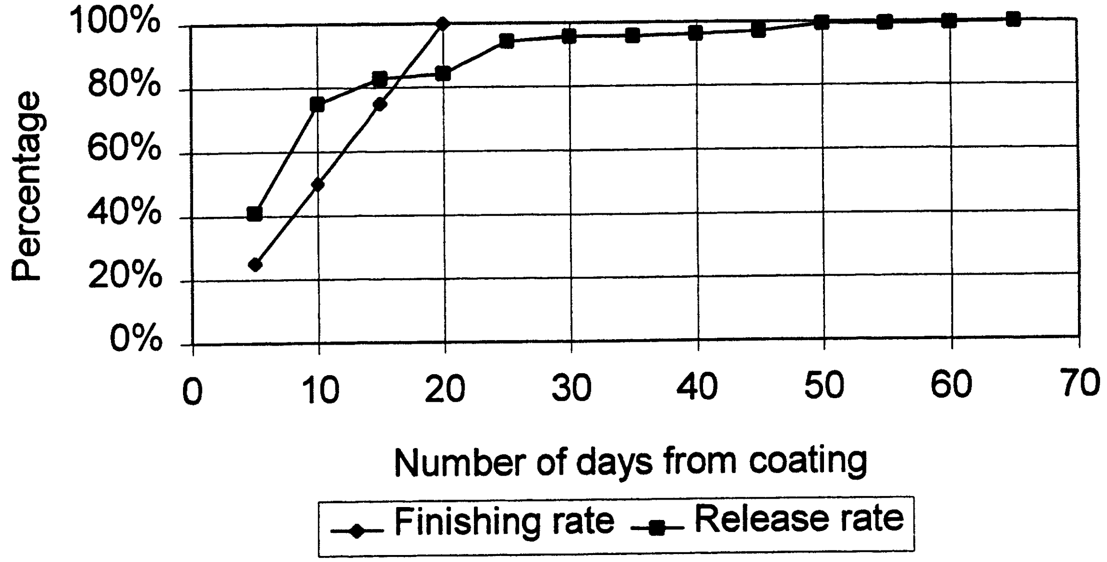


Figure 40: Cumulative distribution of days from sensitizing to release and average finishing rate for product 3 on the sensitizing machine (1/96 - 10/96)

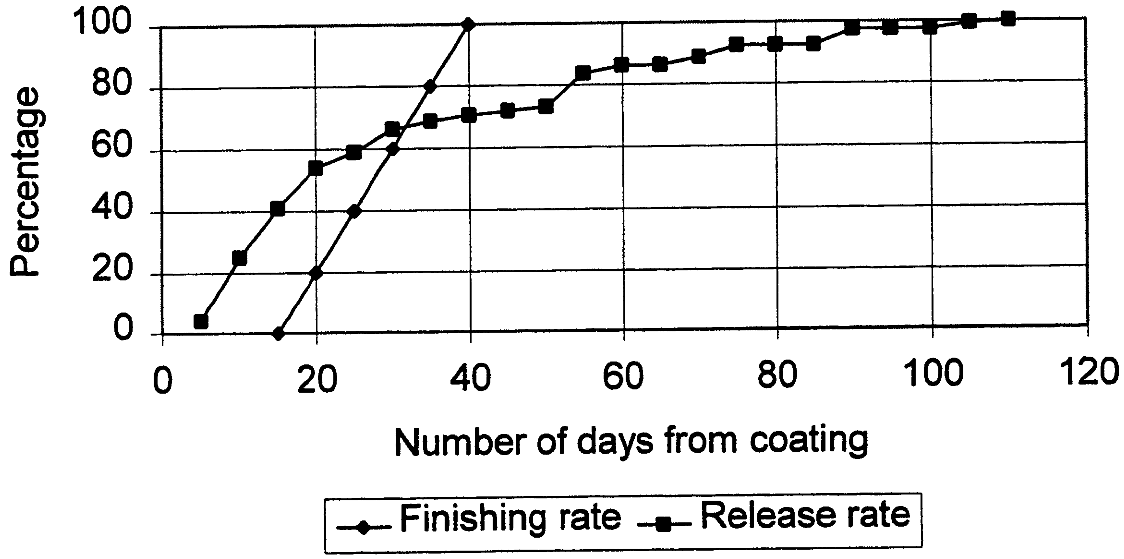


Figure 41: Cumulative distribution of days from sensitizing to release and average finishing rate for 5089 on the sensitizing machine (1/96 - 10/96)

What is immediately obvious is that neither product on average is released nearly in time to satisfy finishing demand completely. This situation of apparently inadequate product for finishing does not lead to frequent stockouts due to several reasons. One, when finishing has consumed all the rolls from event_{N+1}, there are likely rolls that have released from event_N that were not available to finish after event_N and before event_{N+1}. Second, when the wide roll inventory is critically low, wide roll test release can be expedited. The time spent focusing on the release process though takes away from other engineering staff functions such as improving existing film products and developing new ones. Lastly, there is safety stock in sensitized wide roll that helps to bridge the lag between the time of the sensitizing event and the time of release.

