Implementing Postponement into Low-Volume/High-Variability Manufacturing

by

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B.S. Engineering Management, United States Military Academy, 2007

Submitted to the MIT Sloan School of Management and the Engineering Systems Division in Partial Fulfillment of the Requirements for the Degrees of

Master of Business Administration

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Abstract

Aircraft Company X (AX) manufactures and assembles an immense variety of parts utilized as drive systems and rotor components across its multiple aircraft. The company's value proposition is maintaining the ability to build and service all legacy parts and as a result there is a great deal of variety found in its manufacturing processes. This variety stems from upgrades to manufacturing technology, improvements in material science, design variations, and individual part engineering modifications. In order to be responsive to fluctuating demand while minimizing costs, AX must broadly implement postponement into numerous applications as a way to extract the most value from its resources.

This thesis uses multiple applications of postponement within AX to establish a methodology that can be used across various materials, both metallic and non-metallic. This methodology guided implementation of postponement through material physical form consolidation, material substitutions, and even provided insight into which manufacturing technique given a particular material form is optimal. The benefits are numerous to include a roughly 30% inventory reduction, improved buying power resulting in cost savings of over 10%, a reduction of material shortages by over 40%, and shorter lead times for finished goods. Extensions of these applications include aligning AX's supply chain with its suppliers utilizing identified tolerances and adding layers of postponement beyond raw material inputs.

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My wife Alison, for providing the foundation at home that all of my success rests on. Thank you for being a part of this journey and always supporting my endeavors.

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Table of Contents

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List of Figures and Tables

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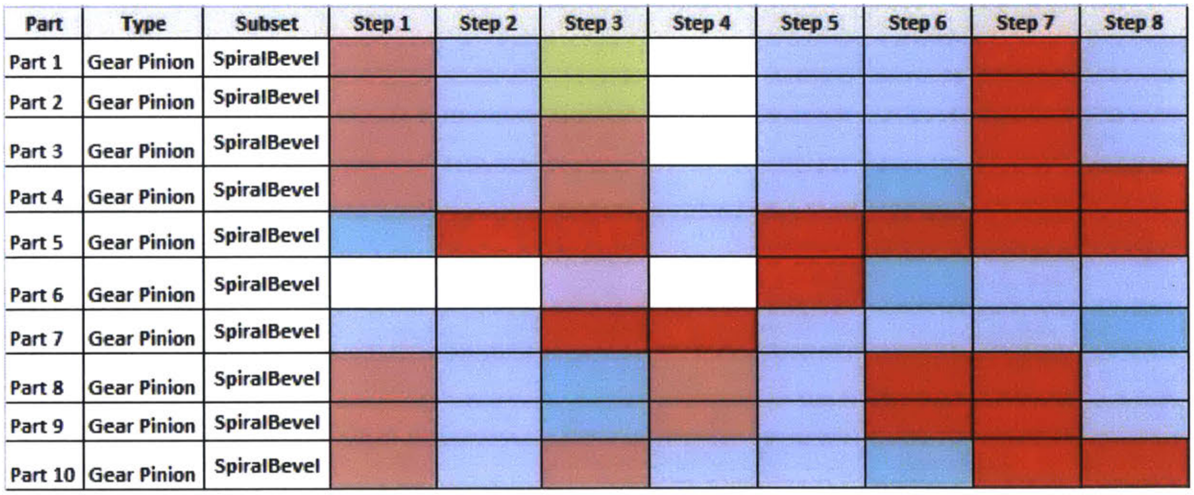
1. Introduction

This chapter outlines the purpose of the project in order to frame the impetus for the effort. Additionally, the problem statement and hypothesis will be outlined as the foundation to the analysis. Lastly, the approach to addressing the problem will be summarized and the thesis structure outlined.

1.1 Purpose of the Project

Aviation Company X (AX) is a manufacturer of aircraft that has a long history of innovation and is renowned for quality. A major part of AX's competitive advantage is its drive and rotor systems' superiority to those of its competitors. AX has retained the sole ability to produce the majority of these components and as a result must maintain legacy manufacturing processes. Over time aircraft design practices changed, machining technology advanced, and material sciences developed stark differences in how similar parts were manufactured. Today, two components that are seemingly identical and serve the same function will be made through vastly different processes. **Figure 1** below demonstrates the current situation. Every row indicates an individual part and the colored boxes are manufacturing steps. Common steps have common colors. All of these parts belong to the same part family, which means they have similar physical features and serve similar purposes. It can quickly be observed that there is almost no commonality in how they are produced and therefore parts are differentiated immediately.



Part	Type	Subset	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8
Part 1	Gear Pinion	SpiralBevel								
Part 2	Gear Pinion	SpiralBevel								
Part 3	Gear Pinion	SpiralBevel								
Part 4	Gear Pinion	SpiralBevel								
Part 5	Gear Pinion	SpiralBevel								
Part 6	Gear Pinion	SpiralBevel								
Part 7	Gear Pinion	SpiralBevel								
Part 8	Gear Pinion	SpiralBevel								
Part 9	Gear Pinion	SpiralBevel								
Part 10	Gear Pinion	SpiralBevel								

Figure 1. Current Manufacturing Process for Similar Parts

The purpose of this project is to a) identify the feasibility of implementing a single layer of postponement with raw material inputs, b) determine the associated benefits, and c) validate the implementation of the proposed consolidation of raw material inputs.

1.2 Problem Statement

The aircraft manufacturing industry is a low-volume high-variability sector. Consequently, it is imperative for a company's success to find an appropriate balance between minimizing inventory costs with being able to meet customers' demand in an expedient manner. One way to accomplish this goal is to introduce postponement, a delayed differentiation between manufactured products, in any way possible. Complicating this effort is the necessary oversight and strict adherence to quality specifications that is a rule of law in the aviation business. One cannot simply swap materials or parts from one aircraft type to another. Understandably, there are explicit material requirements based on vast analysis focused on ensuring parts can withstand the extreme stresses placed on them when in operation. With this in mind, the problem becomes determining opportunities to postpone part production in a manner that satisfies engineering specifications and can be feasibly implemented into a complicated sourcing system.

1.3 Hypothesis

This project hypothesizes that there are various opportunities to delay product differentiation by utilizing raw material postponement. This can be achieved by implementing optimization tools such as integer programming optimization combined with thorough research of pre-determined material specifications. Through this work, a most advantageous variety of raw materials can be identified to minimize variation of inventory while maximizing the company's ability to meet demand in a timely manner.

1.4 Project Approach

In order to test the hypothesis a phased approach was utilized which focused on analyzing a sample with which to prove the methodology. This initial sample consisted of a large number of parts originating from similar materials with similar manufacturing operations. The overall approach is as follows:

1) Identify the material which through analysis could demonstrate the most value.
2) Determine an appropriate sample of parts utilizing the identified material type.
3) Develop a strategy for optimizing the postponement of manufacturing through material consolidation.
4) Analyze results of optimization and determine feasibility for implementation.

5) Evaluate costs and benefits of optimization results for the company.
6) Establish an implementation process that maximizes the likelihood of result sustainment.
7) Identify opportunities for similar methodology application involving other materials.

Essentially, these steps aim to prove the feasibility of implementing postponement, quantify potential benefits, provide a process for determining the optimal postponement outcome, and demonstrate implementation of the proposed solution.

1.5 Thesis Overview

The following chapters of this thesis will provide a background on AX, its industry, and the current state of its raw material procurement strategy (Chapter 2); review the literature of pertinent prior research regarding postponement in the manufacturing industry (Chapter 3); outline the detailed approach utilized to determine the optimal method for applying postponement (Chapter 4); and provide an overview of the implementation of postponement for raw material inputs (Chapter 5). Chapter 6 will summarize the main points learned from the project and provide recommendations for further work.

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2. Background

This chapter will provide an exploration of AX's industry to include current trends which provide the motivation for change to the supply chain. The chapter will also describe the company itself and the current state of their procurement processes.

2.1 Industry

The specific industry in which AX participates accounts for roughly $34 billion annually; 54% of which is accounted for by just five companies (Forecast International, 2015 and Frost and Sullivan, 2016). The market is segmented into categories focusing on the size and lift capability of the aircraft along with whether it serves the military or commercial demand. Some aircraft can serve both commercial and military demand once modified. Despite market competition, the major participants in the market tend to collaborate on technology, especially when serving military interests. North America occupies 42% of global market demand followed closely by Europe (IBA Group, 2016). Due to the complicated nature of the industry's technology, complex supply chains are developed around a vast number of suppliers and partners. Therefore, it is difficult to achieve cost savings through scale as a result of expensive research and development fixed costs. Military aircraft must also go through an extended procurement and testing development process which can be substantially expensive. Recently, there has been a sharp decline in demand for military aircraft and a leveling of demand for commercial aircraft which is further pressuring companies to refine their logistics in order to prepare for decreases in revenue (Aero News Network, 2016 and National Defense Magazine, 2014). While this decline is impacting new aircraft manufacturing there is also still an existing fleet of aircraft in operation that AX and its competitors must be prepared to provide spare parts for. This spare part demand is forecasted relatively accurately by monitoring flight hours but there are still spikes in demand that are unforeseen. Competition has heightened as the major players in the industry are vying for a larger piece of market share in a recently shrinking market.

2.2 AX

AX provides its value proposition through superior quality and customer service. The company has developed and manufactured aircraft for over 80 years providing options across all segments of the market. AX prides itself as an innovator while also staying loyal to customers of legacy aircraft. This simultaneous focus of past, present, and future programs creates a challenging manufacturing environment where resources and capacity must be aligned with production forecasts which themselves are often dynamic. In the face of a declining market and competitor consolidation, AX has responded by investing in new and improved product lines with the goal of obtaining a larger portion of the market share as it anticipates the revitalization of consumer demand. As AX constructs the supply chains for its new programs it will be imperative that it apply the lessons from previous and ongoing continuous improvement initiatives in order to be responsive and cost effective (Womack and Jones, 2003). Not only should operations be optimized for the current state of the business but also be robust and scalable enough so that they can meet demand when aircraft markets and associated demand return to traditional levels.

2.3 The Current State of Procurement

In order to understand the procurement it is first useful to become familiar with pertinent nomenclature within AX. **Figure 2** outlines terminology that will be utilized throughout this paper.

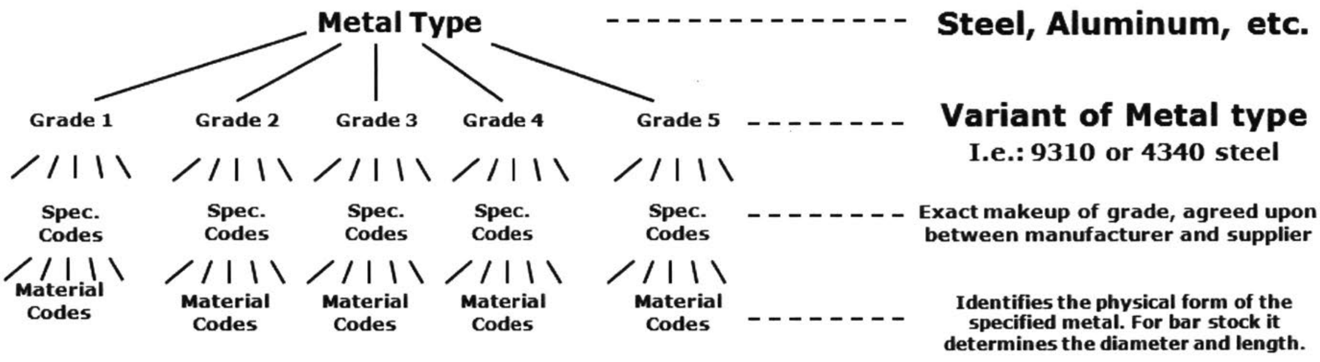

Figure 2. Pertinent Material Terminology

Metallic bar is used for demonstration purposes but this terminology applies to composite materials as well. As one goes down the levels in **Figure 2** they are becoming more granular on how material is described. For instance material code 123-456 is describing a 6 inch piece of bar stock that is specification 1 of 4340 grade steel. 4340 steel will have many specification codes, of which will have many material codes (bottom level of **Figure 2**). Understanding this is important to addressing necessary processes.

