USING VALUE STREAM MAPPING TO IMPROVE FORGING PROCESSES

By

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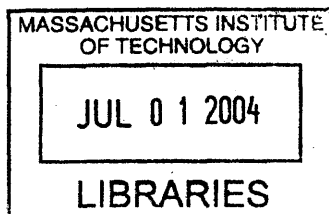
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ABSTRACT

Value stream mapping is a technique that uses icons to map the flow of product through a manufacturing system. These icons are aided by summary statistics to further detail the specific manufacturing system. The value stream mapping process usually consists of defining the current state of the system and then, using the principles of lean manufacturing, mapping an improved future system state. Although this is the popular technique, variants and refinements of it exist. This work examines the various techniques of value stream mapping and the methods used to evaluate value stream maps to improve manufacturing systems. The past and current research into value stream mapping and the methods to analyze these maps are compared and contrasted. A set of core analysis questions is developed that summarize the various value stream mapping methodologies. The application of these questions to an enhanced value stream map is developed as a tool, hybrid value stream mapping. Hybrid value stream mapping is then used to analyze the current state value stream map of a manufacturing process, the forging of automotive ring gears. The answers to the core analysis questions enabled the identification of weaknesses in the manufacture of ring gears and suggested system-wide problems. To further clarify and suggest means to rectify these weaknesses, methods beyond the scope of value stream mapping were utilized. By using systems based on standard inventory theory, economic production quantities, techniques to improve information visibility, and methods to enhance production equipment savings of over $4.7 million net present value were discovered for the ring gear production process.

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ACKNOWLEDGEMENTS

BIOGRAPHICAL NOTE

The author, Stephen King, is a Leader's for Manufacturing Fellow at MIT with the class of 2004. He is a candidate for both a Master of Science in Management and a Master of Science in Mechanical Engineering. His previous post-secondary education consisted of a Bachelor's of Applied Science from Queen's University (Kingston).

Before joining the LFM program, Stephen worked for Honda of Canada Manufacturing as both a process engineer and equipment designer. During these six years he undertook many manufacturing improvement projects and learned the basics of making great products.

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Chapter 1: Purpose, Summary, and Structure

The following are the key topics of this chapter:

- o A narrative about the purpose of this thesis.
- o A summary of the main points of the thesis.
- o An overview of the structure of the thesis.

1.1 Purpose

This thesis is to provide the reader with a methodology to analyze a selected portion of a company's supply chain – the value stream[1] of a product family. The proposed method is a combination of other standard methods with the addition of a strategic component. The outcome of the analysis is an understanding of the weaknesses of the current value stream, ideas about how to correct the weaknesses, and a framework within which to implement corrective projects. Further analysis of these weaknesses is required to actually design the improved value stream. To aid the reader an analysis of a family of forged products is presented as a case study. This case study is a complete analysis and incorporates techniques that go beyond standard value stream mapping. Such additional analysis is required to create an improved manufacturing system.

1.2 Summary

Value steam mapping is traditionally used to examine the details of part or part family flow within a manufacturing plant. There exists much literature about how to use value stream mapping in this manner. A natural broadening of this methodology is to examine the usefulness of extending value stream mapping to map not only the product flow through a single manufacturing plant, but also the product flow through a set of manufacturing facilities, warehouses, and finally to the end customer. This extended value stream has also been examined in literature. Apart from these traditional value stream mapping approaches, people have attempted to improve the value stream through other means. This thesis is an attempt to integrate the various methods of improving the value stream map of a product. This novel combination of techniques will be referred to as hybrid value stream mapping.

This work for this thesis was completed over a period of almost one year. The hybrid value stream mapping methods were applied at American Axle & Manufacturing's (AAM) Tonawanda Forge Plant over a period of seven months. The other five months were spent at the Massachusetts Institute of Technology reviewing the findings and documenting them. During this research effort it was found that:

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[1] A value stream is defined in section 2.2, *Overview of Value Stream Mapping.*

o   Value stream mapping could be used effectively to illustrate both the facility level and supply chain level concepts on a single map. Moreover, by placing both the facility level and the supply chain level concepts on the same map the visualization of multiple methods to improve the value stream was possible.

o   By using value stream mapping and associated manufacturing improvement strategies, cost savings in excess of $4.7 million net present value were identified for AAM. These are only the cost savings resulting from analysis directly related to this research effort. It should be noted that only $3.6 million apply to the ring gear manufacturing process.

o   Although value stream mapping is an excellent tool for the identification of weaknesses within a manufacturing system, determining the best means to improve these weaknesses requires additional analysis. This analysis needs to be predicated on a strong understanding of the manufacturing industry in question and processes under examination. Chapter 5 of this work illustrates these supporting concepts.

1.3 Structure

This thesis is organized in the following manner:

Chapter 1: A description of the purpose of this work, a summary of the findings of the research, and an overview of the organization of this thesis.

Chapter 2: A review of the value stream mapping as a tool for identifying the current state of a manufacturing process and of its use in planning a future state manufacturing process. Both facility level value stream mapping and supply chain level value stream mapping will be discussed. The intent of this chapter is to provide the history and common methods of value stream mapping.

Chapter 3: The different approaches to value stream mapping are discussed and integrated in this chapter. The result is hybrid value stream mapping. The intent of this chapter is to explore an improved means of value stream mapping.

Chapter 4: Hybrid value stream mapping is applied to the manufacture of ring gears at Tonawanda Forge to improve the manufacturing system.

Chapter 5: This chapter extends the analysis of the manufacture of ring gears beyond standard value stream mapping. The chapter provides supporting analysis for the improved value stream map outlined in Chapter 4. This analysis is necessary to determine the parameters for the future state value stream map.

Chapter 6: The strengths and weaknesses of hybrid value stream mapping are discussed. Additionally, potential improvements in hybrid value stream mapping are detailed.

Chapter 2: Value Stream Mapping

The following are the key topics of this chapter:

- o The history and development of value stream mapping.
- o A literature review of specific work in the area of value stream mapping.
- o An illustration of the core methodologies of value stream mapping.

2.1 How Value Stream Mapping Arose from Lean Manufacturing

Value stream mapping has it roots in lean manufacturing. Lean manufacturing is a set of principles used to enable the manufacture of goods with fewer resources.

The term *lean production* was first used by John Krafcik of the MIT International Motor Vehicle Program to describe a manufacturing system that operates with minimal excess assets. Womack and Jones [Womack and Jones, 1996] describe *lean* as the ability to do "more and more with less and less."

Today, many people associate *lean production* or *lean manufacturing*, as it now more commonly called, with the Toyota Production System (TPS). TPS is considered by many people to be the first manufacturing system that fully integrated the various factors of lean manufacturing. This is not to say that other companies have not embraced some or many of the principles that Toyota employs [Hounshell, 1985] [Mckay, 2001], but that Toyota has systematically identified techniques that result in improved manufacturing performance[2].

Toyota is a Japanese automaker that through the use of its production system has produced some of the highest quality automobiles in the world. In post World War II Japan, the lack of resources required Japanese industry to do "more and more with less and less" to attain competitiveness with the rest of the world. This bleak environment spurred Japanese manufacturers (and specifically Toyota) to begin the transformation from high-volume large-batch capital-intensive industry towards continuous flow low-capital industry. Developments such as flexible factory layouts, worker involvement, focused small lot production, and kanban[3] methodology were all stimulated in this environment [Ohno, 1982].

The goal of TPS is to reduce costs and thereby increase profits. As part of the system, Taiichi Ohno, the recognized creator of TPS, identified seven types of waste – waste is a cost to manufacturing that does not increase system throughput [Monden, 1998]. These wastes are:

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[2] Improved manufacturing performance can be defined as that which increases product throughput without increasing manufacturing cost or in concurrence with reducing manufacturing cost.

[3] These terms are defined in Appendix B, Definitions.

o *Overproduction:* Producing goods that do not have buyers creates excess inventory and wastes worker's productive capacity creating products that are not immediately saleable. These excess products require increased working capital.

o *Waiting:* Having workers unoccupied wastes the time of valuable resources.

o *Unnecessary Transportation:* Moving products from one site to another site (or to different areas within the same plant) so that work may be performed at the latter site is non-productive if the work could be performed at the former site.

o *Unnecessary Processing:* Undertaking activities that do not add value for the customer wastes resources that could add saleable value to the product.

o *Unnecessary Inventory:* Having material (in any stage of production) in excess of what is required to meet customer demand increases the amount of work in process (or finished goods) inventory. This inventory in turn increases the required working capital of a production facility.

o *Unnecessary Movement:* Requiring that workers move from the ideal position(s) in which to perform their job functions causes worker time to be wasted.

o *Defects:* Creating products with defects requires rework to or the scrapping of the damaged goods.

Identifying the different types of waste, and eliminating them effectively enables a saleable product to be produced using the least amount of required resources. The methodology of TPS is such that the user examines the entire existing production process[4] to scour for waste and eventually reduce it.

The benefits of TPS were illustrated in the influential work, *The Machine that Changed the World* [Womack, Jones, and Roos, 1990]. The success of this book and its readers requesting more information on the techniques illustrated therein, among other reasons, led two of its authors to write, *Lean Thinking: Banish Waste and Create Wealth in Your Corporation* [Womack and Jones, 1996]

Within *Lean Thinking* a method to improve the existing production process, by the identification and elimination of waste, is illustrated. To add value creation to a process[5] the authors recommend following a five-step method:

1. *Specify Value:* Determine the aspects of the product (or service) that the customers deem valuable. Everything else is waste.