For product 3, finishing demand on average exceeds product released after 17 days, and for product 4, after 33 days. It is very interesting that these crossover points coincide almost perfectly with the outer limit of the first release distributions depicted earlier in Figure 38 and Figure 39. In fact, the average sensitizing frequency over 12 events of product 3 between 3/96 and 9/96 is one event every 17.2 days. It would appear that the wide roll planners know implicitly the reliability of the test release process and schedule new events accordingly. Contrary to this observation is the average sensitizing frequency of one event every 11 days taken over 20 events of product 4 between 1/86 - 8/96. This high frequency of sensitizing is most likely due to the fact that this product is part of a sensitizing family which sensitizes on average every other week. In this case, the CFM Flow can afford to make smaller and more frequent lots of product 4 with little additional setup cost.

From a statistical standpoint, one can look at the distribution of the difference between the number of rolls released in each event (N_R) and the rolls consumed by finishing (N_F) at the time of each sensitizing event. Such a view is shown in generic form as Figure 42, where those curves denoted as **Wide roll testing release rate** are the actual event-by-event distributions.

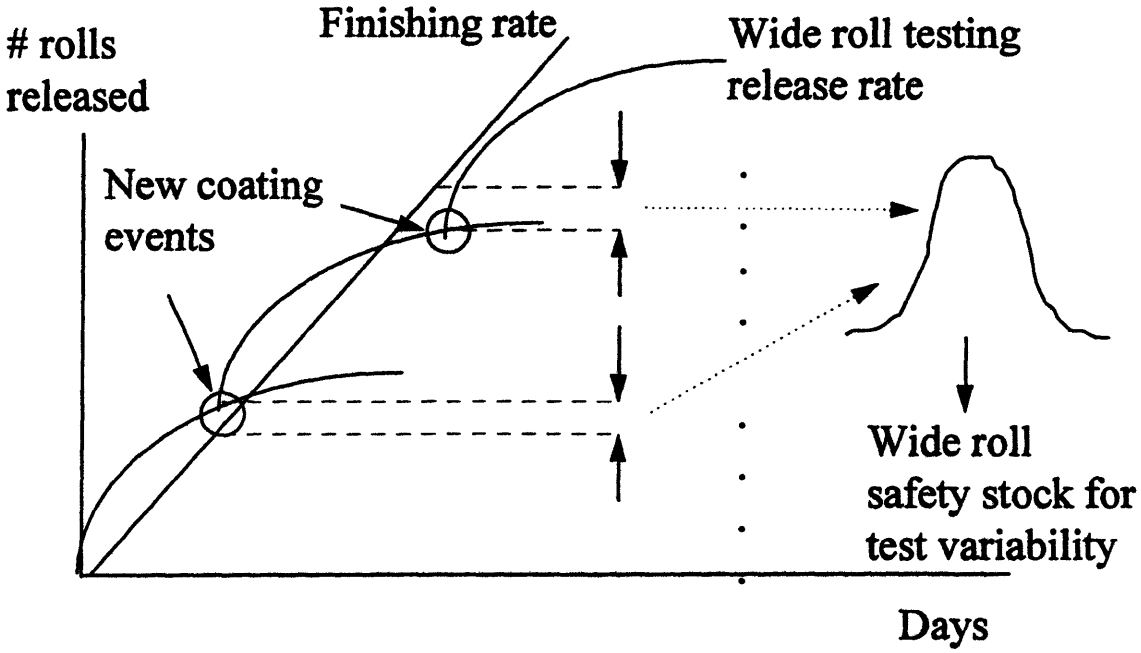


Figure 42: Basis for determination of wide roll test variability for safety stocking

Wide roll planners set the sensitizing schedule outside the fixed zone such that there is always five weeks of time over which any particular event date is set. Every product with significant demand has a sensitizing frequency that is relatively constant over time. Given these two facts, it is highly unlikely that the actual event-to-event sensitizing frequency will be affected appreciably by the difference between what has been released from the last event and the amount of material consumed by finishing since that event. This difference is the quantity $N_R - N_F$. Given the likely independence of sensitizing frequency on $N_R - N_F$, one can use the distribution of $N_R - N_F$ to generate an appropriate measure of test variation.

It is important to understand that for a particular product, a single data point in this distribution will be the value $N_R - N_F$ recorded at the start of one sensitizing event for that particular product. The collection of $(N_R - N_F)$ for all events forms a distribution that is most likely normal. The variance of the distribution of $(N_R - N_F)$ could serve as a measure of test variability in a combined safety stocking policy. In the case of product 3 from Figure 40, one would use the time (17 days) to finish 83% of the target sensitizing footage as the time between sensitizing events. Based on the historical data set $(N_R - N_F)_{\text{product 3}}$, one would calculate a test release standard deviation (s_t) which would then be used in a combined safety stocking and safety lead time policy described in the following chapter.

4.4 Method for combining variability to set safety stock and freeze future orders

The overriding purpose of this policy is to incorporate the three principle forms of variability (process, test, and demand) into safety stock calculations and to allow for freezing by future orders instead of by a fixed period.[26] In the CFM Flow's current method of freezing by period, events are implicitly frozen based on whether or not they are scheduled to run within the current + four week period. However, the number of events frozen depends on the sensitizing frequency and when in the sensitizing cycle one is seeking to make the determination. For instance, if a product sensitizes every three weeks, the number of events frozen over a five week fixed zone will depend on the point in the sensitizing cycle as shown in Figure 43.

---

[26] One must consider here the complicating factor that some products coat as part of coating families. The coat dates of some smaller running products are driven primarily by the schedule of the larger runner(s) in the same family. In most cases though, these smaller runners have average event sizes of < 50 KLF, so they are not covered by this scheduling policy.