Figure 3 depicts the required terminology for composite materials.

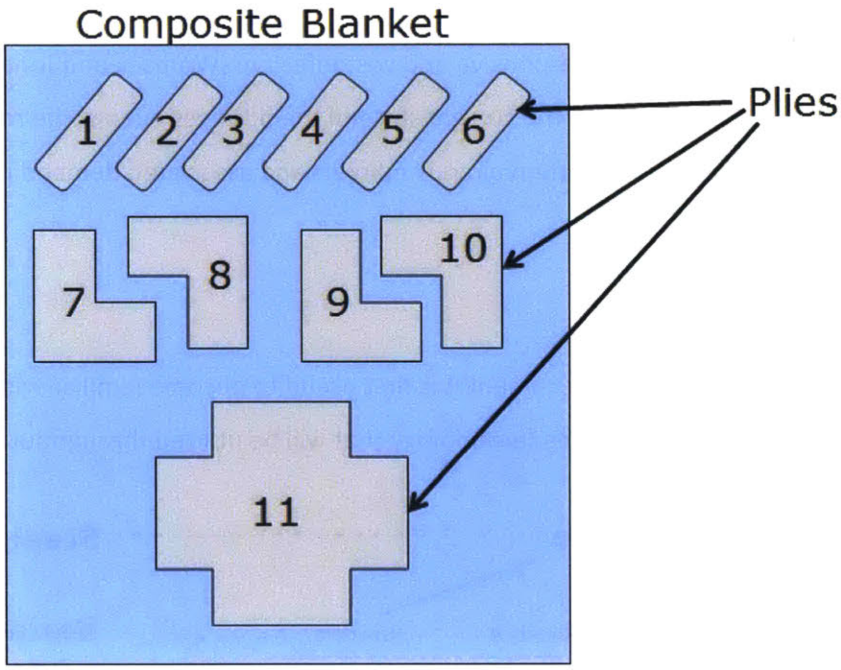

Figure 3. Pertinent Composite Terminology

The blue square represents a segment of composite material, "blanket", from which plies will be cut. The width and length of the blanket is determined by its material code. These plies are one layer of a given part and will be stacked with other plies to form a finished part. It is important to note that various plies on a given part can be from different material specifications. Additionally, while all of the plies on this blanket are referred to as a single "nest", they are not necessarily going to the same part.

Historically, within AX all material requirements are determined by design engineers at the early stages of product development; referred to as the material "call-out." From there, many steps occur that impact the buying of materials and ultimately inventory. Each step is relatively insulated from others and there is limited communication upstream in the process. **Figure 4** portrays this process as well as identifying the responsible function for each step:

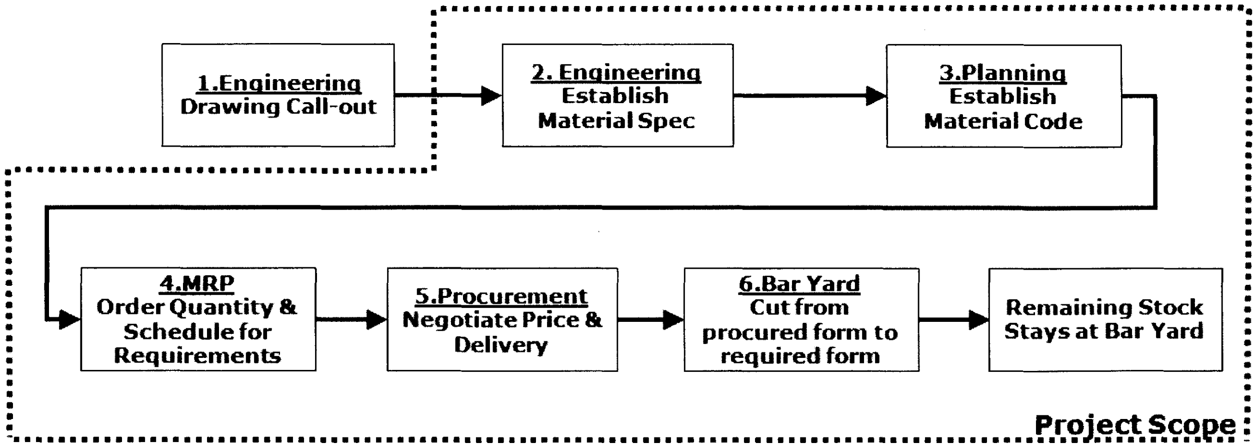

Figure 4. Material Determination Process Map

As **Figure 4** demonstrates there are numerous hand-offs resulting in greater potential for disconnects:

1. to 2.Engineering will design a part's final form and also identify the desired material specifications (spec) that meet necessary performance requirements. Whenever a change is desired, it must be approved by engineering. It retains ownership of material selection and all changes are noted and retained in the company's database.

3. Planning will then take engineering's final form and specs to create a material code. The material code represents the input that goes into all required machining processes with the finished part being the output. Planning also determines all of the manufacturing steps that occur to the material. If a change is made by engineering regarding material type or physical form, planning must revise all of the relevant manufacturing steps.

4. Material Requirements Planning (MRP) will utilize forecasts and lead times to develop a procurement schedule in order to produce the demanded parts when they are desired. The reality is that both the forecasts and lead times are often highly variable. Additionally, there is limited capability to stop a purchase order once it has been fulfilled.

5. Procurement takes the MRP schedule and begins to buy accordingly. These purchases can either be spot-buys or contract purchases. A typical spot-buy involves a buyer researching potential suppliers and requesting prices for the desired quantity. These prices will be at the mercy of current commodity indices and available supplier capacity. Due to suppliers' need to overcome fixed costs associated with making materials, there are often minimum order quantities (MOQ) for a given purchase. These MOQs

effectively require the purchase of more material than actually demanded. A contract purchase will be based off of long-term negotiated quantities and prices, unless there are outstanding market factors requiring a re-negotiation.

6. The bar yard is where inventory is maintained. Often the raw materials are purchased at industry standard dimensions. As an example, varying diameters of bar stock will all be delivered at twelve foot lengths. It is the bar yard's responsibility to take the twelve foot long bar and saw it to desired lengths so that manufacturing can begin the production process planning has laid out. The bar yard then returns the remaining stock into its inventory.

Currently, AX procures all of its materials to the exact dimensions engineering has called out on their part drawings. This is despite the fact that engineering has created blanket allowances for both material substitutions and ranges for starting dimensions. Allowances are important because they provide manufacturing with flexibility regarding what it can utilize as input for a manufacturing process. Examples of this are in the following table.

Table 1. Examples of Engineering Allowances

Type of Allowed Deviation	Scenario Example
Substitution	*Call Out*: 5 inch, spec A, 9310 steel bar *Allowed Material*: 5 inch, spec B, 9310 steel bar
Alternate Material Form	*Call Out*: 5 inch, spec A, 9310 steel bar *Allowed Material*: 5.5 inch, spec A, 9310 steel bar
Alternate Material Process	*Call Out*: Part specific casting *Allowed Material*: Machined 5 inch, spec A, aluminum bar

These allowances are significant but because of the existing processes and systems they are not leveraged. System limitations result in inventory being under-utilized and effectively un-pooled rather than optimally consolidated as demonstrated in **Figure 5**.

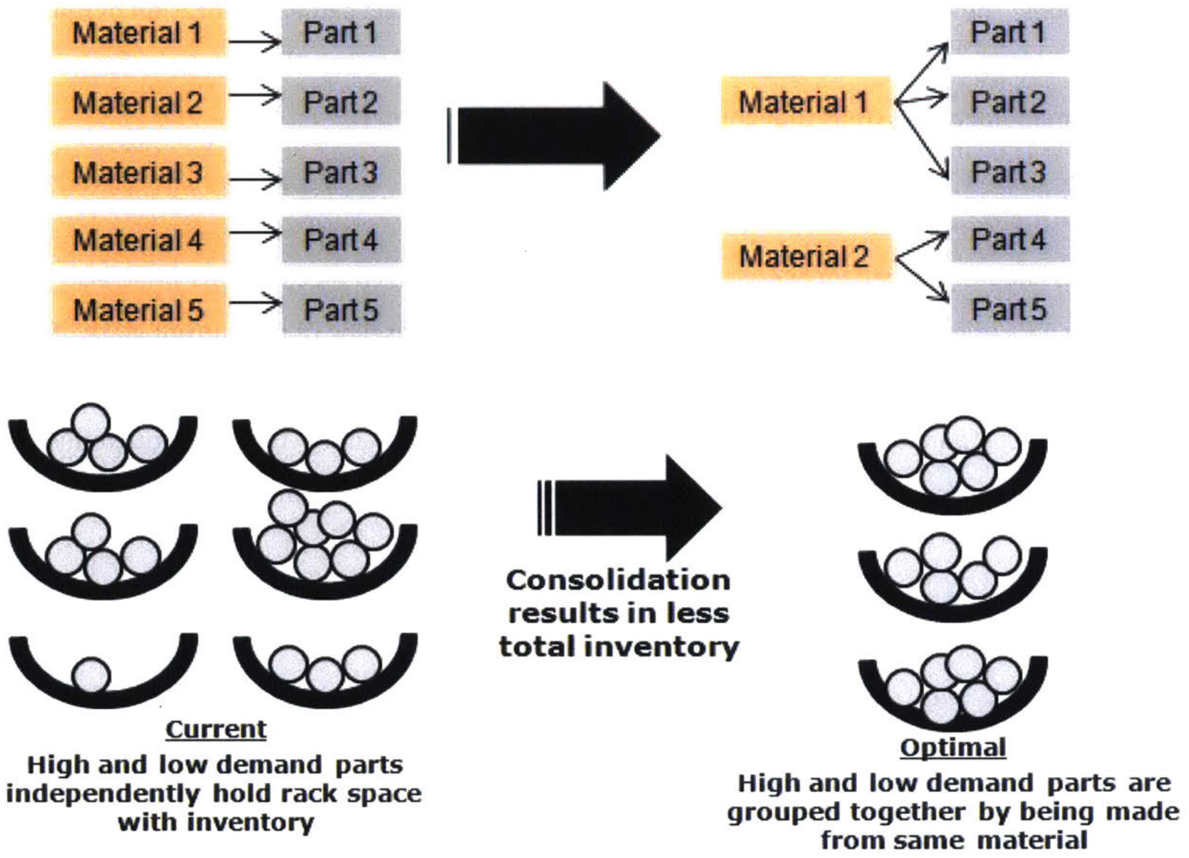

Figure 5. Comparison of Current State to Optimal State

There can be a delay in production due to a stock-out of material even though material that is within allowance is currently available. Often there is excess inventory of a given material code which was procured at MOQ and since the only part(s) that call for it are low demand it will take a longer time to turnover. There may be a higher demand part which could use the allowances to deplete the excess but the system limitations restrict this option from occurring. Occasionally, production will take advantage of the allowances but it is a long and arduous procedure which requires multiple levels of approval.