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[4] The entire existing production process includes not only the physical production process, but the required information flow to enable the production process. It also includes the processes such as product engineering required to develop the product or service.
[5] This is, to increase the "leanness" of a process.

2. *Identify the Value Stream:* Identify the actions that are undertaken to give this product its final value. Of course, there are many actions required to make a product or service that do not impart value, as viewed by the final customer. The sum of these wasteful actions and the value creating steps is the value stream.

3. *Create Flow:* Undertake actions that increase the throughput of the manufacturing system. Generally, this means eliminating batch processing to the extent possible. This step also usually entails switching to product teams as opposed to functional departments.

4. *Use Pull:* Use customer demand to signal when to produce product. Do not make product that is not currently in demand by the customer.

5. *Move Towards Perfection:* Do not ever stop the above four steps. Continuously look for means to create flow and use pull in the existing value stream. As events change the value stream, continue to identify the value (and non-value) creating aspects of the new stream and move the value stream towards a "wasteless" system.

The TPS seven wastes and the process improvement methodology illustrated in *Lean Thinking* are complementary; the *Lean Thinking* methodology is a means to identify and act upon the seven wastes. Step two, Identify the Value Stream, is very similar in nature to looking for the seven types of waste. Steps three, four and five, Create Flow, Use Pull and Move Towards Perfection, are methods for eliminating the various wastes. The purpose of step one, Specify Value, is to help define a goal for the improvement effort. That is, in specifying value, one should examine a process and determine its purpose. After determining the purpose of the processes, activities that do not add value or add waste become apparent.

Value stream mapping, discussed in the next section, is a visual means to undertake the identification and creation of value within a production process. Since *Lean Thinking*, it has been used as a core tool within many organizations to improve their production processes [Fourth Shift, 2004].

2.2 Overview of Value Stream Mapping

The process of value stream mapping is to identify the current value stream of a product (or family of products) and to use this current state as a basis for envisioning the future value stream. Before continuing, the value stream for a product needs to be carefully defined. The authors of *Lean Thinking* define the value stream as:

> *The set of all the specific actions required to bring a specific product (whether a good, a service, or increasingly a combination of the two) through the three critical management tasks of any business: the problem-solving task running from concept through detailed design and engineering to production launch, the information management task running from order-taking through detailed scheduling to delivery, and the physical transformation task proceeding from raw materials to a finished production in the hands of the customer (Lean Thinking, Womack and Jones).*

This is not to say that the authors were the first to identify the concept of the value stream; value stream management can be seen as early as 400 years ago. In 1574, by appropriately managing the value stream Venice Asrenalotti regularly delivered one war galley per day [Childerhouse, Towill, and Denis, 2003]. The TPS methodology, mentioned in section 2.1, *How Value Stream Mapping Arose from Lean Manufacturing*, also recognizes the value stream. Within the toolkit of the TPS methodology, tools similar to value stream mapping exist.

It should be noted that the *value stream* is different than the *value chain*. The value stream is the entire set of activities to create a finished product or service from the point of view of the customer. The value chain is firm and not customer specific [Womack and Jones, 1996]. An individual firm can optimize its own value chain, and leave a sub-optimal value stream.

The concept of value stream *mapping*, in a procedural sense however, is fairly new. The process of value stream mapping is a simple, although not necessarily easy, exercise. In theory the flow of product and information from the design stage until final production needs only be tracked. In practice the entire value stream is rarely mapped. Most people undertaking value stream mapping disregard the problem-solving task of product (or service) creation, and instead concentrate on the physical transformation and information flow tasks. In one popular work on value stream mapping, *Learning to See* [Rother and Shook, 1999], value stream mapping is defined as:

> *Value stream mapping is the simple process of directly observing the flows of information and materials as they now occur, summarizing them visually, and then envisioning a future state with much better performance. (Learning to See, Rother and Shook)*

Like most of the current work, this thesis will also concentrate on only the materials transformation process and the information flow process (relative to the materials transformation process). This was done to narrow the scope of this work. The total value stream for a product is very extensive and mapping it in a concise fashion difficult.

More detail on the construction and interpretation of standard value stream maps is given in sections 2.4, *Applying Traditional Value Stream Mapping*, and 2.5, *Applying Extended Value Stream Mapping*, but a general overview of value stream mapping is as follows. The value stream map starts at the raw material or component supply side of the product in question. The flow of the product is mapped through the production processes. Finally the map illustrates the flow of product to the end customer. There are two other sections of the common value stream map, the information flow section and the production summary section. The information flow section illustrates the flow of information from the planning source to the individual processes. The production summary section provides key process characteristics. In many cases, the production summary section also contains a line summarizing the entire production time.

It is difficult to illustrate a typical value stream map, as there have been different methods proposed to actually create the map and practitioners use different sets of icons. However, the most common method for value stream mapping is that advocated by Rother and Shook in

Learning to See. A completed value stream map using this methodology is illustrated below (Figure 1):
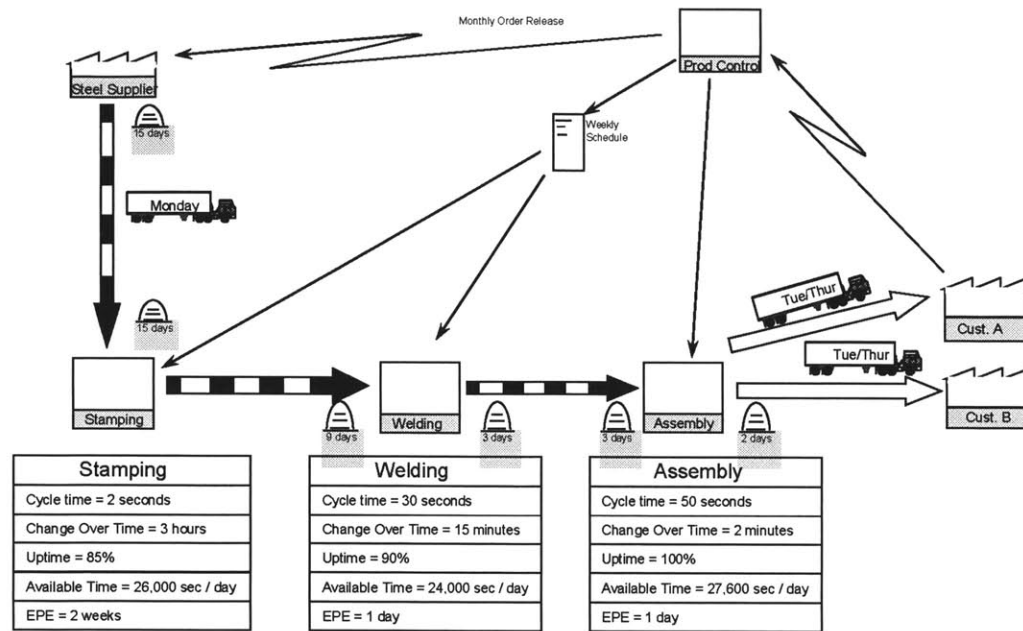
Figure 1: Typical Value Stream Map

In this value stream map, product is delivered on Monday, as signified by the truck labeled Monday on the left had side of the map. This truck contains parts shipped from the steel supplier for the stamping process. The stamping process has a cycle time of two seconds, requires three hours to change between products, is working 85% of the time scheduled, has 26,000 seconds per day scheduled, and cycles through all of the parts every two weeks[6]. This information is summarized in the process data box below the stamping process icon. The round hat icon at each end of the truck arrow symbolizes inventory; there is 15 days of inventory at both the steel supplier and before the stamping process. The hatched arrow symbolizes delivery of product using a push system[7]. Once the product is stamped it is moved to Welding and finally to Assembly. Each of these processes has its own process data box, and inventory can be seen both proceeding and directly following each of these production steps. Finally, there are two customers, and each is sent product on Tuesday and Thursday of each week. The information flow is illustrated above the material flow. For this system Production Control creates a weekly schedule for Stamping and Welding, directly sends information to Assembly (probably allowing management in Assembly to schedule Assembly), and electronically transmits data to the steel supplier. Lastly, one should note that some people might judge this value stream map to be incomplete. For example, some people may want additional summary statistics. In that spirit the value stream maps used in Chapter 4, *Value Stream Mapping: Ring Gear Case Study* are slightly different than that illustrated above[8], providing more detail. When mapping a value stream,

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[6] EPE stands for "Each Product Every" and is used to signify the amount of time required to cycle through all of the parts made at this specific process step.
[7] A push system is defined in section 2.5.
[8] The value stream maps used in Chapter 4 are more detailed than this value stream map. However, the value stream maps shown in Chapter 4 are not as detailed as those initially created for research purposes.

consider those statistics that are pertinent to the value stream.

Note that this is the value stream map for a single enterprise. Value stream mapping techniques have also been used to develop maps for a multiple enterprise systems. In this thesis, such value stream mapping has been referred to as extended value stream mapping. Extended value stream mapping is really a means to visually illustrate supply chain analysis. The extended value stream still falls within the definition, given in section 2.1, *How Value Stream Mapping Arose from Lean Manufacturing*, of value stream mapping. By using the standard notation of value stream analysis, supplemented with some additional icons, the supply chain of an organization may be depicted graphically. This method has been advocated in the popular work *Seeing the Whole: mapping the extended value stream* [Jones and Womack, 2002], by Dan Jones and Jim Womack. Then, in a similar method as to traditional value stream analysis, the extended value stream is analyzed. The techniques illustrated in *Seeing the Whole* comprise the most popular extended value stream mapping method used today.