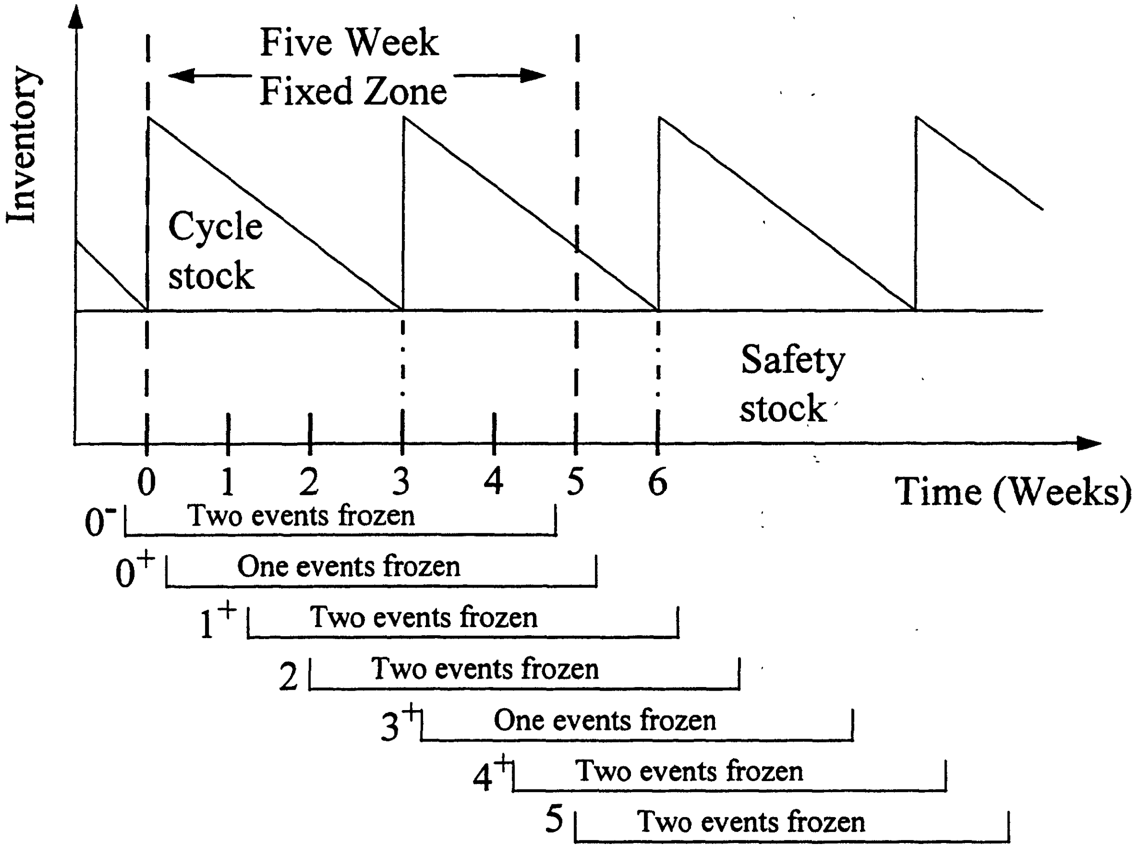


Figure 43: Inventory vs. time showing number of events frozen by point in the sensitizing cycle

The proposed method of freezing targets a certain number of future events to freeze rather than a time period to freeze. (The thesis showed in Chapter 3.2 that order-based freezing offers more stability to the schedule than period-based freezing.) Certain managers in the CFM Flow expressed the desire to freeze larger parts of the sensitizing schedule to reduce the schedule disruption transmitted upstream to raw materials suppliers. This reduced disruption to raw material suppliers would allow these suppliers to reduce their inventory safety stock levels for demand variability, saving money for Eastman Kodak. The optimal number of sensitizing events to freeze for this purpose is outside the scope of this thesis. However, in an upcoming example, the author chooses to freeze two events since it is slightly more "constrictive than a typical product sensitizing every three weeks with a five week fixed zone. The term constrictive here refers to the fact that for this product, only one event is frozen one-third of the time in period-based freezing whereas two events are always frozen in order-based freezing.

When freezing multiple events with independent outcomes, there is a real probability of consuming all safety stock due to a series of negative event outcomes or high demand. To ensure this stockout does not happen, one must "restore" safety stock consumed due to poor yielding events and high demand. Since the sensitizing events are considered to be fixed in size, one must adjust timing of future events to "restore" this spent safety stock.

Because demand variability is considered to be outside the scope of this thesis, the author chose to represent demand variability with a single measure in units of ft/week. In reality, demand variability consists of both monthly forecast error as well as weekly finishing variability. Due to the lead times of the liquid and support components for sensitizing and the high utilization of sensitizing, planners must rely on the monthly forecast to schedule future sensitizing events. They may then "tweak" the event timing as the true weekly finishing demand "rolls in." The author is uncertain as to the most appropriate representation of all sources of demand variability, but for this exercise one quantity will be used to represent it.[27]

With regards to capturing test variability the author makes several assumptions:

1. Average time between sensitizing events is equivalent to the number of days from the occurrence of an event to when the number of rolls released from that event is equivalent to the number of rolls consumed by finishing since the start