Further limitations of this existing process are that there is not enough manpower within AX and a lack of oversight regarding a review of these allowances. Over time, operations have changed regarding material oversight and even physically moved to a different facility. Parts of similar dimensions calling for the same spec may have been made from different material codes just because that was all that was available at a given location. Materials were optimized regionally but not as a whole. These operations were later consolidated but there was never any analysis to identify overlaps of material codes. The end result is composite parts calling for the exact same specification of material at the exact same dimension but being made from different material codes. These differences generate additional manufacturing steps that could easily be eliminated.

2.4 Summary

This chapter offered an overview of the industry within which AX competes while also providing specifics to AX's role in that industry. Additionally, it provided a baseline of the current state of AX's procurement operations, along with its existing limitations, which will serve as the setting for implementing postponement into low-volume and high-variability manufacturing. Through this review it is apparent that AX must take measures to become more flexible in satisfying a growingly customized demand.

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3. Literature Review

This following is a brief overview of pertinent literature regarding postponement as a theory and its current applications to various industries. It is important to understand the complexities when assessing the need for postponement and how to properly implement it.

3.1 Overview of the Concept of Postponement

Postponement or delayed differentiation provides a solution to countless manufacturing issues arising from uncertainty in fluctuating demand, variable process times, and difficult material sourcing. Yang, Burns, and Backhouse provide a comprehensive history of academic literature and applications that serves as a foundation for the understanding of the concept in practice (Yang, Burns, and Blackhouse, 2004). The authors explain the desire of companies to provide customization to customers in the most efficient means possible. This can be achieved by delaying the differentiation of various products until as late in the manufacturing process as possible through changes in logistics, manufacturing, and the supply chain; otherwise known as postponement. The historic technique of mass production with limited variation simply no longer suffices in a majority of marketplaces and businesses must accept that reality.

Postponement itself is not a new concept and can be traced back to 1950 when Wroe Alderson explored its application to achieve marketing efficiency (Alderson, 1950). Alderson argues that careful consideration should be taken when organizing process steps to control costs while maximizing efficiency. Despite being written over 60 years ago, the idea of postponement still maintains relevance. Ferreira, Tomas, and Alcantara extend postponement research beyond the fundamentals of the idea and propose a model for how to approach the implementation of postponement into a company most effectively (Ferreira, Tomas, and Alcantara, 2015). The authors' framework seeks to identify the drivers for adoption of postponement, the steps a company must take for implementation, and finally performance measures to identify the success of the implementation. This framework can be broadly applied as required.

When defending the decision to implement postponement a company will undoubtedly need to quantify the perceived benefits. Lee and Tang's research provides simple models which demonstrate the costs and benefits for three different strategies: standardization, modular design, and process restructuring (Lee and Tang, 1997). Swaminathan expands on these strategies and even introduces another extended application which pertains to procurement itself (Swaminathan, 2001). This insight is especially applicable to the implementation of postponement at AX.

3.2 Current Applications of Postponement

The trend towards less mass production is demonstrated by John Sprovieri's article in which he states that in 1996 25 percent of plants produced more than 1 million assemblies per annum. In contrast, in 2004, only 19 percent of plants met this number. In that same time period the percentage of plants that produced less than 1,000 assemblies increased by 11% (Sprovieri, 2004). This clearly demonstrates that smaller batches and customization have become more prevalent and companies must adjust their business practices accordingly in order to accommodate for this shift.

Examples of companies' responses to these trends through the application of postponement are numerous. Swaminathan and Tayur investigate a useful case of delayed differentiation utilized by IBM through what is termed "vanilla boxes" (Swaminathan and Tayur, 1998). The vanilla boxes refer to generic semi-finished products which can ultimately be used to produce multiple finished goods. The nature of IBM's product line allows for leveraging common components across multiple SKUs and the authors explore a two-stage integer program to find the optimal level of commonality.

Another example of how postponement can be applied to a variety of product lines is provided in Feitzinger and Lee's analysis of postponement at Hewlett-Packard (Feitzinger and Lee, 1996). In their study they emphasize the benefits of the proper application of postponement to balance the desire by customers to both receive goods quickly with the desire that the goods be highly customized. Further, the authors acknowledge accomplishing both of these goals requires an integration of many different functions' processes.

It is not unique to have conflicting goals when designing a company's supply chain, which undoubtedly presents difficult challenges. A thorough review of supply chain design considerations and techniques are examined by authors Simchi-Levi, Kaminsky, and Simchi-Levi in their book *"Designing and Managing the Supply Chain: Concepts, Strategies and Case Studies."* The authors lay out the trade-offs companies face when satisfying their customers and provide tools for analysis in determining the optimal supply chain approach through numerous current examples (Simchi-Levi, Kaminsky, and Simchi-Levi).

3.3 Optimization Tools for Supply Chains

Heuristics and algorithms have consistently been leveraged in order to determine best practices for manufacturing companies. An early application is Vaidyanathan Jayarman's model to determine the best distribution network allowing for minimizing costs while maximizing its delivery effectiveness (Jayaraman, 1998). Bachlaus et al. expanded this approach to fit a multi-echelon supply chain allowing for a more strategic solution (Bachlaus et al., 2008). Both examples provide a foundation of how to apply optimization models to supply chains that can be more broadly applied across various industries. A persistent limitation of optimization tools is that their effectiveness relies upon the quality of the data inputted. In reality, forecasted demand is not as deterministic as most would like and therefore uncertainty is an important consideration. Bai and Liu account for such uncertainty by developing a model that takes advantage of the fuzzy possibility theory, which is based on the notion of accounting for the many sources of uncertainty in a supply chain and ensuring there is not an overreaction to variation (Bai and Liu, 2014). There is no single all-encompassing model that can be effectively applied to any business, but these examples, and many others like it, allow for one to apply the most pertinent models and continue to improve upon them. An overview of integer programming complete with examples can be found in Bertsimas and Fruend's text *Data, Models, and Decisions: The Fundamentals of Management Science.* There are a plethora of pros and cons when determining how to model a business decision and all must be considered to properly replicate a business' environment (Bertsimas and Fruend, 2004). When properly employed, optimization tools can be both powerful and valuable.

3.4 Summary

There is a significant amount of existing literature covering the original theories of postponement and how to apply them. Additionally, researches have put extensive effort into determining how to best quantify the benefits of postponement. Optimization tools prove to be useful mechanisms to effectively implement postponement if variables are understood and accounted for. Lastly, since the application of postponement will vary depending on an industry's and the company's dynamics along with its unique products it is beneficial to review current examples of delayed differentiation in order to identify the appropriate level of implementation. This specific research proves to be unique in that it outlines an approach to achieve the implementation of postponement at the first level of raw material inputs. The approach is developed through analysis of a breadth of applications in a low-volume/high-variability manufacturing environment.

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4. Methodology

In this chapter the approach to implement postponement at AX will be demonstrated through three applications. The first application, steel bar stock, will serve as the basis for the development of the approach. The subsequent two applications, composite material and casting vs. machine analysis, will serve to expand and refine the postponement approach. The three applications demonstrate the broad reach of postponement and its effectiveness at adding value to a low-volume high-variability manufacturing company.

4.1 Postponement Implementation Approach

Implementing postponement requires specialized information and understanding. There are countless factors that play a role in how to best achieve the goal of delaying the differentiation of products. A company's strategic position in their market is the broadest factor and following that it will only become more complicated. Since it is nearly impossible to exactly compare one implementation of postponement with any other, a broader framework is needed to provide an approach any entity could utilize to begin their more specialized execution.

The following approach resulted from iteration and refinement during implementation of all three applications of postponement. It is intended to serve as a general guideline for enactment of postponement in order to provide value to a number of varying types of manufacturing. The usefulness of the approach is unique in that it focuses solely on raw material inputs in order to simplify a company's supply chain as a whole and extract the maximum amount of value from the minimum amount of resources. In AX's specific case there is currently no postponement, so the approach aims to implement the first level at the raw material sourcing step. This approach can also be leveraged to evaluate existing uses of postponement in more established processes.

1) <u>Identify highest volume and highest priced materials used for manufacturing.</u> This is relatively straightforward and in most cases the supporting data is readily available. The simplest approach is to reference existing material tracking systems and identify the most prevailing materials. It is important to understand how the material is procured and where it is utilized within an organization to ensure the postponement is truly beneficial. If procurement is executed in different locations and specifically purchased to accommodate different capabilities the change may require an entire process modification. For AX, this analysis revolved around the material specification and its physical

dimensions. The reason for this focus was the constant fluctuations in part demand and fluid material prices in the commodity market. If the analysis was conducted based solely on current state market demand and prices the conclusions would only be useful in the short-term. For this reason materials were identified based on their prevalence of usage across AX's entire product line, not the market demand or price for the parts. This is an important point to consider when identifying materials to be analyzed.

2) Determine the constraints involved with a given material type. While difficult, this step is crucial to ensure a feasible solution is obtained. Constraints can be both external and internal to a company. In AX's case there are imposed regulations from government agencies and customers along with internal constraints to ensure quality and manufacturability. Additional constraints can originate from supplier capabilities, the material market, internal capabilities, and storage capacities. Working across various functions within an organization is essential to obtain a complete understanding. Early identification of pertinent constraints will eliminate the need to continually modify an application's effort.

3) Observe current operations. Material utilization data can often be misleading and it is critical that one observes operations before trying to solve a problem. This step entails physical tours of manufacturing processes utilizing a given material, discussions with those responsible for sourcing the material (typically engineers who have determined the materials to use), and interviews with various stakeholders. This step proves invaluable when beginning to formulate possible solutions. Often, a company's monitored metrics can mislead the reality of material utilization.

4) Formulate possible approaches for implementation of postponement. At this point one has identified their area of focus, determined limitations, and gained an understanding of the current system. It is time to explore potential solutions. These solutions can be simple applications of lessons learned through previous improvement efforts, suggestions from stakeholders, original models, or a hybrid approach. The solution must fit within the problem statement identified throughout the previous steps.

5) Analyze the costs of the proposed solution against the costs of the current state. With material procurement there are no benefits to the bottom line. Sourcing is a cost center and therefore reducing cost is the ultimate goal. To understand a solution's relative cost reduction and validate it for financial purposes a model must be developed that compares the proposed solution to the current state. This will effectively make the business case for implementation. All changes will inevitably have a fixed cost aspect so identifying a proper time horizon for savings is very important.

6) Implementation. Assuming there is a beneficial business case proposed for a solution, the last step is to implement. In AX's case, this step is the most difficult. Change management techniques are critical and the approach to implementation can often be the determining factor as to whether or not the project is successful. This step will be explored in more detail in **Chapter 5.**

While this approach is laid out in a neat sequential fashion there are countless activities that must take place throughout the process. The list below outlines some major examples but is not an exhaustive list.

- System Capability Analysis: This entails research into what sort of business solutions a company utilizes for supply chain purposes. Understanding these systems and their capabilities/limitations will potentially be a constraint or opportunity into a possible solution's feasibility. It may be worthwhile to explore new applications within the existing system.
- Data and Result Validation: Iterating the validation of both data and analysis results with pertinent stakeholders will ensure a solution's accuracy. Inventory levels and contracts are both examples of relevant information that proves to be dynamic.
- Feasibility Demonstrations: A solution may make sense when first identified but can face obstacles throughout analysis and the beginning of implementation. If possible, it is beneficial to demonstrate all necessary capabilities to include machining capacity, system simulations, and manpower capability.
- Stakeholder Updates: Achieving buy-in from stakeholders, especially those that may be opposed to your project's implementation, will prove beneficial throughout the process and allow one to identify and confront issues as they arise (Camp, 2002). These updates will minimize the need to revisit prior steps in the process and increase the likelihood for full implementation.