Practitioners of value stream mapping tend to map the value stream for two distinct purposes:

1. To define and optimize a value stream internal to a facility (traditional value stream mapping)

2. To define and optimize the value stream that is external to the individual facilities, and instead is the value stream that links these facilities (extended value stream mapping).

The reason for this division is not clear. It is hypothesized that it may exist because those within a facility have accurate information about the internal processes, while centralized "corporate" groups have access to data about the entire value stream without the detailed knowledge of how an individual facility is performing. For this reason alone, breaking the production and information portions of the value stream at the facility level seems reasonable. Creating value stream maps using this arbitrary division of extended and traditional is the most popular method of value stream mapping. However, in some cases value stream mapping tools do not appear to distinguish between enterprise and supply chain level maps. The different methods and interpretations of value stream mapping techniques are discussed in the next section.

Value stream mapping is more than the creation of a value stream maps. Once a current state map[9] (either traditional or extended) is created, it is used as a basis for creating the future state map[10]. Rother and Shook, in *Learning to See*, use a series of eight questions to guide the value stream mapper to create a traditional future state map. These questions are discussed in section 2.4, *Applying Traditional Value Stream Mapping*. Womack and Jones, in *Seeing the Whole*, highlight principles used in the creation of a strong extended value stream and expect these to be applied in the creation of a future state map. A future state map follows the same pattern as a current state value stream map, and using the same icons illustrates material and information flow. Some practitioners highlight change points on the future state map. Many consider the

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[9] A current state map is a value stream map illustrating the current production conditions.

[10] A future state map is a value stream map illustrating the desired production conditions. That is, if one desires to reduce cycle time to four seconds, that value is used in the production summary area of the future state map.

final phase of value stream mapping to be the creation of an implementation plan or implementation itself.

The process illustrated above is the most common interpretation of value stream mapping. In the next section, both this interpretation of value stream mapping and that of others are discussed.

2.3 Literature Review

This section is a review of the popular works on traditional, extended, and similar approaches to value stream mapping. It will illustrate all of the works discussed thus far as well as additional relevant work.

Value stream mapping has been used as formal technique for value stream understanding and analysis since at least the late 1990s. Others may have used techniques similar to value stream mapping or even alternate forms of value stream mapping, but a popular codified approach was first developed by Rother and Shook with their work *Learning to See*. Within this workbook, the authors develop a methodology to analyze the value stream of a single organization, given a set product family. That is, the techniques illustrated within this work, provide a step-by-step guide to analyzing the *intra-organizational* value stream. *Learning to See* has become quite popular, with over 85,000 copies sold to individuals and organizations [Rother, 2004].

One of the other popular approaches to value stream mapping was illustrated by Hines and Rich in their article, *The Seven Value Stream Mapping Tools* [Hines, 1997]. Hines and Rich describe the use of seven different analytical tools to determine how best to eliminate waste from a value chain. It should be noted that the Hines and Rich notion of the value stream begins to cross the boundary between traditional and extended value stream mapping. Also, it should be noted that these techniques still require an understanding of the current state. By examining the current state using a series of seven tools, a future state is developed. These tools and their purposes are:

o *Process Activity Mapping*: Developing solutions to identify waste

o *Supply Chain Response Matrix*: Identification of activities that constrain a process

o *Production Variety Funnel*: Understanding how products are produced

o *Quality Filter Mapping*: Identifying where quality problems occur

o *Demand Amplification Mapping*: Analyzing the increased amplification of demand looking upstream the supply chain.

o *Decision Point Analysis*: Determining where in the supply chain the demand changes from a forecast to a pull signal

o *Physical Structure*: Developing a high-level understanding of the supply chain

Many of the above tools were integrated into the "Learning to See" framework in the work by Jones and Womack, *Seeing the Whole*. The work *Seeing the Whole* is dedicated to extended value stream mapping and together with *Learning to See* forms a cohesive visual methodology for analyzing the total value stream using most of the seven tools. All of the above mentioned methods use a similar visual style and this style has been adopted as the most popular form of value stream mapping.

An offshoot of the "Learning to See" methodology is the book, *Creating Mixed Model Value Streams* by Kevin Duggan [Duggan, 2002]. In this work, Duggan details how to analyze value streams with high product demand variability. Specific tools for determining manufacturing characteristics with a variable product mix are detailed. Some of the tools developed in this work are used in the analysis of the case study in this thesis. Essentially, *Creating Mixed Model Value Streams* is an extension of *Learning to See*.

Hines, Rich and Hittmeyer have also developed a value stream analysis methodology, VALSAT (Value Stream Analysis Tool) [Hines, Rich and Hittmeyer, 1998]. In using this tool one gathers information about the value stream improvements necessary to achieve improved performance through interviews or similar processes. From this data a series of specific fact-based needs, or WHATs, is determined. Then a series of HOWs is created using techniques such as brainstorming. The HOWs are compared with each other to determine an optimal implementation strategy using a quantitative, yet subjective, scoring matrix. This tool is similar to the more commonly known Quality Function Deployment (QFD) technique in use for product development.

Some interesting work is being undertaken at the University of Ohio. Three researchers, Djumin, Wibowo, and Irani, [Djumin, Wibowo and Irani, 2004] have attempted to improve the value stream mapping process by integrating techniques from industrial engineering with traditional value stream mapping ideas. To improve the process of generating a current state map the researchers propose mapping the flow of material on an actual plant layout, and to note the different wastes on the plant layout. To create the future state map, the researchers suggest both using traditional value stream mapping analysis and the industrial engineering tool of Process Analysis and Improvement. To accommodate this increased complexity these researchers also suggest an expanded set of mapping icons. Specifically, the research is aimed at addressing the following concerns with value stream maps:

- o Integrating the value streams of multiple product families (ostensibly that share common resources) to allow the envisioning of a global optimum. Current values stream maps are for single product families only.

- o Addressing the concern of transportation and queuing delays, changes in batch size due to poor plant layout or the transfer of materials between plants. Specifically these items are not captured as measures of performance for manufacturing systems.

- o Having a set economically related definition for "value". Value can be interpreted differently – high profit, low operating expenses, many customers, etc.

o Addressing the inherent limitations of facility, such as facility layout, sequencing concerns for material, container sizes, etc.

o Considering the allocation and utilization of factory floor space.

o Factoring in capacity constraints and delays due to capacity related concerns, such as queuing delays, onto the map.

o Allowing for rapid development of "what if" scenarios to evaluate changes in the manufacturing system.

o Handling complex part lists that translate into many product families.

Their work also suggests that the best future state for a facility is obtained when each of the product family future state maps is examined in concert with the others. The work of these researchers can be found on the web at www.iwse.eng.ohio-state.edu.

Most of the other literature is divided into two categories – evaluating value stream mapping as a tool and case studies of value stream mapping. Below is a highlight of MIT literature that evaluates value stream mapping[11]:

The best application of value stream mapping was evaluated in the graduate thesis, *Manufacturing System Design: Flexible Manufacturing Systems and Value Stream Mapping* [Salzman, 2002]. Salzman conducts a survey of the usefulness of value stream mapping given different conditions. Salzman develops a value stream mapping matrix to aid practitioners in determining the expected usefulness of a value stream mapping exercise[12]. Salzman concludes that in situations with simple value streams and management support for change, value stream mapping is most successful.

Value Stream Analysis and Mapping for Product Development is a Master's thesis by Richard L. Millard [Millard, 2001]. His work examines the applicability of value stream mapping and analysis to product development. He concludes that value stream mapping is applicable to product development, but that the common tools used for product and information value stream mapping must be modified to fit a product development framework. Millard recommends using Gantt charts, Process Flow diagrams, and Design Structure Matrix tools.

The work detailing the application of value stream mapping appears to concentrate on industries with traditional batch-style manufacturing due to machine limitations. Within MIT's Leaders for Manufacturing Program, the following work specifically related to value stream mapping has been undertaken.

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[11] The above mentioned literature that discusses different techniques both evaluates and develops value stream mapping.

[12] A value stream mapping exercise is one in which value stream maps of both the current state and imagined future state are created and actions are taken to change the current value stream to mimic the future state value stream.

Michael Kimber [Kimber, 1999] uses value stream mapping to illustrate an ideal state for an aluminum foil mill located in Shanghai, China. The ideal state was one in which coils of aluminum foil were scheduled using a visual pull system. This system was used to reduce some of the major production problems plaguing the Shanghai facility and it led the facility towards reduced inventory and faster delivery. The time to produce one coil of steel was estimated to have been reduced from 19 days to 15.5 days.

In a similar application, Richard J. Welnick [Welnick, 2001] uses value stream mapping to illustrate how lean manufacturing can be accomplished in an automotive stamping plant. Welnick discusses value stream mapping in detail, but only with regards to his specific application at the Ford Motor Company.