---

[27] To account for both forecast variability and finishing variability, one might divide the monthly forecast error by 30/7 (number of weeks in average month) to arrive at forecast variability by week. Then one could combine this measure and the weekly finishing variability into the $\tau\sigma_d^2$ expression as the following:

$$\tau\sigma_d^2 = \tau(\sigma^2_{\text{d-forecast}} + \sigma^2_{\text{d-finishing}} - \alpha_{\text{d-fore-fin}}\sigma_{\text{d-forecast}}\sigma_{\text{d-finishing}})$$

Here, τ is defined as the timing of the $n + 1$ event, where n = number of events that are frozen. The author is uncertain as to the degree of independence between forecast variability and finishing variability and the coefficient $\alpha_{\text{d-fore-fin}}$ very well may be 0. Further understanding and investigation into the causes of finishing variability would be necessary to determine the extent of correlation.

of the event. One can define this length of time as the following: $t_{avg}(\text{Event}_{N+1} - \text{Event}_N) = t(E(N_R - N_F) = 0)$, This combined policy will only consider the variability in $(N_R - N_F)$, defined earlier.

2. Over a sufficient timeframe, the number of rolls entering testing ≅ number of rolls exiting testing. This allows for rolls held from one event to be replaced by rolls released from previous events.
3. All rolls that enter testing eventually make it out, i.e. no rolls are discarded. For purposes of a combined protection policy, this is a good assumption. The current inventory position I(0) over time will capture this difference and future event timing will be adjusted to correct this difference over time.
4. Test time is independent of common cause process outcome. There is a temptation to believe that products which experience problems and have low yield might take more time to test. Although it has not been statistically verified, the experience of individuals in the Flow indicates this is little correlation between the two variables. This seems reasonable since there here are a number of sources of uncertainty impacting test time which are unrelated to the outcome of the most recent event (such as competition for sensitizing staff's attention.)

Deriving expressions for both safety stocks and event timing for a product P requires defining the following variables for product P:

t = average time between events in weeks
n = number of events that are frozen and that have not occurred
Q_{target} = target footage for an event in feet (assume constant)
τ = time for event n + 1 in weeks (decision variable)
s_p = standard deviation of process variation in ft/event
μ = mean demand by finishing in ft/week
s_d = standard deviation of demand variation in ft/period-week
s_t = standard deviation of test release variation as defined by $s_{(NR - NF)}$ in feet/event

It is apparent that the inventory at some time in the future just prior to the n + 1 event is the sum of the current inventory and the footage produced by the next n events minus the demand between now and the n + 1 event. In equation form,

$$I(\tau^-) = I(0) + n\tilde{Q} - \tilde{D}(0, \tau)$$

where $\sim$ implies these parameters are non-deterministic.

In setting the timing τ of the n + 1 event, one desires the probability that the inventory just prior to this n + 1 event exceeds 0 to be some high number, such as 0.98 or,

$$\Pr(I(\tau^-) > 0) = 0.98$$

The expected value of the inventory just prior to the n + 1 event can be expressed as

$$E(I(\tau^-)) = I(0) + nQ_{target} - \mu\tau$$

where μ is defined as the mean demand per week. The variance and standard deviation of $I(\tau^-)$ can be expressed respectively as

$$Var(I(\tau^-)) = ns_p^2 + ns_t^2 + \tau s_d^2 \text{ and}$$

$$s(I(\tau^-)) = (ns_p^2 + ns_t^2 + \tau s_d^2)^{0.5}$$

To have 98% confidence that a stockout will not occur, one wish to set τ such that

$$E(I(\tau^-)) = 2s(I(\tau^-))$$

or simply the safety stock level. Using the earlier definition of $E(I(\tau^-))$ and $s(I(\tau^-))$ the following equation results:

$$I(0) + nQ - \mu\tau = 2(ns_p^2 + ns_t^2 + \tau s_d^2)^{0.5} \qquad \text{Equation 2}$$

For the stockout protection policy that is being recommended, the yield outcome of the most recent sensitizing event is included in the safety stock calculation. The concept of number of events frozen can be confusing due to the nature of the process variation considered here. As was discussed earlier in the thesis, all process uncertainty appears immediately in the outcome of the sensitizing event itself. However, test release uncertainty (as it has been defined in this thesis) for one event does not appear until the time of the next event. In other words, one is exposed to test release uncertainty from the most recent event to the next event and therefore must protect over this period.

This policy allows for adjustment in timing of event n + 1 until immediately after the most recent event has occurred. Consequently, freezing n events that have not occurred has the following implications for safety stock and future event timing:

- safety stock must protect against process variability over n events, and test release variability over n + 1 events
- the timing of the next event following the n frozen events will be used to accommodate the actual process outcome from the most recent event only.

Therefore, since the evaluation of τ will be made immediately after the most recent event, equation 2 becomes the following:

$$I(0) + Q_{\text{most recent event}} + nQ_{\text{target}} - \mu\tau = 2(ns_p^2 + (n+1)s_t^2 + \tau s_d^2)^{0.5} \quad \text{Equation 3}$$

where I(0) remains the inventory level just prior to the most recent event.

As an example of setting safety stocks for combined variability and of timing future events to avoid stockout (see Figure 44 for depiction of this policy), suppose one enacts a policy of having <u>one</u> event (event 2) frozen beyond the most recent event (event 1) and one bases the decision for timing of the event (event 3) following the frozen event on the yield outcome of the most recent event.