A graphic overview of the postponement implementation approach is depicted in **Figure 6.**

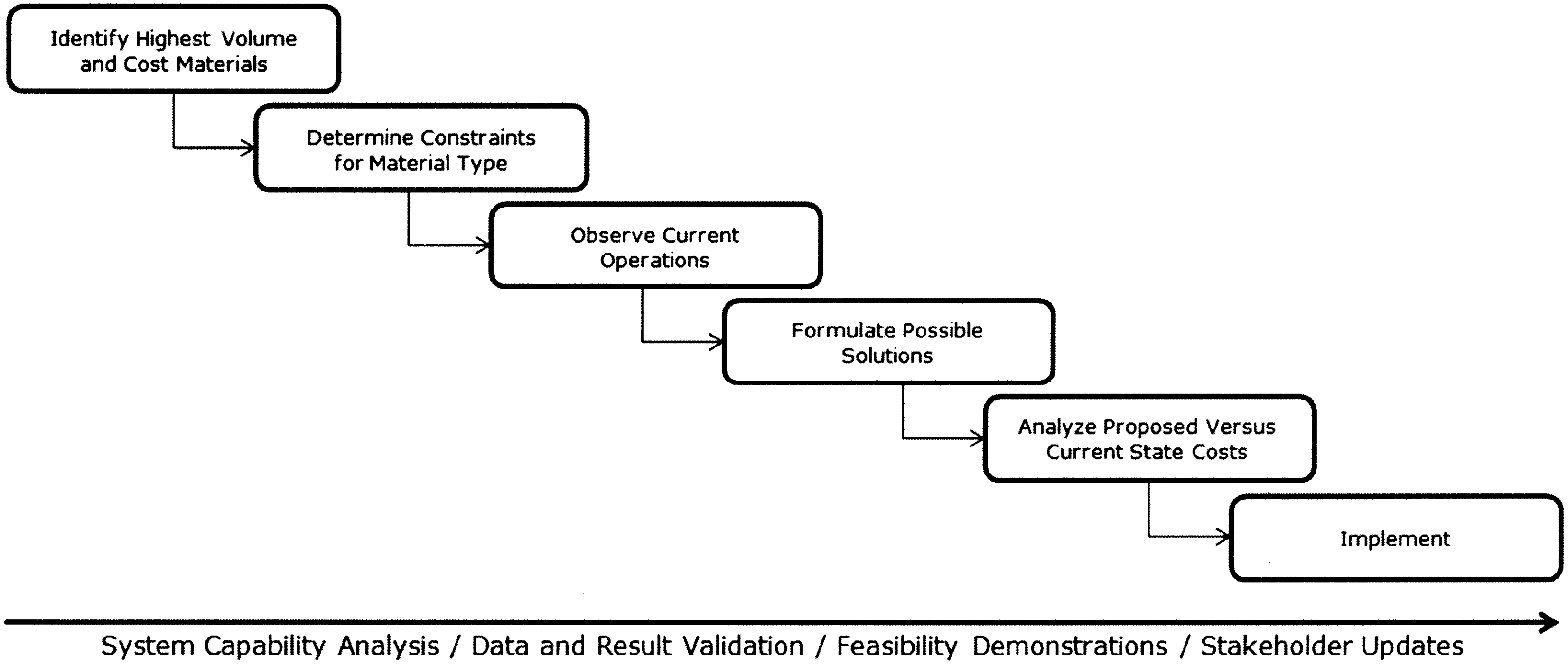


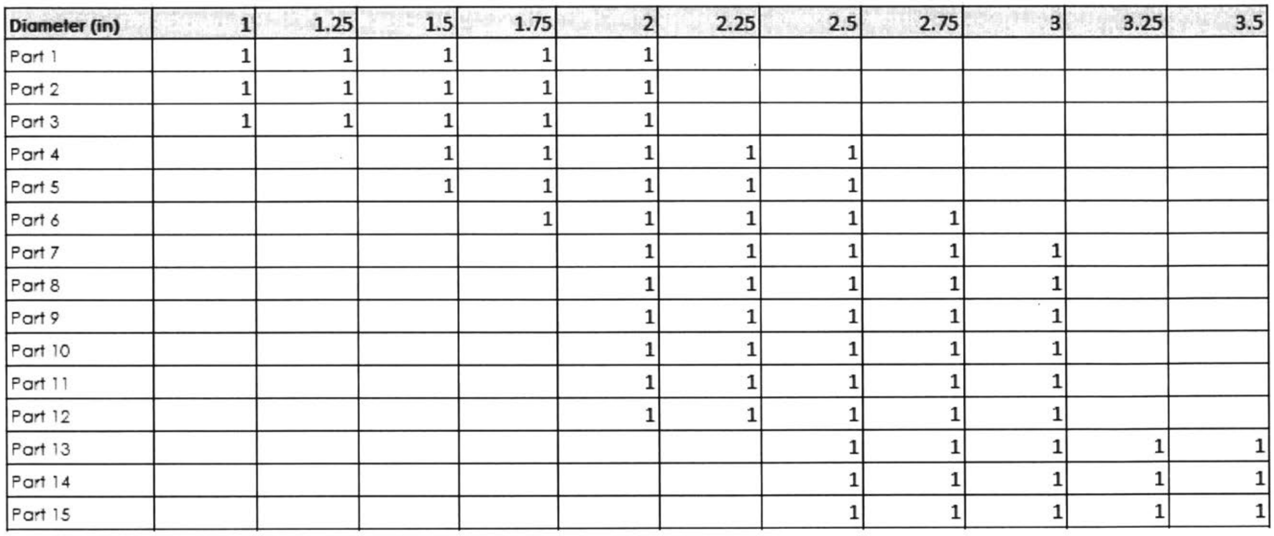
Figure 6. Postponement Implementation Approach

The following applications of this approach demonstrate the variety of uses for the implementation of postponement to explore how these steps can be utilized. The goal is not to try and exactly duplicate any of the applications but to use them as examples from which another specific application could be performed.

4.2 Steel Bar Stock

Steel bar stock served as the basis for the development of the postponement implementation approach due to its prevalence in AX's drive system components. Of the roughly 550 parts made at the drive system plant, nearly 80% require steel bar. In a given year the amount of steel bar stock demanded costs millions of dollars to procure and thus draws much attention. Another important detail regarding bar stock that made it a desirable candidate for postponement is that it is relatively simple to procure, machine, and understand. All of these factors made it the ideal option to explore.

There are number of existing constraints applied to steel bar stock. The first constraint can be determined by compiling a complete list of parts requiring steel bar and then identifying the called out material form. Determining the called out material can be accomplished by reviewing individual drawings by part number. In AX's case, there are a small percentage of parts whose drawing specifies an extended allowance for bar diameter. The data of called out material can be used to batch all parts into groups based on material specification. Material specification ultimately becomes the basis on which to conduct all grouping because it is the defining factor for material use. The next step is to review all pertinent material usage guidelines as outlined by the engineering function. These will dictate all allowed tolerances one can take advantage of to consolidate. Fortunately, while the guidelines are intended to be restrictive it does allow for flexibility. The inherent allowance regarding bar stock diameter is a one inch above call out umbrella tolerance. However, another constraint to consider is supplier limitations. For steel bar specifically, this included diameter limitations as well as purity limitations. An example is that suppliers will be unable to extrude odd diameters of bar or do not have the capability to achieve a certain purity level that a material specification demands. Lastly, a limitation to consider is AX's own machine limitations. These can include maximum diameter capabilities with lathes or even length maximums when sawing through bar. Understanding these constraints provided boundaries and measured guidance within which the true analysis could be completed. A graphic example of the resulting information is provided in **Figure 7.**



Diameter (in)	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3	3.25	3.5
Part 1	1	1	1	1	1						
Part 2	1	1	1	1	1						
Part 3	1	1	1	1	1						
Part 4			1	1	1	1	1				
Part 5			1	1	1	1	1				
Part 6				1	1	1	1	1			
Part 7					1	1	1	1	1		
Part 8					1	1	1	1	1		
Part 9					1	1	1	1	1		
Part 10					1	1	1	1	1		
Part 11					1	1	1	1	1		
Part 12					1	1	1	1	1		
Part 13							1	1	1	1	1
Part 14							1	1	1	1	1
Part 15							1	1	1	1	1

Figure 7. Steel Bar Parts Diameter Constraints

This data provides a known range of diameters of bar stock that can be utilized to manufacture each part; indicated by a "1". For example part 3, AX can source steel bar of the same specification from 1 to 2 inches. A quarter inch interval is used because of supplier limitations.

The next step in the approach is to observe steel bar operations. At AX steel bar is procured at standard industry lengths regardless of what lengths of bar a part calls for. This fact requires AX to saw the bar to its desired length for manufacturing. This length of bar, referred to as a slug, is then given to the drive system plant as the input for its manufacturing processes. The function performing the sawing also contains the ability to lathe to desired diameters which is infrequently required for unique diameters not readily available from suppliers. Any change to a procedure, to include the initial rough cut of a bar's diameter requires an update to the manufacturing planning by the planning function.

There were two potential solutions to the effectively un-pooled material sourcing regarding steel bar stock. The first is to simply utilize the engineering tolerances for bar diameter (material form) to find the minimum number of material codes required to satisfy all parts' material needs all within their existing material specification. The other option is to find the minimum number of material codes utilizing *BOTH* the tolerance on diameter (material form) and alternate material types (substitution). Both approaches are suited for integer programming with the objective of minimizing total material codes. Upon setting up the program, it became apparent that two iterations were necessary for the program. The first iteration serves to identify the minimum number of material codes within a material specification. Initial testing indicated that there could be multiple solutions, i.e.: the solution may be three diameters but those diameters after subsequent runs of the program changed. A second iteration was developed with the newly determined constraint of minimum material codes and an objective of minimizing overall diameter. The assumption is that with all other variables equal a larger diameter bar costs more than a smaller diameter bar. The program is formulated as follows:

First Run-Determines minimal number of bar diameters to satisfy all parts

Variables: x_{ij} – use of bar stock diameter i to satisfy part j, $x_{ij} \in \{0,1\}$

d_j- allowable diameter for part j, $d_j \in \{0,1\}$

Objective: Minimize $\sum\sum d_j x_{ij}$

Constraints: $\sum x_{ij} \geq 1$, for all parts j (Ensures every part has diameter assigned)

$x,d \geq 0$, integers

Second Run-Minimizes the total diameter (in) of bar to minimize cost

Variables: x_{ij} – use of bar stock diameter i to satisfy part j, $x_{ij} \in \{0,1\}$

d_j- allowable diameter for part j, $d_j \in \{0,1\}$

D_j- potential diameter for part j (inches), $D_j \in$ {specified diameter, max allowable diameter*}