Outside of the Leaders for Manufacturing Program work has been undertaken on non-standard value stream mapping techniques. At British Telecom (BT), value stream mapping has been used to map the different processes required to service customers. Jones et al. [Jones et al, 1999], take the idea of value stream analysis from the manufacturing industry to the service industry By using the concepts of value stream mapping, the required processes to complete communications services were mapped by teams at BT and by using lean techniques future state maps were derived to eliminate waste from the system.

Other British work in the area of value stream mapping includes David Brunt's paper, *From the current state to the future state: Mapping the steel to component supply chain* [Burnt, 2000], illustrating an application of traditional value stream mapping. Taking an example from the automobile industry, the production of a sub-frame, Burnt illustrates the complete process of constructing a current state map and creating a future state map using the "Learning to See" process.

In addition to these case studies, many trade journals contain brief examples of the successful application of value stream mapping. Due to the popularity of value stream mapping, there has also been substantial unpublished work on value stream mapping. Many of the major consulting firms, such as Ernst & Young and McKinsey, have developed their own proprietary techniques for value stream mapping. Many consulting groups also maintain reports on the effectiveness of value stream mapping. A methodology has been developed at AAM. The AAM techniques are discussed in Chapter 4, *Value Stream Mapping: Ring Gear Case Study*.

Other work, besides strict value stream mapping has been used to attempt to understand the value stream. Christopher and Towill [Christopher and Towill, 2002], have developed a technique called DMV[3] to determine "focused demand chains". This technique takes a holistic approach to the products a company produces and clusters the products into value streams. The application of these "focused demand chains" is undertaken by Childerhouse et al. [Childerhouse, Aitken and Towill, 2003]. The techniques illustrated in this paper are variants of those used in value stream mapping.

Childerhouse and Towill [Childerhouse and Towill, 2003] have also written about a concept called the twelve simplicity rules [get correct reference for]. The simplicity rules are a set of guidelines for value stream improvement created after reviewing writing of authors such as

Burbidge, Drucker, Wilkinson, and Lane. These rules apply to both traditional and extended value streams. The simplicity rules are listed below:

1. Only make products that can be quickly dispatched and invoiced to customers.

2. Only make in one time bucket those components needed for assembly (or further processing) in the next period.

3. Streamline material flow and minimize throughput time. That is, compress all lead times.

4. Use the shortest planning period. That is, use the smallest run quantity that can be managed effectively.

5. Only take deliveries from suppliers in small batches and when needed for processing or assembly.

6. Synchronize "time buckets" throughout the supply chain. That is, synchronize production and information flow batch sizes. For example, have all entities within the supply chain forecast for a set period of time.

7. Form natural product clusters and design processes appropriate for each value stream.

8. Eliminate all uncertainties in a process.

9. Understand, document, simplify and only then optimize the supply chain.

10. Streamline and make highly visible all information flows throughout the supply chain.

11. Use only proved simple but robust decision support systems.

12. Create operational targets to enable the seamless supply chain. That is, get all players to "think and act as one."

Childerhouse and Towill later performed a study to examine the impact of following these simplicity rules [Childerhouse and Towill, 2003]. A high correlation of profitability and adherence to the rules was observed.

Another work that relates to optimizing the value stream is *The Goal* by Eli Goldratt [Goldratt, 1992]. Using a narrative, Goldratt illustrates the principle of understanding the goal of a manufacturing facility (to make money) to optimize it. By first understanding the goal of a manufacturing facility and then undertaking steps to optimize flow within the facility, the fictional plant manager rescues a troubled facility.

At least one attempt has been made to improve standard value stream mapping techniques through the use simulation. McDonald, et al.[McDonald, et al. 2002] used Arena® to conduct a simulation of a proposed future state map. The simulation was used to determine WIP levels, and

equipment and space constraints. Simulation packages, directly using the "Learning to See" symbols have even been developed. One such package, ValueStreamDesigner©, can be found at www.valuestreamdesigner.com. Simulating improvements in the value stream seems a natural extension of value stream mapping.

This literature review is not exhaustive. The intention is to highlight some the key works in the area of value stream mapping and to illustrate other work as it relates to value stream mapping.

In the next section, common value stream mapping techniques mentioned above are examined in detail.

2.4 Applying Traditional Value Stream Mapping

The essence of value stream mapping is that once a "picture" of the value creation process is created, problems within this chain become easier to see. Of the different techniques of value stream analysis, the "Learning To See" approach is the only one dedicated to traditional value stream mapping and many other approaches build on the "Learning To See" approach. Hence, it will be used as a guide to develop and understand the methodology of applying traditional value stream mapping. The intent of this section is not to be repetitious, but to carefully detail the "Learning To See" approach, so that it may be used as a basis for developing hybrid value stream mapping.

As described before, the first step to any value stream mapping approach is to illustrate the flow of a part or part family from a given start point to a given end point. In traditional value stream mapping this is usually from the delivery of raw materials to a facility to the shipping of finished product. The practitioner needs to remember that a part family needs to be selected carefully – common processing steps for all members of family are required. Similarly, this mapping process is completed for the information flows required to manufacture the product. That is, the information flow used to signal demand to the information required to signal the purchase of raw materials is visually illustrated. A common set of symbols has been developed to represent these manufacturing and information flow processes.

Concurrently while creating this map, a set of key statistics illustrating both the individual processes and the manufacturing system is collected; these are placed in the production summary area. Rother and Shook recommend the following process summary data as applicable:

o *A process description*: A quick description of the process, such as "1st Welding Station."

o *The available working time at the process*: The amount of time a worker could be working on the process. This value is the total amount of time that the plant is in operation minus the amount of time assigned for worker breaks during that operation time. This calculation assumes that a process such as having relief workers operate machinery while primary workers are resting is not in place. In such a case, the time assigned for worker breaks would be zero.

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o *The cycle time of the process*: The amount of time that passes between the production of one product and the next product being created.

o *The number of workers at the process*: The number of workers assigned to the process. Rother and Shook do not discuss recording this statistic when the number of workers at a process varies. The author, however, finds it useful to quickly describe how the manpower is used at the process; for example, "One person 50% of the time". Understanding the manpower situation allows one to obtain a quick estimate of the expected output of a process[13].

o *The change-over time of the process*: The time required to change a process from one part to another. Strictly, it is the time between the production of the last good part of the former process and the production of the first good part of the new process.

o *The uptime of the process*: The amount of time that the process is actually producing product. It is usually defined as a percentage of the available working time.

o *The EPE*: "Each part every" (EPE) defines how often batches of parts are manufactured at a given process. The value given is the average time it takes for a process step to have had a production run of every product it produces. Some practitioners use lot size[14] and number of products in a similar fashion to the EPE statistic.

o *The scrap rate*: The percentage of product produced at a given process that does not meet quality standard for that process. In a similar fashion one could use quality rate, the rate of good quality product produced.

o *The pack size*: The standard amount of product that is grouped as one unit of production. This is value is not the same as batch size. Batch size is the total number of "packs" that are produced in one lot.

Not all value stream maps use all of the above process summary data. Some practitioners have different metrics. Listed above are the most common and those suggested in *Learning to See*. It will depend on the goal of the mapper as to which metrics are used for a given map.

Summary statistics for the entire system include the following:

o *System lead time*: The entire time that is required for a product, from raw material entry into the value stream, to be manufactured into a complete product and shipped to the customer.

o *Product Demand*: The amount of product demand per unit time for finished goods. Note that this is the actual product demand and not the amount used by process(es) in the

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[13] The expected output of a process can be obtained by multiplying the "uptime" of a process by the percentage time that a process is operation, usually the percentage of the available working time that the process has an operator, and dividing this value by the cycle time of the process.

[14] The amount of a single product produced during a single production run.

manufacturing system. Note that product demand is independent from the rate of production. This value is normally expressed as takt time.

Once the current state map is complete, it should look similar to that shown in Figure 1. The next step is to envision the lean future state. In *Learning to See*, eight questions are used to guide map-makers through mentally improving a value stream. By understanding the answers to these eight questions a good basis for improving a value stream is created:

1. *What is the process takt time*[15]: Takt time is the rate at which customers are demanding products. A truly lean system would have product flow from it to the customer at exactly this rate. A system producing consistently at takt time could possibly eliminate inventory.

    Improvement Idea: Understanding takt time provides a baseline to determine the ideal rate of production. A company should strive to attain the ideal production rate by producing product at the takt time.

2. *Will goods be stored before shipping or will they be directly shipped to the customer*: Producing to fill some form of storage creates inventory and thus is not the ideal state. However, with an unreliable process that cannot consistently deliver within the expected lead time some type of inventory is required to maintain a steady flow of product to the customer.

    Improvement Idea: Inventory is not required for reliable processes that can produce within their individual lead times. Striving towards quick responding reliable processes will allow inventory to be eliminated. It should be noted that safety stock can be used to make a series of unreliable processes more reliable in aggregate.[16]

3. *Where can continuous flow be used*: Continuous flow is producing product using a batch size of one. This is a very efficient means of production since no inventory is created between process steps. An automobile assembly line is generally an example of continuous flow. The downside of continuous flow is that the lead time and downtime of processes are now linked. When one station of an automotive assembly line stops working, the entire line stops working.

    Improvement Idea: Link reliable processes together so as to eliminate inventory between them and produce product in the most efficient manner.

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[15] $\text{Takt Time} = \dfrac{\text{Available Working Time}}{\text{Demand during Working Time}}$ The available working time is generally defined as the total working time available during a given period minus the amount of time for breaks, lunch time, etc.