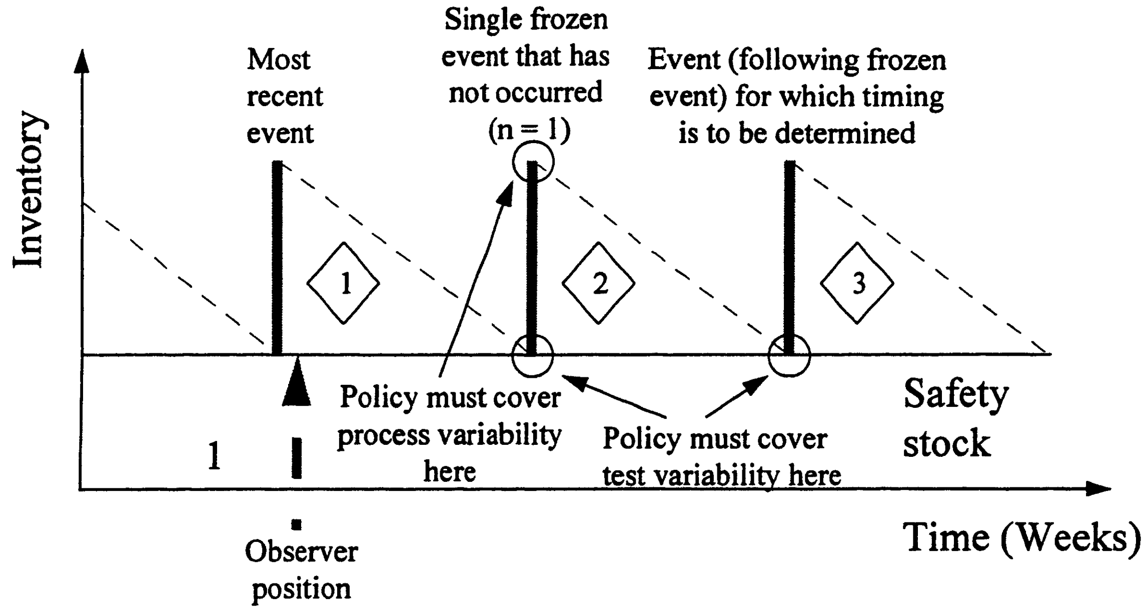


Figure 44: Event freeze and timing for stockout protection policy with one frozen event

This policy would need to protect against process variability in the single future frozen event (event 2), and against test release variability for the most recent event (N_R - N_F recorded at the time of event 2) and the single frozen event (N_R - N_F recorded at the time of event 3.) As defined, this would imply n = 1, the number of future events frozen that have not occurred using an observer position immediately following the most recent event.

To continue with the example, suppose a sensitized product P of concern has the following parameter values:

n = 1 frozen event that has not occurred (as just defined)
Q_{target} = 100 ft
s_p = 10 ft/event
t = 5 weeks between sensitizing events(average)
μ = 20 ft/week
s_d = 5 ft/period-week
s_t = 5 ft/event

To keep the example simple (see Figure 45 for depiction of the example), the author has chosen to use linear feet of material expressed as "feet" as the units of the parameters. (Yield fraction and demand variability as a fraction of event size work as well.) The expected safety stock levels for both sources of variability are calculated using the right side of Equation 3 with $\tau = nt$ (where n = 2, one event that just occurred and one event frozen beyond this):

$$\text{Safety stock (98\%)} = 2(1(10)^2 + (1 + 1)(5)^2 + 10(5)^2)^{0.5} = 40 \text{ ft}$$

Now let us suppose in Event 1 there was a yield outcome of 85% ARF or 85 ft and that the actual inventory position just prior to Event 1 was 26 ft. One can use Equation 3 to determine the proper placement τ of Event 3, the event following the frozen event as follows:

$$26 + 1(85) + 1(100) - 20\tau = 2(1(10)^2 + (1 + 1)(5)^2 + \tau(5)^2)^{0.5}$$

which solves by quadratic formula to the real solution of τ = 8.6 weeks. These policy actions are depicted in Figure 45.