Objective: Minimize $\sum\sum D_j x_{ij}$

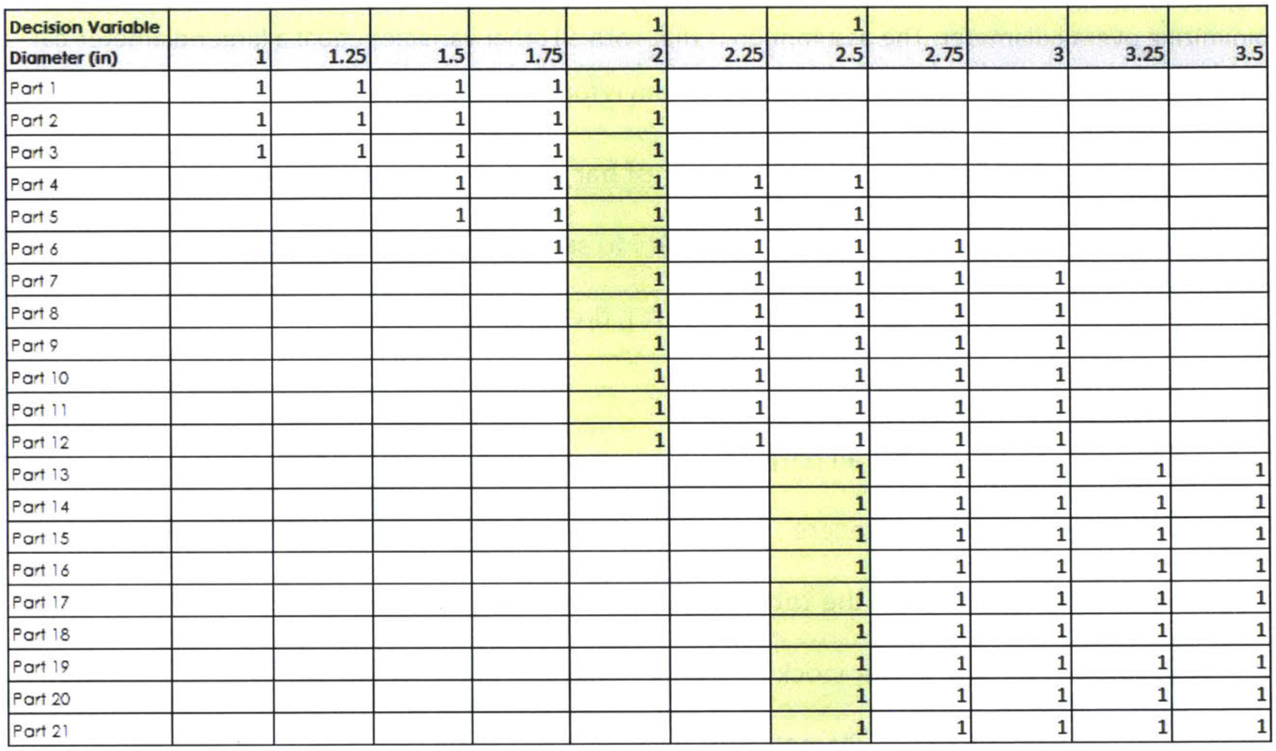
Constraints: $\sum x_{ij} \geq 1$, for all parts j (Ensures every part has diameter assigned)

$\sum\sum d_j x_{ij}$ (Run 2) = $\sum\sum d_j x_{ij}$ (Run 1), (Ensures continuity from first run)

$x,d \geq 0$, integers

*possible diameters in .25 inch increments

The program can be depicted visually in **Figure 8.**



Decision Variable					1		1				
Diameter (in)	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3	3.25	3.5
Part 1	1	1	1	1	1						
Part 2	1	1	1	1	1						
Part 3	1	1	1	1	1						
Part 4			1	1	1	1	1				
Part 5			1	1	1	1	1				
Part 6				1	1	1	1	1			
Part 7					1	1	1	1	1		
Part 8					1	1	1	1	1		
Part 9					1	1	1	1	1		
Part 10					1	1	1	1	1		
Part 11					1	1	1	1	1		
Part 12					1	1	1	1	1		
Part 13							1	1	1	1	1
Part 14							1	1	1	1	1
Part 15							1	1	1	1	1
Part 16							1	1	1	1	1
Part 17							1	1	1	1	1
Part 18							1	1	1	1	1
Part 19							1	1	1	1	1
Part 20							1	1	1	1	1
Part 21							1	1	1	1	1

Figure 8. Visual Depiction of Integer Program

The Decision Variable indicates the utilization of a given diameter of bar stock. Highlighted in green are the potential parts whose material requirements are satisfied by the identified material diameter. **Figure 8** depicts a scenario where 21 parts had previously required five different material codes (diameters) and the program has determined that all parts could be fulfilled with just two diameters, essentially eliminating three material codes. This program can be utilized to analyze both the material form and substitution options. When substituting material the number of parts in each grouping simply becomes larger within a given material specification and there is more opportunity to consolidate. This is because a viable alternate material consumes another grouping. **Table 2** provides an example of how the two options differ where consolidation represents the percent reduction in unique material codes.

Table 2. Depiction of Part Sample Grouping

Option	# of Groupings	Average # of Parts in Each Grouping	% Consolidation
1) Material Form	12	40	54%
2) Substitution and Material Form	8	70	65%

Now that there are solution options a mechanism to compare the two must be determined. Costs will drive the analysis, therefore a model must be created to capture and adequately contrast the proposed states' costs with the current state. For this analysis' purpose costs will be evaluated on an average year basis. Average year will be leveraged because year to year demand changes drastically and solely looking at next year provides a nearsighted viewpoint. Additionally, at AX demand forecasts are created for a multi-year horizon so an average year's demand is easily calculated. The total cost will be calculated as follows:

Total Cost (Average Year) = Labor Cost + Material Cost + Inventory Cost + Stock-out Cost
**Proposals will have additional fixed costs associated with updating processes*

Labor cost can be determined by reviewing process times as outlined by part planning. Material cost data is also available through suppliers and Last Price Paid (LPP) archives. Inventory costs are determined by modeling safety stock. The safety stock calculation utilized is as follows:

$$\text{Safety Stock} = z * \sigma * \sqrt{L}$$

Where: z = safety factor

σ = standard deviation of demand (annual)

L = lead time (annual)

The safety factor is a function of the service level that a company wants to achieve in delivering its product in the form of a percentage. The z is a value in terms of standard deviations from the mean in order to achieve the designated service level. The last portion of the total cost equation is stock-out cost. For the purpose of this comparison, the stock out cost will be the value of a part so that it is counted as a lost sale. The last pertinent cost consideration are the expenses incurred to change the process for the proposed states. These include the labor costs for engineering and planning updates.

The results and implementation will be explored in **Chapter 5.** At this point in the approach we have all the necessary data and evaluation criteria to determine if either of the proposed solutions are worthwhile pursuits.

4.3 Composite Blankets

At AX, composite blankets are utilized for various aircraft components and make up the bulk of material purchases by unit volume. Additionally, material utilization is a critical metric closely observed across multiple business functions. Scrapping material can occur because of a number of reasons. The primary contributors are that the material is perishable, the stacking of blankets is an arduous primarily manual process lending itself to defects, and there are technical limitations as to how an individual ply is cut resulting in wasted material. All of these factors make the composite material sourcing an ideal candidate for the application of postponement.

There are a similar number of constraints concerning composites as there are with steel bar stock. The supplier limitations are more complex because composite blankets are produced at what are essentially industry standard widths. This is due to the complexity and variety of the materials themselves. A more in-depth review of composite materials in general can be found in Chapter 7 of the Federal Aviation Administration's manual titled *Aviation Maintenance Technician Handbook-Airframe*. The manual offers descriptions and graphics regarding the filaments and resins making up blankets and the challenges faced when producing them (FAA, 2012). Engineering specifications are still a limitation and therefore all analysis of composites must be done around the existing material specification; unlike steel bar, there are no substitutions available. However, while there was a constraint for steel bar diameter, there is no constraint on the width of blanket utilized for a nest's cutting. This allows flexibility despite the technical limitation restricting the dimensions and orientations of a given nest.

Current composite operations at AX are straightforward. A part is required so the necessary blankets are laid out for cutting of the nest. Interestingly, nests are considered "joint" because they can contain plies from various parts. While joint nesting does allow for batching it is clear that this also hamstrings production and lends itself to overproduction. Also, the nests are static and unable to be changed. For this reason the variables one can change when observing composite materials are simply the blanket widths utilized for cutting of nests. The composition of the nests themselves must remain the same. This may appear to be a severe limitation but the reality is that the width of a called out blanket can in fact be the cause of considerable waste. One such instance of three nests being cut from a single width and the resulting waste is demonstrated in **Figure 9.**

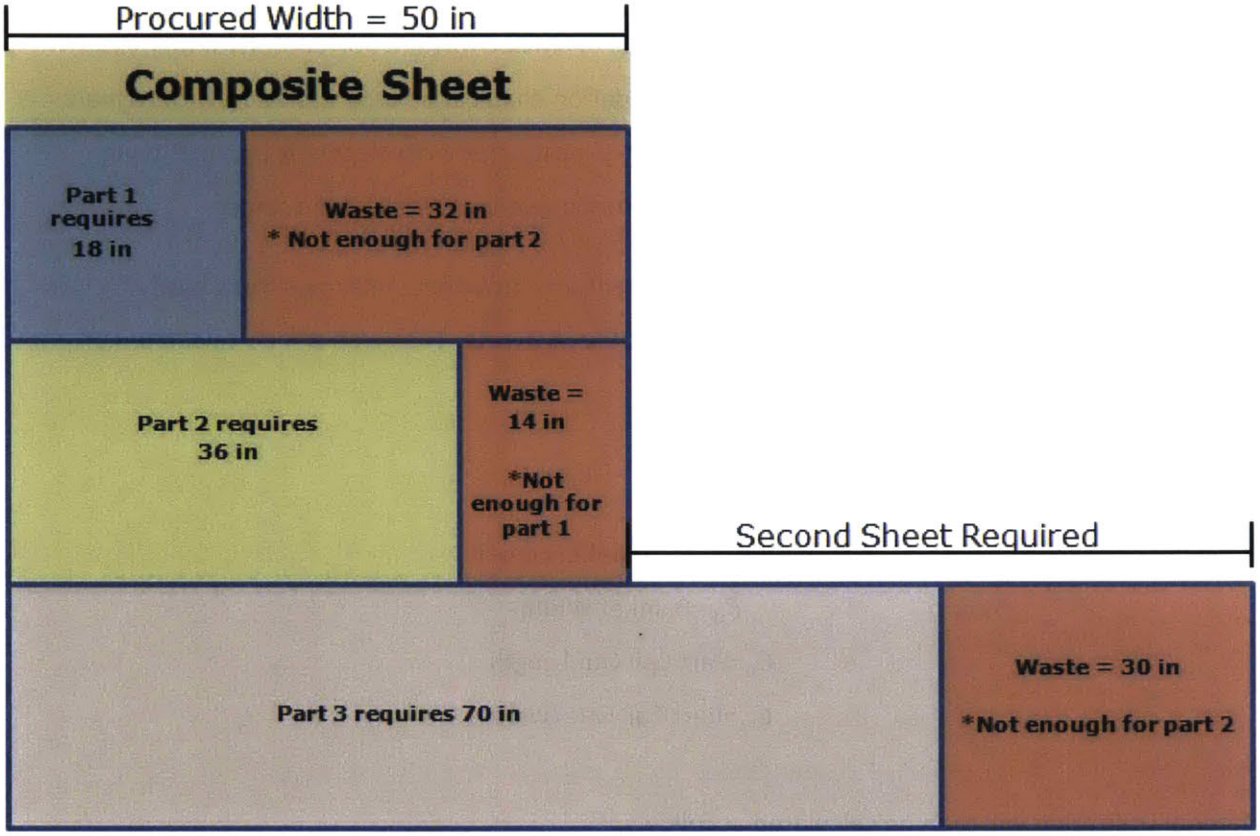


Figure 9. Composite Utilization Example

It must be noted that left over material from a cut sheet is not then re-used for another nest. This scrap occurs because often nests require varying lengths and also because of obsolescence of the perishable material once it is removed from its cold storage. Part three in the figure depicts an example where two widths of material must be "spliced" together allowing for the total desired width that is required. A tremendous amount of scrap is created before a single ply is cut. This example only portrays scrap involved where there is a standard procured width. For most specifications of blanket at AX, multiple widths (material codes) are procured resulting in similar levels of scrap.