[16] Assume two processes occur in series. Imagine large amounts of inventory in front of the first process and between the first and second processes. With sufficient inventory between the processes, finished goods can still be supplied from this manufacturing chain if the downstream process is functioning even if the upstream process is not working. The downstream process will simply consume the inventory between the upstream process and the downstream process.

4. *Where can "supermarket" pull systems be used*: A "supermarket" pull system is illustrated in Figure 2:
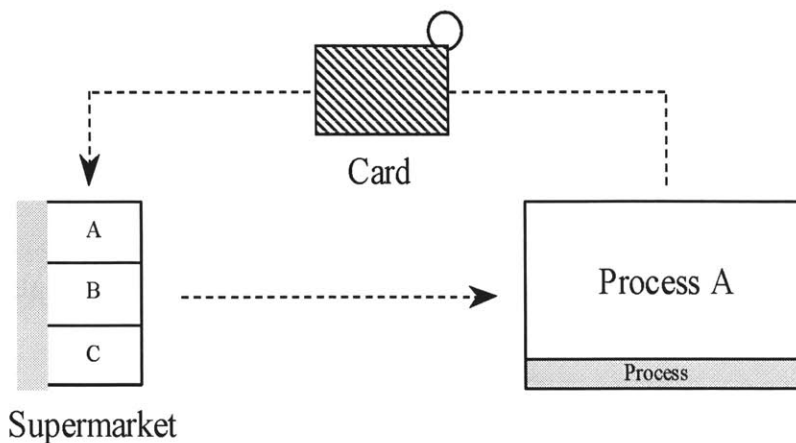
Figure 2: Supermarket Pull System

The square labeled "Card" represents a means to signal inventory to be moved from the "Supermarket" to "Process A." In many cases the "Card" is a physical indicator that is moved between "Process A" and the "Supermarket", while in other cases physical items, such as empty carts, act as signaling methods. To maintain a set amount of inventory, a known number of cards is maintained within the above loop. The "supermarket" is an organized amount of inventory and controlled to a maximum level by the number of "cards" in the system. "Process A" represents any manufacturing process. The loop represented above is commonly known as a material pull-loop. If the "supermarket" shown above was actually a processing step, then the "card" would not represent pulling material from storage, but a signal to begin the production of the item. This is commonly referred to as a production pull-loop.

The pull system must have the following attributes to be effective:

o The amount of inventory within the loop must be controlled. A maximum amount of inventory needs to be set.

o There must be a signaling device to notify the provider of material to provide the material (or make the material) in a timely manner. The pull signals must be transferred at a steady pace and not batched in groups.

o The loop needs to be monitored to ensure that the control mechanisms remain in place. That is, if the loop is defined by tagging containers with reusable paper tags, the number of paper tags needs to be monitored to ensure that tags are not lost or destroyed.

The first two points define a pull system [Monden, 1998] and implementing the last point will ensure that the pull system functions properly. It should be noted that more than one process can be placed inside a pull loop. Variants of the

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simple pull loop have also been developed and shown to have superior performance in some instances [Bonvik et al., 1997].

Improvement Idea: A "supermarket" pull system is designed to organize and control the amount of inventory within the loop. Controlling inventory in such a manner allows for systematic inventory usage to be developed and for the tracking of inventory. With increasing process improvement or more consistent scheduling the amount of inventory controlled inside the pull loop can be gradually reduced.

5. *At what point in the production chain should the production schedule be released*: In a truly lean production system, the production schedule is released to only one place on the production line.

   Improvement Idea: When the production schedule is only released to one location on a production line, and the information flow of the line is linked through pull systems and the like, the effort required to coordinate the system is a minimum. Moreover, as there is only one schedule on the line, there is little chance of an accidental WIP build-up between stations

6. *How can the production mix be leveled*: To ensure that a steady mix of saleable product flow from the manufacturing plant, the production schedule is matched as closely as possible to the demand pattern.

   Improvement Idea: When the demand pattern and the production pattern are matched, there are generally two effects:

   - Little inventory is in the system because as product is produced it is consumed.

   - Worker competency in production of a variety of products is maintained since most products are made frequently.

7. *What increment of work will be consistently released*: What amount of product should be requested to be produced in any one time period.

   Improvement Idea: By standardizing the amount of product to be produced at any one time, the production scheduling process becomes easier. In the ideal lean system this amount is one. This corresponds to single piece flow and if the pattern of production is matched to demand no inventory is held and maximum product variety is had.

8. *What process improvements are necessary to attain this state*: Are there any projects or improvement programs that are required to attain the desired future state?

   Improvement Idea: The future state will not happen without targeted improvement efforts in terms of process or equipment. By implementing these process improvements the future state will become the current state.

The above eight questions the thoughts of the reader on specific areas of the value chain. After asking and answering the above questions, and computing the appropriate summary statistics, the practitioner should be able to envision a future state map that provides for a faster, level, and overall "leaner" value stream. The summary statistics of the new system are then compared with the summary statistics of the future state maps to demonstrate the improvements.

2.5 Applying Extended Value Stream Mapping

Extended value stream mapping is used to map the macro-level supply chain in an attempt to visually illustrate the production and information flows to create a product family. To illustrate the process of extended value stream mapping, the process used in *Seeing the Whole* will be illustrated[17]. This process was chosen since it nicely complements the popular "Learning to See" approach and is a popular mapping method. The process of extended value stream mapping is very similar to that of traditional value stream mapping, using mostly the same icons. The intent of this section is to provide the reader with a strong understanding of extended value stream mapping to allow for it to be used as a basis for hybrid value stream mapping.

The steps to create an extended value stream map are identical to those required to create a traditional value stream map. First the product family being mapped is decided upon, then the material and information flows are physically mapped starting at a raw material supplier and moving downstream.

At each point along the material flow of the product, a set of statistics is captured. For each facility they are listed below:

o   *A process description*: A quick description of the process, such as "Stamping Facility" is sufficient.

o   *The location of the facility*: The physical location of the production facility.

o   *The amount of inventory within the facility*: The amount of raw material, work in process and finished goods is determined for each facility

o   *The number of shifts within the facility*: The scheduled number of working shifts per day that the facility is operational.

o   *The number of days per week that the facility is operational*: The scheduled number of days in each week that the facility will be operating.

o   *The number of days required to produce at least one of each part*: The number of days it takes, on average, for a standard quantity of each part to be produced at least once.

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[17] The process given in *Seeing the Whole* is similar to that of applying all of the seven value stream mapping tools used by Rich and Hines.

- o *The defect rate coming from the facility to the next production stage*: The number of parts at the facility that are produced with unacceptable quality for a given total number of parts produced.

For each transportation link the statistics are as follows:

- o *The transportation distance*: The distance from facility to facility including an intermediate steps such as cross-docking or intermediate storage.

- o *The amount of product transported per shipment*: The average amount of product on a standard shipment to the destination facility.

- o *The amount of defective product transported*: The percentage of product shipped that is unacceptable to the destination firm.

- o *Number of deliveries expedited per year*: The average number of deliveries per year that are transported to the destination firm by a means that is faster than the regular delivery method.

For the information flow the summary statistic are:

- o *Type of communication*: Communication can take many forms, email, fax, telephone, etc.

- o *Frequency of communication*: How often does the communication occur. For example, a weekly schedule could be faxed to a supplier and a daily email sent to introduce schedule changes.

- o *Location of the communication system*: The location of the communication system is defined by the "to" and "from" portion of communication and the physical owner of the system. That is, it could be that Company A's ERP system creates a schedule and this schedule is sent from Company A to Company B. Then, Company B sends it to Company C.

- o *Communication backlog*: The length of time it takes for a communication to be processed once it is received. Although an email is sent at the beginning of the week, it could take a couple of days for the recipient to respond to the email.

- o *Demand amplification due to information flow*: Demand amplification occurs when upstream facilities in a supply chain produce above or below the current customer demand. It is measured as a percentage over/under of the true customer demand. That is, if the true customer demand was 100 units and an upstream fabricator produced 120 units, then the demand amplification would be 20%.

As with traditional value stream mapping, different practitioners mix and match the summary statistics. Depending on the level of analysis and the purpose of the analysis, different summary statistics will need to be collected.

Once created, the extended value stream map is analyzed in a similar manner to that of the traditional value stream map. There are a series of five points to be considered when constructing the ideal extended value stream map:

1. *Is everyone in the entire value stream aware of the rate of customer consumption of the product at the end of the stream?*

   The final product is purchased at a certain rate[18]. In most cases, the final rate of purchase is a relatively constant function compared with that of the upstream production of product. This relationship has been studied since 1958 with the work of Forrester [Forrester, 1958]. One of the means to minimize demand amplification is to notify all of the members of the supply chain of the actual demand. This strategy was proposed both by Forrester and by Lee [Lee and Pradmanabahn, 1997]. The paper, *Measurement and Analysis of Demand Amplification Across the Supply Chain* by Taylor [Taylor, 1999] presents an excellent overview of demand amplification.

   Improvement Idea: By minimizing demand amplification, product can be produced in the batch size in which it is required by the customer, decreasing both inventory and lead time.

2. *Is the minimum amount of inventory present in the value stream?*

   The minimum amount of inventory is, be definition, no inventory. However, zero inventory is not a practical minimum. A practical minimum amount of inventory allows all processes in the supply chain to function normally, given that disruptions to the manufacturing system will occur. Researchers have proposed various methods to determine the appropriate amount of inventory. Within this thesis a set of equations proposed by Simpson in 1958 is used to size inventory.