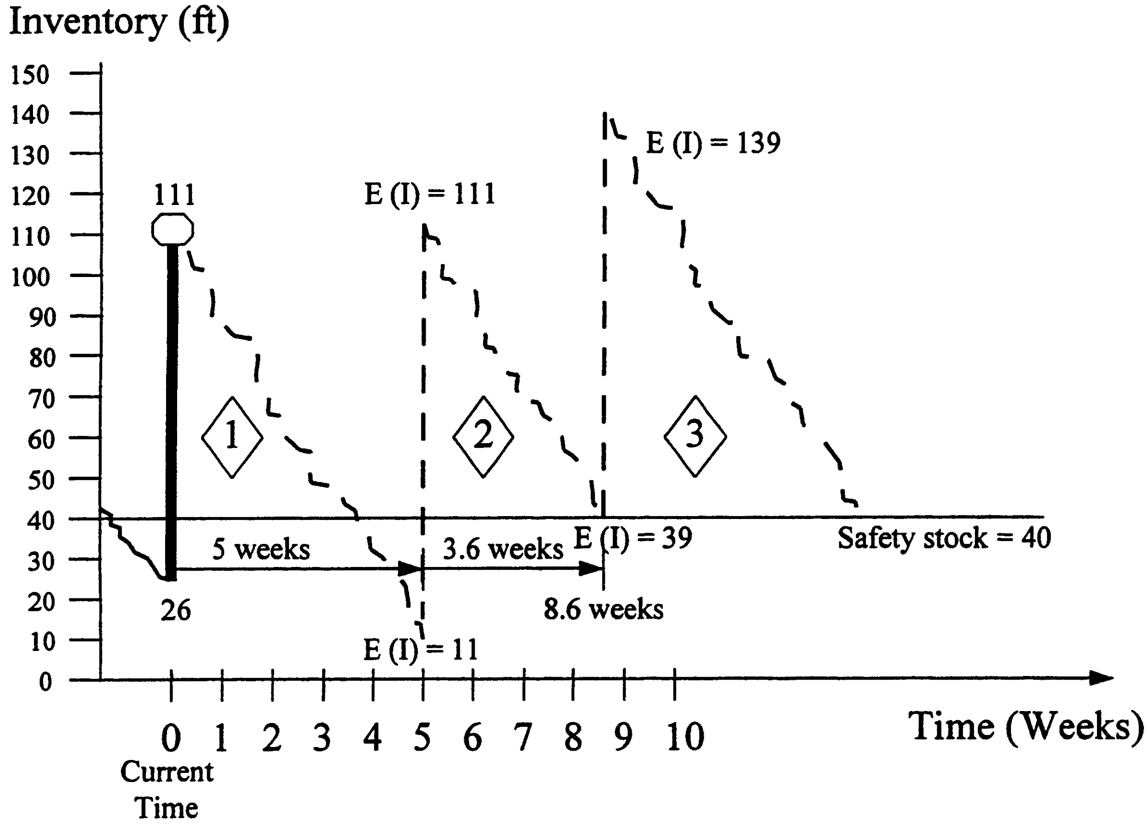


Figure 45: Inventory vs. time for scheduling of n+1 event

In this figure, current time is taken as t = 0. Based on the combination of the inventory position I(0) of 26 just prior to Event 1 and Event 1's outcome of 85 ft, inventory increases to 111 at time t = 0. Equation 3 directs us to shift Event 3 inward 1.4 weeks so that it occurs 3.6 weeks after Event 2. (If the inventory position I(0) had been 45 (design safety stock level) and Event 1 had reached the target footage of 100 ft, then Event 3 would remain scheduled to occur 5 weeks after Event 2.) One sees that in terms of replenishing safety stock, process outcome is taken into account by the $Q_{\text{event 1}}$ value and demand outcome and test delay by the I(0), the actual inventory level just prior to Event 1.

Since this policy allows the CFM Flow to freeze future orders (while protecting the customer against stockout), there will be a reduction in schedule disruption transmitted to raw material suppliers. The lower raw material inventories that can result from this reduced disruption has the potential for significant savings.

4.5 Impact of general headroom changes on bow wave

Prior to and during the author's tenure at the host company site, the CFM Flow Division was considering changes in the headroom allocated to the sensitizing schedule. Towards the end of the internship, three significant scheduling-related changes took place:

- the sensitizing machine went from a five-day to a seven-day a week operation in November 1996 (a result of increased demand for sensitized goods, not a result of the internship findings)
- the capacity manager put significant additional "headroom" into all future sensitizing weeks in November 1996 to allow for common cause process and demand variability (partly a result of the internship findings)
- the CFM Flow implemented the Headroom for Incident Failure Plan in week 12 of the September 1996 such that it was first available for use in early December 1996 (a direct result of the internship findings)

It is difficult to specify the particular impact of each of these policy changes on the accuracy of future sensitizing workload. However to get an idea as to how effectively the CFM Flow was allotting future capacity, the author gathered scheduling data after the end of the internship and built the plot of weekly machine hours planned vs. number of weeks in the future. As the reader can revisit, this was the basis for displaying the schedule loading disparity in Chapter 3.1.2.

Figure 46 compares the schedule loading disparity for the period May 1996 - September 1996 to the schedule loading disparity for the period October 1996 - March 1997. One can see that there is a dramatic difference in the two lines.