After consideration, two possible solutions appear. The first is to identify where there are discrepancies between a nest's called out material width and the utilized width. Once this information is obtained individual specifications can be optimized to minimize waste. Another solution is to create a dynamic nesting capability. This would allow for plies to be cut exactly as demanded in order to remove the potentially unnecessary cutting that joint nesting creates. Another benefit of dynamic nesting is that it will allow a nest to adjust according to the blanket dimensions rather than the nest demanding a particular width as is the case currently. Dynamic nesting is obviously the optimal solution however; it is a primarily technical solution and therefore will not be examined further. Fortunately, simplifying current procurement through material width consolidation enables the progression towards dynamic nesting. Both potential solutions employ the concept of postponement effectively by simplifying material inputs and delaying the product produced from a given material by one stage.

To analyze the costs associated with the current and proposed states one must solely focus on the scrapped material and the consequent material utilization rate. The scrap will be calculated as follows:

$$S = B_L * B_w - C_L * C_w$$

Where: B_L=Blanket Length
B_w=Blanket Width
C_L=Part Call Out Length
C_w=Part Call Out Width

Material Utilization will then be calculated as follows:

$$\text{Utilization} = \frac{C_L * C_W}{B_L * B_{W_L}}$$

The blanket width and blanket length will be the changing variables due to current limitations on the physical capacity of hardware used to cut plies. Cost data is available per square foot across all composite materials so a relative cost comparison is easily calculated. As with steel bar, there are additional fixed costs associated with updating planning but in composite's specific case there will be no additional man hours required for the change. Ultimately, there will most likely be a decrease in man hours required due to the elimination of some cutting operations that currently take place.

The review of the results and required implementation is detailed in the next chapter. The results are solely based on the potential solution to determine optimal material widths. There are other technological solutions that AX could pursue but they are outside of the scope of this research.

4.4 Casting vs. Machining

Within AX there has been an ongoing effort to minimize the dependence on castings. This is a primary example of how machine technology advancements can make previous design decisions no longer valid. According to multiple engineers and managers, the old way of designing a part was to try to get to as close to a final form as possible in order to limit material waste. Another factor was that machines weren't as capable and features-that today would be deemed relatively simple-were thought impossible in the past. The end result is a large number of parts made from castings that could easily be machined from metal plate or bar stock. Castings themselves present a multitude of challenges, the two most important are that they are expensive and have much longer lead times. In some cases castings lead times are a troublesome bottleneck. AX does not retain the capability to build its own castings so outside suppliers are relied upon. Therefore, AX has lost the ability to control a cost margin on its products and quality issues are a constant nuisance.

The careful consideration of whether or not a part can be machined instead of made from a casting is a major constraint. The decision requires tedious review of design drawings and is not often a top priority within an organization. Another constraint, as with all previously considered applications of postponement, is that there are guiding engineering specifications. Similar tolerances to those involved with material substitution exist to allow castings to be made by machine; however, the opportunities are few and if a part is transitioned re-designs can be required. Still another constraint pertaining to changing which process to use is internal machine capability and capacity. While a certain feature of a part may be possible to machine, there will need to be tooling, planning, programming, and quality control procedure updates. It is no small undertaking to update a small part. In the end, the majority of the constraints are not feasibility restrictions but rather personnel bandwidth restrictions.

When observed, castings are used throughout various components of AX's products. The majority of the incoming casting parts still require machining operations conducted within AX's manufacturing plant. As a result, the lead times of these parts are only compounded. Additionally, the costs for the casting parts are extraordinarily higher than that of similar dimensioned parts using bar or plate. A sampling of parts revealed that castings cost an average of nearly 18 times more than material costs. Additionally lead times were on average 12 times higher for castings. This demonstrates the business necessity to bring the parts production back into AX's operations if possible. There is a precedent for machining parts that were previously castings. However, these examples are typically more reactive to a supply chain disruption and not necessarily meant to be a permanent change. Due to the rushed nature of these examples there was little structure developed into evaluating if it would be beneficial in the long term. Observations concluded that there is a real need for conversion where possible but that a structured evaluation framework would be required.

The potential solution to the issues facings castings are straight forward: avoid castings when able. Fortunately there are tolerances that allow castings to be substituted with machined bar or plate. These tolerances depend on the material specification of the castings. The substitution opportunity is also dependent on whether the existing machines have the capability to create desired features. Another solution is for AX to produce its own castings. This however, is not feasible due to it being outside of AX's core competencies and will not be examined any further. Achieving postponement will require the ability to use common material inputs to make parts that are coming from various castings. The proposed state as compared to the current state is depicted in **Figure 10.**

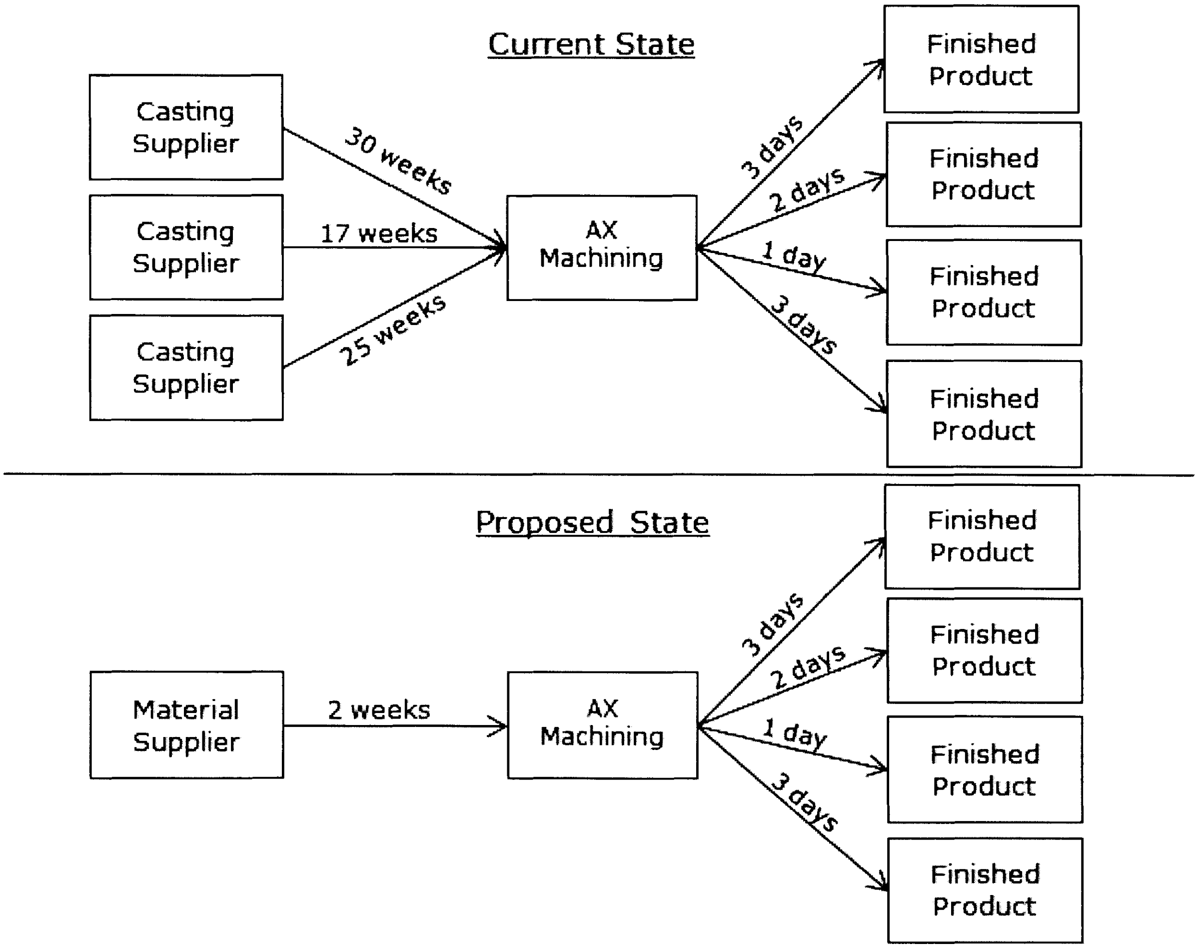


Figure 10. Current and Proposed State for Casting vs. Machining

Analysis to demonstrate cost savings is the great challenge in determining whether or not to change the material process of a part. As previously demonstrated, costs will again serve as the basis for comparison. Since material cost and lead times are the primary factors it is important to consider both procurement and inventory expenditure. The following metric was developed:

Total Cost (per part)= Material + Pipeline Stock Cost + Cycle Stock Cost + Safety Stock Cost + Labor Cost

Where:

*Pipeline Stock Cost = Holding Rate * Material Cost * Lead Time * Average Demand*

*Cycle Stock Cost = Holding Rate * Material Cost * (Average Demand * Review Period/2)*

*Safety Stock Cost = Holding Rate * Material Cost * (Safety Stock)*
Determine Safety Stock as previously detailed

Labor Cost = Machine Cost + Wages

Holding rate will be a percentage of the material costs that accounts for opportunity cost of expending cash on inventory instead of other investments. One can use expected market rates of return if there is not an available hold cost metric available. Onetime costs must be overcome when making the change and in this particular case they are abundant due to the nature of the update. Ultimately, the two states can be compared by cost and then the cost savings of the change must additionally outweigh the one-time fixed costs incurred to implement the change.

Results and Implementation will be outlined in **Chapter 5.**

4.5 Summary

In this chapter an approach to implementing postponement was introduced and explained. Three applications, each differing in complexity and scope were explored in order to demonstrate the potential uses for postponement. Each case serves as an example of the application of postponement approach and allows one to observe the benefits once analyzed.

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5. Results and Implementation

This chapter will review and quantify the benefits of applying postponement to AX through utilization of the approach laid out in the previous chapter. Each application requires a unique approach to both comparing benefits to the current state and pursuing implementation. The comparison is necessary in order to justify – from a business standpoint – that the necessary changes are worthwhile.

5.1.1 Steel Bar Stock Results

The collection of data regarding parts made from steel bar stock revealed a sample of 426 total parts eligible to be inputted to the integer program. The sample of parts included eight different steel types, 14 material specifications and ultimately 172 unique material codes. This represents a part to material code ratio of 2.47. It is important to note that the parts in the sample are included regardless of the aircraft model they contribute to or current demand. Since demand is in constant fluctuation a solution geared towards a current snapshot is inadequate. Once all parts were categorized into their respective material specifications the model outputted the following results as depicted in **Table 3.**

	Analysis across Gears, Shafts and Couplings					
	Alloy Steel Bar Stock					
	Spec Code	Metal Type	# of Parts	# of Material Codes	Proposed # of Material Codes	Percent Reduction
	9	H	15	8	3	62.50%
	5	G	28	17	4	76.47%
	10	F	17	15	5	66.67%
	4	C	24	12	6	50.00%
	6	C	34	20	7	65.00%
	11	E	13	7	4	42.86%
	14	A	3	2	1	50.00%
	1	B	94	25	7	72.00%
	7	A	33	12	5	58.33%
	3	C	47	15	6	60.00%
	8	B	32	14	5	64.29%
	2	D	68	18	6	66.67%
	13	B	6	3	2	33.33%
	12	A	12	4	3	25.00%
Total	14	8	426	172	64	62.79%

Table 3. Steel Bar Stock Consolidation Results

The results indicate generally, as one would assume, that the metal specifications with the largest number of parts offer the greatest opportunities for consolidation. There are outliers to this assumption as seen with specification code 5.