   Improvement Idea: By reducing the amount of inventory in the supply chain to a minimum, both working capital requirements and lead time to the customer are decreased.

3. *Are the transportation links between the production steps at a minimum?*

   There are commercial packages available to optimize logistics and transportation costs. Complicated transportation networks require such analysis packages. For the purpose of this work, the number of nodes, the total distance traveled between locations, and the need for the product to travel to that location was examined.

   Improvement Idea: Excess transportation leads to increased cost with no value added to the product. Not only does excess transportation add the cost of moving the goods, but it also delays shipment of product by the amount of time the product is in transport. In

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[18] This thesis is concerned with constant rate purchase of goods. The case of variable demand is not addressed in this document.

effect, excess shipping increases inventory.

4. *Is as little information processing as possible used with information flow? That is, is the information pure signal and no noise?*

Information, above and beyond the end customer demand, is required to coordinate the supply chain. Efficient interaction between members of the chain requires that this information to be pure. That is, does the information transmitted between members have extraneous or incorrect data. The ideal information flow contains the minimum amount of (correct) information required.

Improvement Idea: By including only the minimum amount of information (and in a common manner) the entire supply chain can correctly coordinate its relative functions. In doing so waste will be eliminated.

5. *Is the shortest possible lead time engineered into the system?*

The ultimate goal of the extended value stream is to process raw material into quality finished product, within reason, as quickly as possible. A value chain needs to be examined in light of this goal and improved upon to move it closer to the ultimate goal of "instantly" creating product.

Improvement Idea: A short lead time allows for customer demand to be met quickly, low inventory, and minimal working capital.

In the last two sections both traditional and extended value stream mapping was reviewed. One can see that both traditional and extended value stream mapping are similar processes and combining them may prove useful. The next chapter examines both the strengths and the weaknesses of traditional and extended value stream maps and explores means to improve these mapping techniques.

Chapter 3: Improving Value Stream Mapping

The following are the key topics of this chapter:
- o The concerns with traditional and extended value stream mapping addressed in this thesis
- o Development of hybrid value stream mapping.

3.1 What Traditional and Extended Value Stream Maps Don't Do

Value stream mapping is a tool that takes material flows and information flows and effectively illustrates them across the facility (traditional value stream mapping) or across the supply chain (extended value stream mapping). However, the process of creating and analyzing value stream maps has its limitations.

Given the complexity of a manufacturing system, value stream mapping is a relatively simple tool. Recent research has addressed some of these concerns. The work undertaken by Djumin, et al. [Djumin, 2004] is one such attempt. Within this thesis the following limitations of traditional and extended value stream mapping are addressed:

- o *Evaluating the manufacturing system through means other than lean manufacturing techniques:* Lean techniques are but one set of a many methods to improve manufacturing systems. By using only lean techniques, potentially beneficial means to improve a manufacturing system may be ignored.

- o *Integrating the traditional approaches and the extended value stream approaches:* The traditional and extended value stream mapping approaches are very similar in process and result. Integrating these approaches may enhance the ability of practitioners of value stream mapping to envision improved future states.

- o *Creating future state value stream maps that explicitly incorporate the strategy of the organization:* The strategy of an organization has a profound impact on its manufacturing system – a job shop cannot be run in the same manner as an automated production line.

- o *Providing the user with analytical techniques to determine the best alternatives for a future state map:* Value stream mapping techniques do not include analytical models for the manufacturing system. However, these models are useful for determining the parameters of the future state.

This work contained in this thesis illustrates a modified value stream mapping approach to address the above the concerns. These four points will be addressed using a system dubbed hybrid value stream mapping.

This is not to say that this thesis has now presented all of the limitations of value stream mapping. Some other potential improvements to value stream mapping are discussed in section 6.2, *Additional Research.*

3.2 Hybrid Value Stream Mapping

The project upon which this thesis is based was a request from AAM senior management to better understand the flow of product within the Tonawanda Forge facility. Specifically, management was interested in the value streams of the ring gear and net shape gear product lines. However, in addition to understanding the internal value stream, management wanted information to be able to optimize the extended value stream.

Upon examining the value streams of both the ring gear and net shape gear product families the following was noticed:

- o Product flows for Tonawanda Forge are fairly simple. That is, the flow of product is linear and serial.

- o Due to Tonawanda Forge (or at least AAM) having direct responsibility for the inventory of many of its suppliers it was possible to control inventory levels in much of the supply chain.

- o Manufacturing processes (or the capabilities to undertake manufacturing processes) were distributed throughout the supply chain and a means to determine which party in the manufacturing system should perform specific manufacturing functions was required.

As such, it was possible and beneficial to illustrate both the traditional value stream and the extended value stream on the same map. By illustrating both value streams on a single map one could imagine combining different processes at different manufacturing entities, while adjusting inventory levels to obtain a truly lean system.

This led to the concept of hybrid value stream mapping. Hybrid value stream mapping still conforms to the definition of value stream mapping given in section 2.2, *Overview of Value Stream Mapping*. Like both traditional and extended value stream mapping, it does not explicitly map the product development process portion of the value stream. A working definition of hybrid value stream mapping is:

> *A process of directly observing the flows of information and materials as they occur in the* **entire manufacturing system***, summarizing them visually, and the envisioning a future state with improved performance.*

The key purpose of a hybrid value stream map is to seamlessly integrate the formerly mostly distinct traditional and extended value stream mapping approaches. In doing so, recent research in the area of value stream mapping was also incorporated into the technique.

3.3 Developing Hybrid Value Stream Maps

The first step in creating a hybrid value stream map, much like any other value stream map, is to define the product family under analysis. Different techniques have been illustrated in the literature for determining a product family. For the purpose of this research the simple technique of picking a product family based upon the downstream commonality of manufacturing processes was chosen. When a set of products pass through a similar group of manufacturing processes this product set can be considered a product family. This strategy is espoused in the article, "Getting Started on the Lean Journey, Talk a Walk!" [Womack, 2004]. Another technique for determining product families is to examine the Product Varity Funnel, outlined as one of the seven value stream mapping tools [Rich and Hines, 1997]. In any case, a product family based upon common processing steps is determined.

In the work *Seeing the Whole*, the authors suggest that the first step to optimizing the product family value chain is to optimize the internal facility. However, before this is attempted, the company strategy for that product family should be investigated. That is, the current strategy of the firm selling the product family, with respect to the product, needs to be investigated. Only by determining the goal of the product and hence the manufacturing system, can a true optimum be achieved. This optimization technique is promoted to some extent by Eli Goldratt in his work *The Goal* [Goldratt, 1992] and by the VALSAT [Hines, Rich and Hittenmayer, 1998] tool. When the analysis of hybrid value streams is conducted without first understanding the goal or strategy of the organization for that product family, comparing the various future states to determine an optimum is not possible. This is not to say that a mathematical optimum will be determined once a product strategy is understood, but that better choices can be made if the strategy is known.

The strategy determination step is absent in much of the current documented work on value stream mapping. This step, however, may be the most important. For example, if the firm plans to discontinue the product family next year, incorporating a large number of changes into the value stream, if they do not create an immediate economic value, is not a good decision. However, understanding product strategy seems to be implied when educated practitioners instruct those undertaking value stream mapping to use cross-functional teams. In any case, there is a base strategic knowledge that must exist within the individual or team undertaking the mapping.

For the purpose of this thesis, the product strategy was determined through a series of informal interviews. The information gleaned from these interviews deemed important to value stream mapping is listed below:

o *Product Family Life:* What is the product life cycle? Is this product at the start or the end of the product life cycle?

o *Product Family profitability:* Is this a highly profitable product or one that does not make profit? If the product is unprofitable, would an enhanced value stream allow profitability?

o *Targeted customers:* Who are the targeted customers and where are they located? Can these customers move or would it be easier to relocate your production facilities close to these customers? Where should the manufacturing facilities be located relative to the customers?

o *Life of current customer base:* Which customers will be future customers and how long will they be customers?

o *Desired supplier base:* Who are the current suppliers? Will these companies change in the future? How does this supplier base relate to current and future technologies?

o *Future products for the product family:* Are there any future products that might influence the customer base? Will these future products require difference processing steps?

o *Technology under development for the product family:* What technology is under development that may affect the value stream of the product? How can this new technology be integrated into the existing value stream?

o *Production equipment / process planned obsolescence at the factory level:* What equipment will exist in the next few years? Can production equipment be successfully transitioned from one style to another while maintaining the current or improved value stream?

It should be noted that this is not an exhaustive list of questions. And, in many cases, the appropriate cross-functional team will be able to answer them. It is important that the stakeholders in the value stream agree upon the answers to these questions as the answers to the questions form the basis of an improved value stream. Moreover, the above list is not the complete array of questions that were asked during the creation of the hybrid value stream maps for this research, but after reviewing the decisions that needed to be made to create the hybrid value stream maps the answers to these questions were deemed important. Future research into the importance of different questions guiding the creation of the future state would be informative.

This work assumes that the product strategy is already set and that the future state value stream map should account for it. It may be the case that the future direction for a product is determined in concert with the creation of a value stream map. In this case, the answers to the above questions are dynamic and a series of "what-if" scenarios is probably in order. This research effort does not attempt to use value stream mapping as a strategy creation tool.