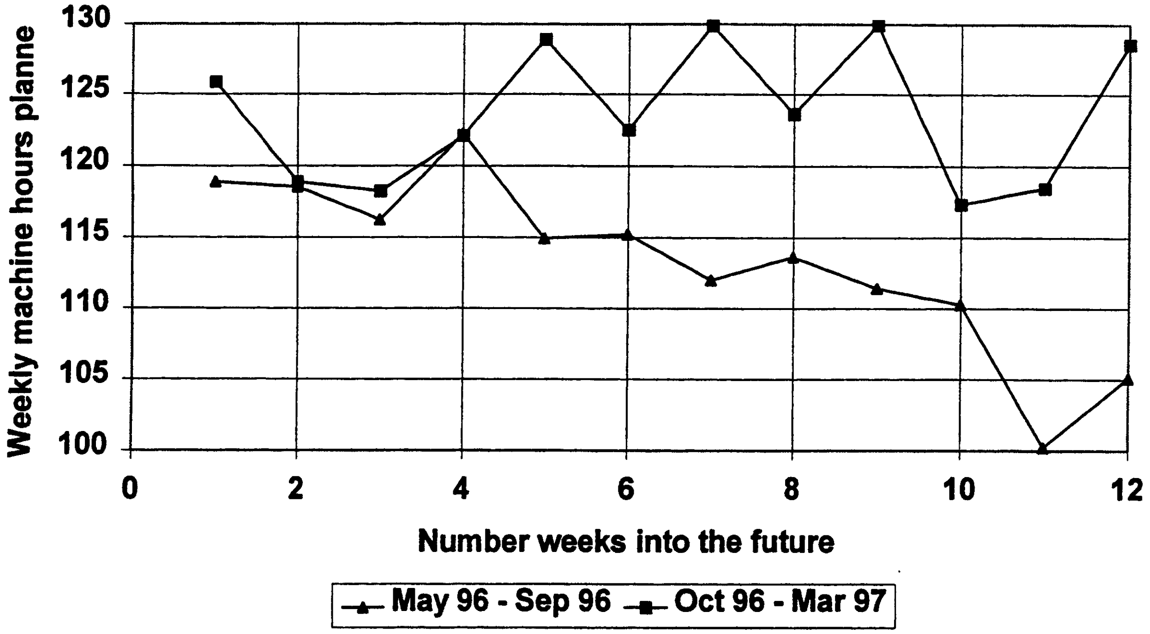


Figure 46: Average of sensitizing machine weekly machine hours planned vs. number of weeks into the future (5/96 - 9/96 & 10/96 - 3/97)

The weekly hours planned for the earlier period follows the schedule loading disparity pattern with near-term loading exceeding long-term loading. The plan for 11 and 12 weeks in the future was for a load of 100 - 105 hours; and as time rolled forward, the planned load increased to 117 - 118 hours for 1 - 2 weeks in the future. However, for the later period, the same phenomena did not occur. The plan for weeks 11 and 12 carries 118 - 128 hours and for weeks 1 and 2 in the future carry 119 - 126 hours. It would appear that the combination of new scheduling policies is doing a much better job of aligning anticipated machine load with actual machine load. From this viewpoint, the bow wave has disappeared.

5. Recommendations for Future Work

Although the author would like this work to be the comprehensive solution for Commercial Film's variability problems, this simply will not be the case. The issue of variability in the Flow is a complex one, made difficult by the large number of varied products, the multiple sources of variability, as well as the difficulty of the film sensitizing process itself.

The author can recommend several areas for follow-up work in the future:

- determine the parameter values for the combined variability policy an implement the new safety stocking policy
- determine the optimal number of future sensitizing events to freeze as impacted by
- evaluate the component supplier financial opportunities created by reducing schedule disruption through sensitizing order-freezing
- streamline the actual process of updating calculations of variability
- find opportunities for transforming the wide-roll evaluation and testing process from a primarily staff function to a primarily production function

Pursuing improvement in these and related areas should allow the to provide excellent protection to its customers at low cost.

6. Conclusions

From the study of the Commercial Film Flow of Eastman Kodak Company, the thesis author has concluded the following:

- segmenting the three forms of process variability (common cause process, uncommon cause process, and test release) and developing individual planning, scheduling, and inventory policies that are customized to each variability form has resulted in significant financial gains to the CFM Flow
- incident failures (uncommon cause low yield) are unpredictable at an item level, but their frequency of occurrence is fairly predictable in aggregate
    - for products that sensitize in events > 50 KLF, the CFM Flow should protect against incident failures with undedicated machine capacity, not with wide roll safety stock
    - for products that sensitize in events < 50 KLF, the CFM Flow should protect against incident failures with wide roll safety stock, not with undedicated machine capacity
    - a policy for allocating undedicated capacity in the future schedule to allow for remake of products that have suffered incident failures has proven to be significant in reducing the need for safety stock inventory
- a significant percentage of wide roll entering testing is released very soon after in predictable fashion. However, a number of rolls take much longer and their eventual release time is highly unpredictable. To protect against test release variability, the CFM Flow should keep safety stock inventory based on the variability in the distribution of the difference between the number of rolls released in each event and the rolls consumed by finishing at the time of each sensitizing event.
- common cause process variability for the wide roll sensitizing is a normal distribution. Safety stock should be used to protect against this form of uncertainty.

- a safety stock and future event timing policy that allows freezing of future sensitizing events so as to reduce the schedule disruption transmitted to raw material suppliers. Implementation of this policy could result in significant savings across the supply chain

Many times, all that is needed to change an organizational culture is education. The willingness of the individuals in the CFM Flow to try the policies recommended in this thesis and the success these policies have had are a direct result of the following:

- the proper characterization of the phenomena under study by the thesis author and the uncovering of its root causes
- the gathering, analysis, and presentation of relevant data that substantiate the reasons for the policies.

Production planning and scheduling systems that do not recognize and accommodate process variability with an understanding of that variability will incur significant schedule disruption and require substantial inventories to provide adequate customer service. This thesis has shown that, through statistical analysis of the individual sources of this process variability, one can improve the planning, scheduling, and inventory policies to reduce the impact of the variability and realize significant cost savings.

7. Appendix

7.1 Step-by-step comprehensive policy

The following is intended to serve a summary guide for how the author recommends the individual sources of variation be characterized and combined into a policy that protects against stockout at reasonable cost.

Steps for Capturing Variability

I. Remove all sensitizing biases (both process bias and calculation size). (Removing sensitizing bias properly may require some iteration between calculation of the true mean yield and the determination of incident failures. Some judgment must be used since incident failures will reduce to calculated true mean such that the incident failure may not be outside the 20% range. One can refer to the discussion of calculating standard deviation for product 3 following Figure 29 for a further description.)