These results represent utilizing only the allowance for diameter within a given material specification. When the model was applied to the parts utilizing material substitution, an overall consolidation of over 70% was achieved. It quickly became clear that material substitution was not a viable option due the significantly larger price for the alternate materials and the lack of available suppliers. The alternates, when substituting, were purer forms of steel which required additional processes during production. Price increases were found to be a multiple of current costs. For this reason analysis only regarding form allowances was conducted.

Figure 11 graphically depicts the impact of the reduction of material codes. While the current state has the part to material code ratio of 2.47, with the model output the ratio is now 6.66. In essence, materials usefulness is increased across a multitude of parts.

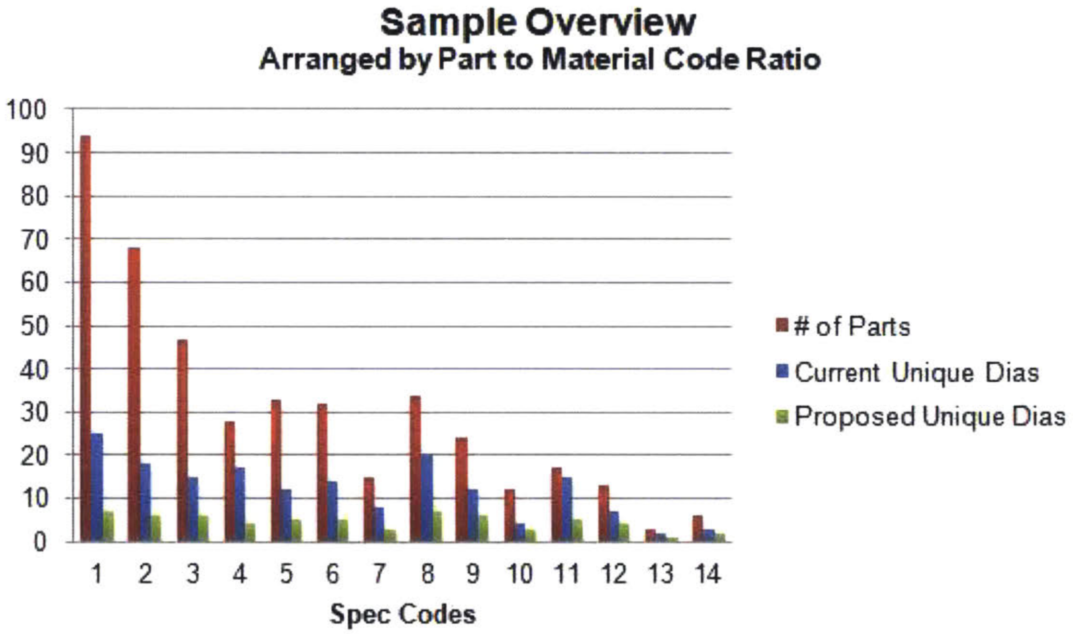

Figure 11. Steel Bar Stock Part to Material Code Comparison

The benefits of the achieved 62% reduction in material codes are numerous when compared to the current state. The first is price reduction for materials due to purchases at larger volumes. Using industry wide available material price indices and correspondence with suppliers it became clear that there would be at least a 10% discount for roughly 20 of the remaining 64 material codes. Another significant benefit is an inventory reduction of approximately 30% when analyzing safety stock. This reduces not only the footprint required for the maintaining of inventory but also the material cost.

Perhaps most importantly, the consolidation of material codes provides an increased ability to meet demand. In 400 simulated iterations of forecasted demand fluctuations of +/- 7.5% the proposed state's occurrences of material stock-out were 45% lower than the current state's occurrences of stock-out. This directly addresses the issues regarding demand uncertainty that AX faces. By pooling the materials to make a larger variety of parts the cost of reacting to demand uncertainty is dampened. The value of that can be measured by attributing the cost of the part at the first stage of production, but in reality these parts are merely components of much more valuable upper assemblies. Having material on hand and available provides immense benefits.

These cost decreases are not an exhaustive list of the benefits of material code consolidation. There are still more to be considered to include avoidance of minimum order quantities which represent a root cause of excess inventory, reduction in the number of transactions required for material purchases, and simplification for demand forecasting. The only increases in cost occur with increased labor and tooling wear. When totaled, the cost savings of the proposed material state compared to the current state is more than $1 million annually. The application of postponement significantly reduces inventory, improves AX's ability to meet demand, and increases its buying power.

5.1.2 Steel Bar Stock Implementation

Implementation of postponement for materials is consistent regardless of the specific material type and there are three major stakeholders: engineering, planning, and procurement. Engineering must approve of all material changes and when necessary update individual part call outs. Planning is tasked with updating manufacturing processes since additional steps are necessary to bring raw material form to its desired form. Lastly, procurement must change purchasing priorities for the new material codes and in this case enter into new purchasing contracts.

Due to the cost of material inventory it is beneficial to deplete existing inventories during implementation. It is tedious, depending on the size of the impacted part population, to manually monitor material inventory levels and determine when to begin utilizing a material code. For this reason, automating the process when possible is beneficial. At AX specifically, the supply chain systems offer functionality that can automatically perform the necessary transitions from one material to another for a given part. Unfortunately, the variable demand nature of the industry makes it difficult to fully implement quickly because of slow moving material. There are two potential avenues to accelerate full implementation: 1) prioritize excess inventory as available material for high demand parts 2) sell excess inventory to suppliers or other customers. While full implementation is not an overnight endeavor, the greatest value originates from the highest volume parts which are in high demand, and therefore will become visible earlier. The majority of the large volume materials will changeover within a year while the slowest moving and lowest demand parts/materials will take multiple years to do the same.

It is advantageous throughout implementation to test and simulate functionality and the change process whenever possible. With AX, critical lessons were learned regarding the supply chain systems that prove invaluable not only for final implementation of the steel bar stock proposal, but also for postponement applications with other material types. Once the implementation process is established, follow on postponement applications become significantly easier.

5.2.1 Composite Blanket Results

While the application of postponement to composite blankets entailed significantly more constraints positive results were still obtained. Once discrepancies between material widths and part width requirements were identified a set of opportunities for improvement were identified. The sample of parts included roughly 150 parts across seven material specifications which accounted for ten different material widths. It is apparent that simplification of total material codes has already occurred, yet there still remains room for improvement. **Table 4** depicts the current material utilization across the sample.

Composite Spec	Current Procured Width (in)	Current Utilization
1	50 inch	0.671
2	48 inch	0.611
3	36/48 inch	0.544
4	48 inch	0.75
5	36 inch	0.5
6	60 inch	0.587
7	35/36/48 inch	0.64

Table 4. Composite Blanket Utilization

Analysis was again conducted by material specification groupings. Within each group there were multiple ways to both improve utilization and decrease the number of material codes (widths). Examples of these approaches were to either choose a more optimal single width or consolidate to a single width. Specification 1 in **Table 4** and depicted in **Figure 9** serves as an apt illustration if we assume a part demand for each part of ten units a year. Let's also assume the length of each part is uniform at 20 inches. The following is determined:

Current Total Annual Scrap:

Part 1: (50 – 18) inches * 20 inches * 10 units = 6,400 in^2/year
Part 2: (50 – 36) inches * 20 inches * 10 units = 280 in^2/year
Part 3: ((50*2) – 70) inches * 20 inches * 10 units = 6,000 in^2/year
Total: 12,680 in^2/year

Proposed Total Annual Scrap (36 inch wide material):

Part 1: (36 – 18) inches * 20 inches * 10 units = 3,600 in^2/year
Part 2: (36 – 36) inches * 20 inches * 10 units = 0 in^2/year
Part 3: ((36*2) – 70) inches * 20 inches * 10 units = 400 in^2/year
Total: 4,000 in^2/year

A decrease in scrap of 68% is achieved through simply determining a more optimal width for material procurement. By utilizing this analysis method and optimizing utilized materials the following results in **Table 5** were achieved across all specifications analyzed.

Composite Spec	Current Procured Width (in)	Current Utilization	Proposed Width (in)	Proposed Utilization
1	50 inch	0.671	36 inch	0.933
2	48 inch	0.611	24 inch	0.984
3	36/48 inch	0.544	only 36 inch	0.702
4	48 inch	0.75	36 inch	1
5	36 inch	0.5	18 inch	1
6	60 inch	0.587	26 inch	0.979
7	35/36/48 inch	0.64	only 36 inch	0.802

Table 5. Composite Blanket Consolidation Results

The consolidation of materials and optimization of utilized widths yielded on average an increase of utilization of 29.9%. When totaling scrap utilizing forecasts and individual part lengths the total scrap eliminated is valued at nearly $500,000 annually.

The dynamic nesting capability is not yet implemented at AX. While it remains the ideal solution there are steps that must be taken beyond just achieving the software capabilities. First, all plies that can be cut from a common material specification must be grouped. Second, a single optimal material code must be identified for each specification. This analysis does the second step and ultimately enables the continued effort towards dynamic nesting. Just as with the steel bar results, there are many benefits when implementing postponement beyond simply reducing material scrap. For example, an increase in purchasing power through larger volume purchasing of remaining material codes, a simplification of material procurement, and a responsiveness to demand. The responsiveness to demand is achieved through pooling of raw materials to make a larger number of parts, as that which occurred during the steel bar application. Doing so allows AX to be more flexible in reacting to demand uncertainty observed across all parts. As demand variation increases the proposed state demonstrates more value through reduced stock-outs while if demand stays steady the proposed state still provides value through bulk purchasing. These benefits can still be obtained prior to full implementation of dynamic nesting and ensure an optimal state once specific capabilities are achieved.

5.2.2 Composite Blanket Implementation

The same stakeholders exist for composite implementation as did with steel bar. The only addition is that of the group responsible for the nesting of plies. Prior to the achievement of dynamic nesting, the changing of material widths will require a review of all nests to ensure plies are still provided with adequate material. Beyond this concern, there is minimal impact to current operation outside of procurement.

Procurement for composite blankets is limited to two large suppliers and in this case all materials are on existing contracts with relatively long time horizons. The implementation of the proposed changes requires initiating communications to determine suppliers' flexibility with material widths and existing capacity. The result is not a smaller amount of material purchased but simply a different physical form of the same material specifications. Once it is determined that a new material width will be used, AX can still employ existing nests to the new materials' dimensions.

Again, it is imperative that existing inventories of given materials are depleted. For composites this feat is accomplished much sooner since, by nature, it is a perishable item. The essence of the systemic implementation is identical to that of bar stock and was proven through test implementation.

5.3.1 Casting vs. Machining Results

To identify a sample data set for evaluation a visual review of current casting parts was conducted. The purpose was to identify parts which originate from the same material specification and have generally the same physical dimensions. Another important factor to consider is that the parts do not contain any features which are too intricate to machine using hardware currently available in AX's manufacturing facility. The review yielded a sample of 15 parts which fit the necessary criteria. Each one of the parts could be machined using the same diameter of aluminum bar stock instead of the current unique castings.

A comparison of current state and proposed state was necessary to determine cost savings. Ultimately, material and inventory costs were reduced by 93.8%, before labor costs. Even after accounting for labor, the savings are still significant. This demonstrates the benefit of maintaining operations internal to AX's manufacturing and that the suppliers are charging for the risk they inherit by taking on casting manufacturing. For just this small sample, and after labor costs, the cost reduction still represents hundreds of thousands of dollars in savings. It is also important to note that the reduction in cost calculations only considered the expected lead times for each casting. In reality, lead times often ballooned to multiples of what was expected. **Figure 12** depicts the savings by SKU when consolidating around one single part.