Independent of these questions, most people would agree that the goal of the firm is to make money, as directly stated by Goldratt in *The Goal.* The answers to these questions are the means by which the firm is attempting to achieve that goal – to make money. In accordance with the main goal of making money, changes to the value stream are evaluated financially. This step is discussed later in this section.

The purpose of investigating strategy prior to creating the current state map is to enable the practitioner to understand the relative importance of current state data. For example, if a company is looking to expand into the Mexico, the portions of the value stream that allow for Mexican expansion must be more carefully analyzed than those located in the Eastern United States that might remained unchanged.

Before beginning the actual current state mapping, the scope of the hybrid current state needs to be determined. That is, at what point should the current state map begin and at what point should it end. To determine scope, it is suggested that the following question be answered:

What portion of the extended value stream does this firm have influence over?

The scope should be limited to those areas in which the firm has influence. In many cases, a firm will have little influence over its customers and thus mapping them in detail may not prove useful.

This question was answered for the Ring Gear case study, in Chapter 4, and was found to be an effective means to determine the scope of the map. When the maps for this research were first created, they were designed to span the entire value stream. The data collection phase to create the current state maps was long as a result. Moreover, little of the data obtained about members of the value stream over which AAM had little influence was used in deciding on the future state. In the end it was decided to make the assembly plant of the upstream customer one end of the value stream and the other end was to be the company supplying the raw steel. Within these bounds Tonawanda Forge management had some authority to affect change.

Another method to determine the scope of the current state map is to pick the facility(s) of the company undertaking the mapping and move upstream one or two facilities. This approach is proposed in *Seeing the Whole*. The concern with this approach is that it may expand the scope of the map to areas over which the mapper has little influence or miss areas of important influence.

To create the current state maps, the following procedure is recommended (and was utilized for this research):

1) Start with a base facility – the most important facilities in the process. Create a facility level current state map as illustrated in the methodology in section 2.4, *Applying Traditional Value Stream Mapping*. Obtain and record the information listed in that section. As noted in the section, it may not be possible or practical to obtain all of the information discussed in that section of this work.

2) Extend the value stream upstream and downstream of this facility keeping in mind the answer from the above question. This extended value stream should be mapped as shown in section 2.5, *Applying Extended Value Stream Mapping*. To that information add the following:

   o A facility level map or list of the processes undertaken with each of the individual facilities mapped. For the work accompanying this thesis, describing the processes

undertaken for each member of the supply chain proved useful in understanding the complexities of the supply chain. For the net shape gear supply chain, production processes were undertaken at AAM facilities that could have under performed at supplier facilities for potentially less overall cost.

3) In addition to creating a facility level map, obtain a scale drawing of the facility and trace the product family flow on it. The purpose of this exercise is to illustrate areas of high congestion, common flow paths, and potential traffic bottlenecks. This step is an attempt to incorporate the research of Djumin et al. [Djumin et al., 2004] into this work[19].

4) Highlight on the current state map if the information flow is unidirectional or bidirectional. That is, does information flow both to the process steps and back to scheduling or is it only from scheduling to the process steps.

In an attempt to expand the scope of analysis to not only include traditional and extended value stream mapping additional questions have been integrated into the analysis of the current state maps. Moreover, when analyzing the current state maps, the analyst must be mindful of the product strategy. The methodology used for analysis in this research was as follows:

1) To ask and answer the seven questions from the "Learning to See" methodology. To these questions the following were added based upon current research:

a) *What is the appropriate process batch size for this product?*

This question was added since batch size is a key process parameter related to the flow of material through the system. Lean thinking tends towards targeting a batch size of one, but this may not always be the most economical batch size. This question was also added in response to the second and fourth simplicity rules.

Improvement Idea: The appropriate batch size is one in which the goal of the firm, to make money, is maximized. The methodology suggested herein is asserts that the goal of the firm is to maximize the firm's present value. There exists a batch size that accomplishes this goal.

b) *How can the information flow be streamlined and made highly visible in the factory?*

The "Learning To See" methodology maps the information flows but does not specifically question them. The tenth simplicity rule addresses information flows within (and external to) an organization.

Improvement Idea: Streamlined and highly visible information flow will allow those people involved in the manufacturing process to make decisions accurately and in the least amount of time.

c) *What is the appropriate amount of raw material to receive at one time?*

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[19] Although this step is recommended and was completed it will not be illustrated in the case study.

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Similar to determining appropriate process batch size, the appropriate raw material delivery batch sizes needs to be determined. Again, the evaluation criterion is the maximization of the firm's present value. This question addresses the fifth simplicity rule.

Improvement Idea: There exists some ideal batch size which minimizes the cost to hold inventory and the cost to deliver inventory.

d) *What are the sources of uncertainty in the manufacturing system and how can these be minimized?*

Uncertainty in any part of the manufacturing process, be it in production or transportation, causes disruptions in product flow. In response to the eighth simplicity rules this question was added.

Improvement Idea: Variability in a manufacturing process increases the need for inventory, and other stocks to maintain product flow in the event of reduced production. These stocks require working capital. By reducing variability, these stocks can be reduced.

2) To ask and answer the five questions from the "Seeing the Whole" methodology. To these questions the following were added based upon other research:

a) *Has there been an operational target(s) created to which the entire supply chain is held responsible?*

Operational targets align the objectives of the supply chain. This question addresses the last of the twelve simplicity rules.

Improvement Idea: By aligning the incentives of the manufacturing system, entities within it will naturally act in a manner that benefits the system as a whole. These actions, in turn, should maximize the present value of the manufacturing system.

b) *How can shipments be better synchronized so that inventory and processing times are reduced?*

The sixth simplicity rule relates to synchronizing "time buckets" throughout the supply chain.

Improvement Idea: By aligning "time buckets" in the supply chain, excess inventory due to processes producing product at different rates can be eliminated.

c) *Is this a natural product group for the rest of the supply chain?*

The seventh simplicity rule is that products should be kept in product families and that

these product families be common to all of the members of the chain.

Improvement Idea: Additional cost may be imposed on the supply chain if the product family is not universal to the entire supply chain.

3) Consider the information gleaned from understanding the strategy of the organization. How can it be used to design a better value chain?

It is important that the strategy of the organization fit with the future state value stream. Examples illustrating this point have been given above.

This methodology does account for the other simplicity rules not specifically translated into questions. The first simplicity rule, making products that can be quickly dispatched and invoiced, is to some extent ignored. The product is taken as a given in this analysis, but this analysis might detect means to improve the dispatching or the invoicing of product. The third simplicity rule, stream lining operations, is a consequence of this analysis in that operations are streamlined to the point that streamlining is economical. The ninth simplicity rule, using the UDSO improvement methodology[20], is addressed in the "Learning To See" questions. The eleventh simplicity rule, using simple but robust decision support mechanisms is addressed through the creation of this methodology.

The answers to the above questions allow for the identification of weaknesses in the current state and act as a guide to envisioning the future state. Creating the future state map is accomplished by addressing these weaknesses through further analysis, while focusing on the product strategy. In the case of this research, the weaknesses were addressed through the creation of projects to correct them. As each manufacturing facility is different, the specific projects to correct the weaknesses will be myriad. The case study developed in the next section will act as a guide to develop future state maps.

This future state value stream map is illustrated using the same icons as those of the current state map. Given the timing to undertake these projects, their life spans, and their economic value as a group, an implementation plan can be created.

The evaluation criteria for each project are the project's net present value (NPV). To determine which of the projects should be completed as a group, the NPV of the group of projects should be determined. This work will not go into the details of computing the net present value of a project. Most introductory finance textbooks will explain the details of these calculations [Brealy and Myers, 2003]. Note that if project have sufficient option value then a real options analysis may also be required.

The analysis procedure listed above is summarized, in stepwise fashion, as follows:

1) Determine the product family to be analyzed.

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[20] The UDSO methodology is "understand, document, simplify and only then optimize."

2) Examine the company strategy. This step consists of gathering information about product direction, technology development, and supply chain strategy. Remember that the goal of the firm is to make money.

3) Create a current state map of the product using the enhanced icon set (see Appendix A). This current state map will illustrate the specific flow of product within the facility and the flow of product at all of the upstream and down stream facilities within the supply chain.

4) For each specific facility, illustrate the flow of product within the facility on a scaled drawing.

5) Examine the system using the series of questions listed above to highlight potential improvement areas. Keep in mind the product strategy when answering these questions.

6) Create a future state map given the current information. A future state map is created by addressing the weaknesses identified in the current state map and by undertaking additional analysis to create a system to remove these weaknesses. To remove the weaknesses a series of projects will be required.

7) Evaluate the projects that need to be undertaken to create this "end goal" future state map. The NPV of the projects should be evaluated in concert. Those projects that attain the highest NPV and attain the goals of the firm should be implemented.

Chapter 4: Value Stream Mapping: Ring Gear Case Study

The following are the key topics of this chapter:
- o The use of value stream mapping at American Axle & Manufacturing
- o The background of American Axle & Manufacturing and the applicable products
- o Using hybrid value stream mapping to analyze the ring gear product family at American Axle & Manufacturing.
- o Creating a future state map for ring gears using hybrid value stream mapping.