   A. Using sensitizing yield data for the past 12 months, confirm the existence of sensitizing bias for each product by sensitizing family if one exists, otherwise calculate it by product.

   B. Make an adjustment in expected footage from a given quantity of emulsion as specified by the bias such that 100% PF is the true mean yield.

   C. Until such adjustments are made, calculate the standard deviation from the calculated mean of the set of actual outcomes for sensitizing variability rather than from the target 100% PF.

II. Recalculate the standard deviation of sensitizing common cause process variation (s_p) every six months

A. Search the last 12 months of sensitizing yield data for incident failures (incident failures being defined as events having PF > 50 KLF and %ARF < 80% PF.) Remove these from each product's set yield data.

B. Check for uniqueness of yield distribution between each line of business and the set of all products sensitizing on the machine (as of 11/96, H is the only unique line of business at 90% confidence)

   1. line of business- Combine the remaining sensitizing yield outcomes by line of business
   2. Sensitizing machine- Combine the remaining sensitizing yield outcomes for all products sensitized on the machine.
   3. Calculate a chi-square value between each line of business yield distribution and the entire product set yield distribution to test for goodness of fit
   4. If the confidence in uniqueness exceeds 90%, consider that line of business distribution unique. Otherwise, consider it part of the sensitizing population.

C. Using the appropriate data set, calculate the standard deviation (s_p) as follows: $s_p = \left((\text{sum}(\text{true mean yield} - \%\text{ARF for each event})^2)/(n-1)\right)^{0.5}$ where n = number of events in the data set. The parameter (s_p) can be kept in units of percent or multiplied by average event size to get units of KLF (thousand linear feet.)

III. Recalculate the standard deviation of test release process (s_t) every six months

A. For each line of business, calculate the data set ($N_R - N_F$), the distribution of the difference between the number of rolls released in each event (N_R) and the rolls consumed by finishing (N_F) at the time of the each sensitizing event.

B. Calculate the standard deviation $s_t = \left((\text{sum}[\text{mean}(N_R - N_F) - \{(N_R - N_F) \text{ for each event}\}]^2)/(n-1)\right)^{0.5}$ where n = number of events in the data set.

The parameter (s_t) can be kept in units of KLF (thousand linear feet) or divided by average event size to get units of percent.

IV. Recalculate the standard deviation of demand (s_d) at an appropriate frequency

  A. Use a method for calculation that considers the variable nature of both the monthly forecast and weekly finishing rate.

  B. Keep s_d in units of % or KLF (thousand linear feet), but be consistent with the other two sources of variability.

V. Utilize the method for combining variability and freezing orders discussed in Chapter 4.4 to set safety stock levels and determining scheduling of future sensitizing events.

  A. For each product determine the desired number of events to freeze (n)

  B. Based on the known measures of variability, use actual sensitizing outcomes, and inventory positions to determine timing of the event immediately following the n frozen events.

VI. Continue using the Headroom for Incident Failure Plan described in Chapter 4.1.2.2.

7.2 List of Acronyms and Explanations

BOM- bill of material

bow wave- same as schedule loading disparity

CFM Flow- Kodak Commercial Film Manufacturing Flow Division

common cause variation- day-to-day variation

Freeze, frozen, or fixed zone- the portion of the production schedule, usually in the near term, that is considered fixed and unchangeable without significant reason for a change.

Code Names for film LOB's:

headroom- undedicated capacity in the future sensitizing schedule

incident failure- a sensitizing event yield outcome < 80% of target footage

MPS- master production schedule, the schedule for finished goods from which the schedule for component suppliers is determined

MRP- material requirements planning

MRP II- manufacturing resources planning

nervousness- schedule disruption transmitted to component suppliers from changes to the master production schedule for finished goods

safety stock- inventory carried to protect against stockout due to variation in supply, demand, and process variation

schedule loading disparity- near-term higher loading, long-term lower loading in the future sensitizing production schedule

shortfall- a sensitizing event outcome of < 100% target footage

UMC- unit manufacturing cost

uncommon cause variation- significant variation with a special, infrequent source

8. Bibliography

Ho, Chrwan-Jyh. "Evaluating the impact of operating environments on MRP system nervousness." International Journal of Production Research, 27 no. 7 (1989): 1115-1135.

Homsi, Kristopher. LFM Masters Thesis: Information Flow and Demand Forecasting Issues in a Complex Supply Chain. MIT Sloan School of Management, MIT Department of Chemical Engineering, (1995), pp. 19 - 22.

Hopp, Wallace J., and Spearman, Mark L. Factory Physics- Foundations of Manufacturing Management. Irwin Publishing. Chicago. 1996.

Kruger, Greg. "Supply Chain Analysis- Managing Uncertainty." Hewlett-Packard publication, 7/17/96.

Madsen, Jakob Brochner. "Test of rationality versus an 'over optimist' bias." Journal of Economic Psychology, 15 (1994) 587-599.

Sridharan, V., Berry, W.L., & Udayabhanu, V. "Measuring master production schedule stability under rolling planning horizons." Decision Sciences, 19, no. 1 (1988): 147-166.

Wilson, John J. LFM Masters Thesis: Determination of Optimal Safety Stock Levels for Components in an Instant Film Assembly System. MIT Sloan School of Management, MIT Department of Chemical Engineering, (1996), page 39.