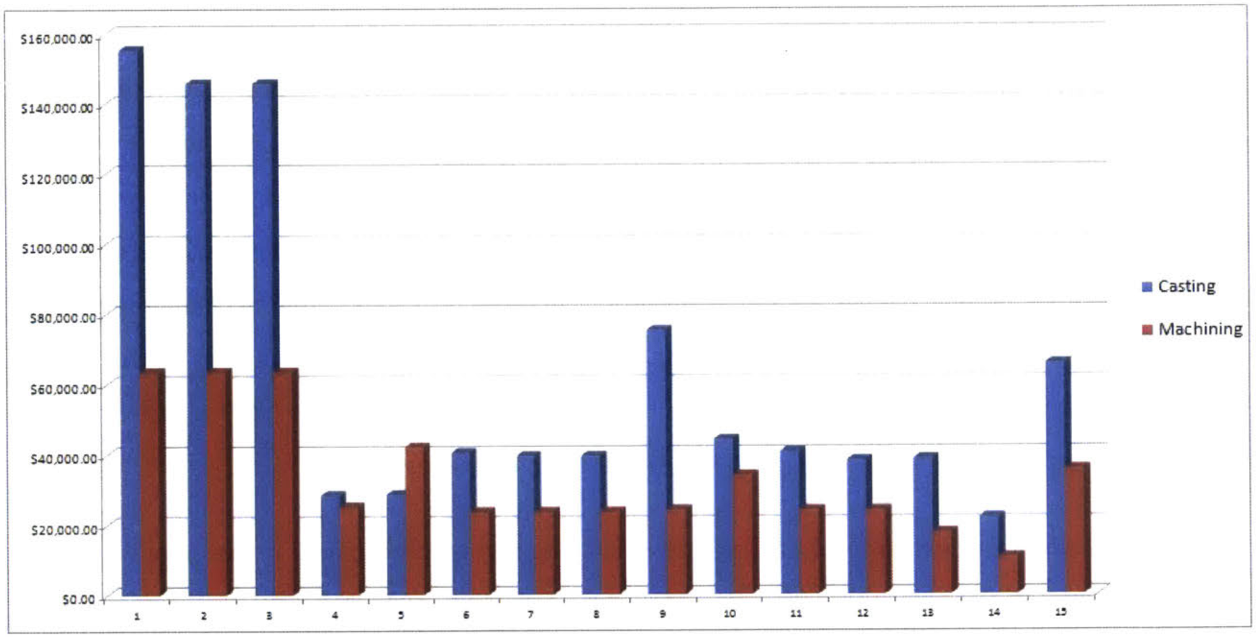

Figure 12. Casting vs. Machining Cost Reductions

The results demonstrate a consistent decrease even when considering labor costs. The only outlier, part 5, demonstrates an increase in costs owing to a significantly cheaper casting material cost when compared to all others. This slight increase in cost for a single part would easily be overcome by the volume purchase discount offered by buying all part demand material from a single supplier.

This significant reduction in costs and decreased lead time demonstrates why converting casting parts to machined parts is valuable. The importance of reduced costs and lead times holds true when analyzing for demand uncertainty. Even if only a single unit were produced for each part the costs to machine are still lower than purchasing outside castings. Further analysis was conducted comparing total costs with fluctuations as large as multiples of forecasted demand and the results indicated lower costs from machining. For the analyzed parts, there was simply no scenario of demand where castings made better economic sense. This is due to the significantly larger purchase cost from a supplier, with built in margin, and very long lead times.

However, the decision to convert is still not as obvious as it may seem. Onetime costs are significant and manufacturing capacity is an ever present constraint. The sample demonstrates a positive example, but careful consideration must be made when identifying other potential samples due to the complex nature changing from a casting to a machined part.

5.3.2 Casting vs. Machining Implementation

This application of postponement provides the most implementation challenges. These challenges are not from a procurement viewpoint but rather the necessary engineering and planning changes. With steel bar and composite implementation the design and process changes were very minor and existed only at the very first manufacturing steps. In this particular case an entire redevelopment of the manufacturing planning is required along with potential part redesigns. The cause for planning changes is obvious: a manufacturing process plan must be created for what previously arrived at near final form. The engineering changes are not as obvious. The cause for these potential changes exists because design called for a casting and parts made from castings require unique features by the nature of their production. These can include features that are machined upon arrival at AX. If a part is no longer made from a casting certain designed features are then unnecessary.

The steady state costs of both casting and machining parts is determined in the analysis but it is much more difficult to quantify the onetime costs. Examples of onetime costs include but are not limited to Numerical Control (NC) programming updates, tool design and fabrication, and production planning. Any one of these tasks can take as long as a week's worth of time; especially if part redesigns are required. This is significant because of the unique method in which labor is calculated. For this reason a part-by-part analysis is required beyond the cost model and must include estimates of implementation costs.

5.4 Summary

This chapter provided an overview of the benefits of applying postponement into low-volume high-variability manufacturing across three unique applications. Each application required differing techniques and implementation but still demonstrated significant financial and production benefits. It also highlighted that establishing a process for implementation through a successful pilot utilizing a single application can benefit follow-on implementation for different applications.

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6. Conclusion

Postponement proves to be a truly valuable concept, especially when operating in a low-volume/high-variability manufacturing environment. This research demonstrates three applications of the implementation of postponement into unique aspects of manufacturing and their positive results. While these are specific examples, broader analysis provides a general framework which can be used by any company to evaluate the benefit of postponement in their operations. Each application possesses its own unique set of challenges but through proper utilization of the postponement implementation approach terrific results are achieved. The applications are not meant to be all inclusive of useful postponement opportunities but rather an exhibition of the breadth of opportunities. AX serves as an ideal testbed, possessing extraordinary levels of difficulty due to its intense focus on quality yet the postponement approach ultimately provides fruitful outcomes. It is only logical to assume that in industries with fewer constraints the opportunities would be far greater.

The implementation of postponement is an ongoing process and demands consistent evaluation. Revisiting assumptions and proposed solutions is inevitable but provides important learning. Additionally, the variables involved when conducting analysis may change due to uncertainties in both demand and material costs. It is important to monitor any significant shifts in either and ensure the logic to assess the proposal is still sound. This chapter will discuss some key findings that came as a result of the applications and also identify potential opportunities for further research.

6.1 Key Findings and Recommendations

A number of important insights resulted from the implementation of postponement at AX across the various applications. One of the most important was understanding the capabilities and functionalities of material tracking systems. This includes the procurement process, the inventory management process, material-to-part assignment, and material utilization tracking systems. Within AX, and most likely in a majority of manufacturers, there are a multitude of software solutions varying in usefulness and formality. Aligning all of the systems is absolutely essential to adequately implement postponement and ensures that the skill sets to utilize the systems at their maximum functionality are retained. This will ultimately make the difference between success and failure. An inability to achieve both of these goals can cost a company substantial amounts of cash. Over time temporary solutions are created in an effort to patch together the systems or because a function with historical knowledge has been eliminated. These short-sighted solutions inevitably bog down the supply chain and result in the waste of valuable resources. It is easy to lose sight of the importance of ensuring systems are aligned if temporary solutions are keeping operations moving. However, when a serious issue arises it may indeed be too late to adequately address it without significant expenditure. For these reasons, a periodic formal review of all supply chain systems with the goal of identifying alignment gaps and fostering new solutions is beneficial. One example of a solution that arose from the work at AX was the ability to use an inventory system functionality to deplete excess material that had not been utilized in many years. The ability to do this was only discovered after connecting separate project groups across multiple functions. Without any forcing function, this opportunity would never have been realized.

Another critical finding from the work of implementing postponement was the necessity for designing for supply chain. Currently, design for manufacturing is a field that deservedly receives a lot of attention in manufacturing circles. This however does not go far enough when applied to an industry where the products themselves have long life-spans. Instead of a new product phasing out an old product, as may be seen in the automotive industry, new products are manufactured alongside legacy products. Due to this simple fact it is beneficial to consider resources already established in the existing supply chain when developing a new product. Taking advantage of economies of scale and existing knowledge will only benefit the new product in the long run and can encourage synergy within a company. AX, for example, may use steel bar stock extensively at a given diameter for one legacy product and then go on to design a new product which utilizes the same material specification of bar stock only at a quarter inch diameter difference. This slight difference results in the separation of procurement, material tracking, required tooling, and a plethora of n^{th} order effects. Therefore, when designing new products the existing supply chain must be an important consideration. This may take the form of supply chain personnel being involved in design or even an engineering mandate limiting designers to given material options.

One last key finding from this research is that a company's organizational structure must support efforts to maximize resource utilization. Opportunities for improvement can be identified throughout any business but without proper fostering and avenues for their completion these opportunities will be missed. Historically in AX there have been continuous improvement initiatives but the implementation was not properly executed for a number of reasons. The most common motive was that there was not a proper project champion with the ability to reach across necessary functions. It appears there is often a disconnect between end users or those on the manufacturing floor and the people with the necessary stature to push an initiative. This is not a unique issue within AX and represents a classic business challenge: **how to maintain current success while simultaneously improving**. Jim Collins and Jerry Porras explore this question which appears to suggest that you can only have one or the other in their classic book "Built to Last" (Collins and Porras, 1997). After much research, Collins and Porras conclude that to be a truly great company an organization must pursue both ends: maintain the current business while also improving. AX, and any other company, can greatly benefit from this insight by placing importance on improvement and innovation not only in its products but also its internal systems. Ultimately postponement is a simple idea with obvious benefits, but the actual energy and insight required to properly implement it is substantial. When properly implemented the benefits are easy to demonstrate but it is an effort which demands support. Building a company's structure to support these efforts and others of similar ends is crucial to their success and to a company's success.

6.2 Opportunities for Further Research

There are a number of opportunities for further research from the topics explored in this thesis. Two that are especially valuable are the effort to utilize postponement to align suppliers' supply chains with an original equipment manufacturer's (OEM) and also implementing additional layers of postponement through grouping of parts or components. Both of these efforts would greatly improve a manufacturer's operational efficiency.

The research required to implement postponement involves identifying overlaps in the utilization of resources. With the applications discussed previously in this paper, a range of potential material inputs are identified which creates a valuable database. The model proposed amounts to a prescriptive outcome of which materials to procure from suppliers. Another possible function of the model is to instead determine what materials are already produced at scale by a supplier or more cost effective to produce. The model can than in turn be constrained in a way that determines the optimal material forms which minimize cost. This is interesting because it achieves the alignment of both supply chains which benefit all involved, both upstream and downstream to the customers. In order to understand the benefits, further work is required to identify suppliers' most cost effective materials and expanding the existing model to encompass these potential inputs. Following this discussion with suppliers, and expansion of the model, a simple comparison can be completed demonstrating the decrease in costs.

All applications of implementing postponement at AX involved only a single layer: raw material input. This single layer proved to be very valuable and provided positive results, therefore additional layers would logically increase the benefits to the supply chain. In order to identify the opportunities for added layers of postponement research is required to present a second database which goes deeper into physical form overlap of parts and components. This requires grouping parts in a manner that provides subsets for various uses such as required material specification, required material form, and required machining processes. From these grouping it can be identified where opportunities to consolidate around inputs or tools can provide additional postponement. The outright goal is to differentiate parts as late as possible. Doing so allows a company to be responsive to demand while minimizing the complexity involved in its supply chain. The complexity of parts does not make this grouping a simple task, but the benefits will greatly outweigh the costs.

6.3 Summary

This chapter outlined the general key findings and recommendations for how to effectively implement postponement in a low-volume/high-variability manufacturing environment. Additionally, opportunities for further research are identified in order to allow for an extension of the existing applications. While this research outlines specific models, examples, and results it is important to understand the generic findings in order to broadly apply the lessons learned from the implementation of postponement at AX. The findings herein can provide an outline of how to achieve the benefits of implementation across numerous applications in a variety of companies and industries.

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