4.1 Current Lean Manufacturing Practices at American Axle

American Axle & Manufacturing developed its own unique value stream mapping processes. In 1999, AAM initiated its American Axle Manufacturing System modeled on the systems of similar companies such as Toyota's TPS. The AAM manufacturing system consists of ten modules, listed below, each illustrating specific lean manufacturing concepts:

1. *Value Stream Mapping*: Traditional value stream mapping.
2. *Workplace Organization*: Effective organization of a workplace.
3. *Total Preventative Maintenance*: A program to maintain equipment to prevent equipment failure
4. *Standardized Work*: The creation of processes to balance a set amounts of work
5. *Built-in-Quality*: Improving (or removing) inspection, building products correctly the first time, and the error proofing of production.
6. *Flexible Operations*: Cellular manufacturing and converting to a cellular structure
7. *Quick Changeovers*: Reducing the time to change between part types.
8. *The Pull System*: A system whereby material to be processed is called by a downstream manufacturing step.
9. *Leveled Production*: A process of smoothing production volume and mix over a given time period to match customer demand.
10. *Problem Solving*: Processes to facilitate rapid problem resolution.

The majority of the tenets of lean manufacturing as illustrated in such works as *Lean Thinking* and *The Machine that Changed the World* are included in the AAM Manufacturing System. AAM is striving to become a leader in lean manufacturing techniques.

Of particular interest to this work is the value stream mapping section. The value stream mapping section focuses on traditional value stream mapping and is modeled on the "Learning To See" approach.

4.2 Using Value Stream Mapping to Improve American Axle

AAM employees (and hired consultants) had previously undertaken work to map the individual value streams for certain forging process. However, none of these maps encompassed both the traditional and extended value streams. Most maps stopped at the facility level or were partial attempts to map the extended value stream.

For this research the goal of AAM management was to create an ideal future production (and information flow) process to enable it to manufacture ring gears and net shape gears in the most competitive manner possible. With that goal in mind, hybrid value stream mapping was used as the tool to illustrate and envision the ideal future state processes.

To create hybrid value stream maps the author created traditional value stream maps for the facilities controlled by AAM that processed product for the ring gear and net shape gear product families. These traditional value stream maps were then connected to each other and to external companies using extended value stream mapping techniques. Through trial and error the procedure outlined in Chapter 3 was developed.

Only AAM controlled facilities were individual mapped because:

a) The data for these facilities was readily available and trustworthy. The data for external firms was available, but upon visiting the external firms it was found that the data was questionable. It should be noted that when similar process were completed at both AAM firms and external facilities, the process layout at the external facilities was noted on the map. This was to allow for the possibility of mixing processes to envision differently arranged processing steps.

b) Even in the event that traditional value stream maps could be accurately created for external facilities, AAM had little authority in these facilities to implement change.

c) The purpose of the value stream maps was to develop a best case future state for the processing of ring gears and net shape gears. The future state may or may not have included any specific outside facility and mapping non-used facilities is wasteful.

d) Including extensive data on outside facilities in the value stream mapping effort may have required the sharing sensitive internal AAM data.

"Ignoring" the internal value stream maps of individual facilities is against the advice of various practitioners [Jones and Womack, 2003] and this was not done. Where reliable external data was available, it was considered in the analysis, but the facilities to which it applied were not mapped.

The next section provides background on AAM and begins the value stream mapping journey.

4.3 American Axle, Tonawanda Forge, and the Cheektowaga Machining Facility

The work documented in this thesis was conducted at AAM during a seven month period. The majority of this endeavor was undertaken at the Tonawanda Forge facility and the Cheektowaga Machining Facility.

In 1994, the American Axle & Manufacturing (AAM) Company was founded by Richard F. Dauch, the current CEO, and his partners. This new company consisted of entities from General Motors' component plants for drive train component creation and assembly. These properties

were located in either Michigan or western New York. The creation of AAM was part of General Motors' strategy of increased outsourcing. Since that time, AAM has expanded to over 12,000 people and 14 different manufacturing facilities. AAM has invested in manufacturing facilities in Mexico, Brazil and Europe. In 1998, the company became publicly traded [American Axle and Manufacturing, 1999].

One of the original AAM properties was Tonawanda Forge. Tonawanda Forge began operations as a General Motors in-house component plant in 1953. Since then Tonawanda Forge has expanded operations, to over 1,000 employees and over one million square feet of manufacturing space. Tonawanda Forge conducts over $200 million dollars in business annually. It chiefly supplies other AAM facilities with forgings for driveline assembly plants. The two major components examined in this thesis, ring gears and net shape gears are both manufactured at Tonawanda Forge[21].

Ring gears are components that are situated in the rear axle assembly, also called the differential. The ring gears are attached to the differential. The turning of the differential pinion via a gearing system causes the rear wheels of the vehicle to rotate. As part of this gearing system there are four gears (net shape gears for differentials produced by AAM) located deep inside the differential. It is these four gears that allow the wheels to rotate at different rates when a car is turning. When the one rear wheel needs to rotate at a different speed than the other rear wheel, the side gear attached to that wheel (via the axle) rotates against its pinion (or "spider") gear. There is one set of side and pinion gear per rear axle. Figure 3 illustrates the differential assembly.
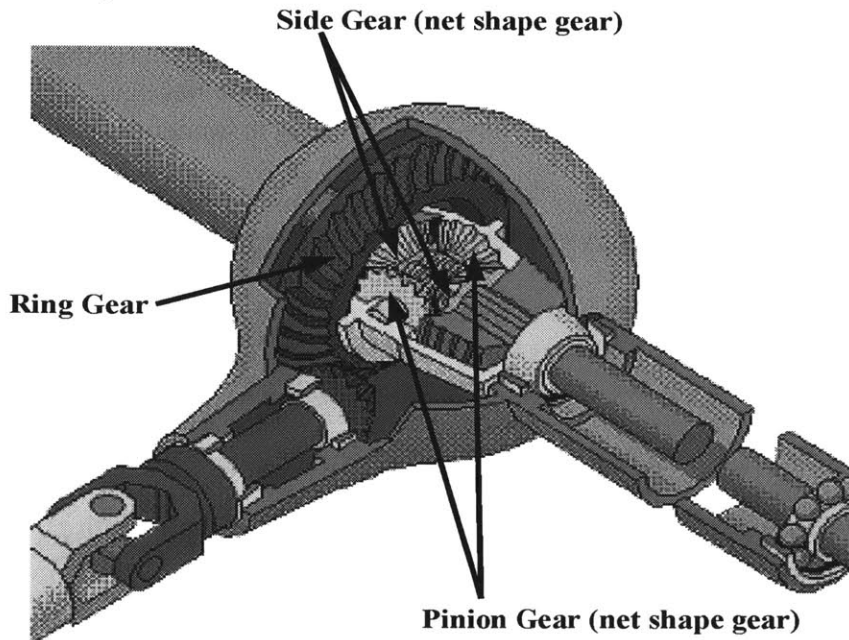

Figure 3: Differential

The following picture (Figure 4) illustrates a forged ring gear blank (not machined), and a final rear gear used in the differential: (left ring gear is a forged blank; right ring gear is a finished

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[21] The exact manufacturing process for ring gears is discussed in section 4.2.

product):
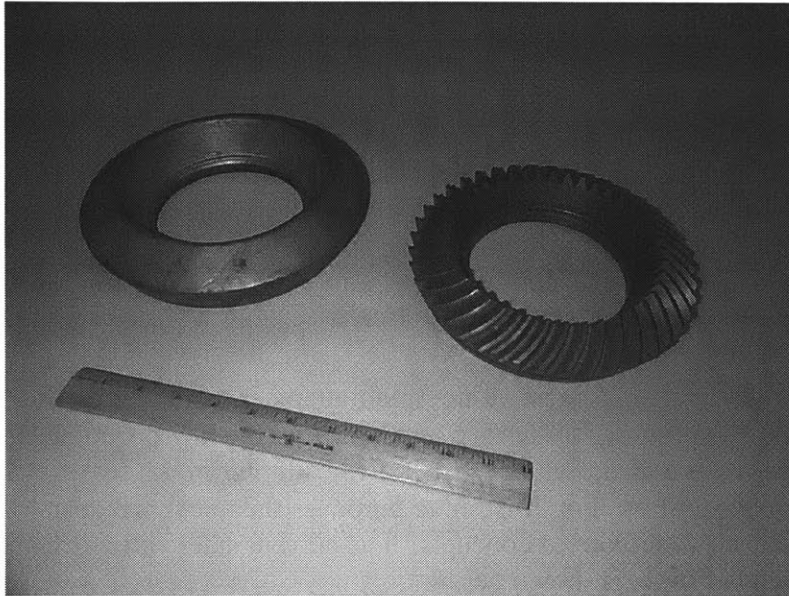
Figure 4: Ring Gears

Below is a picture of a pinion gear (Figure 5: left, finished part; right, forged blank). Note that the teeth of the gear are formed on the forging blank; the term net shape indicates close tolerance forging, generally when the teeth are forged and not machined.

Figure 5: Net Shape Gears

In addition to a forging process at Tonawanda Forge, net shape gears undergo operations at the Cheektowaga Machining Facility. The Cheektowaga Machining Facility was created by AAM in 1999. It is currently dedicated to secondary operations on net shape gears. The facility processes more than 300,000 gears per week, and has yearly revenues in excess of $25 million.

Most of the ring gears and net shape gears are placed into rear axle differential assemblies at AAM owned assembly (driveline) plants.

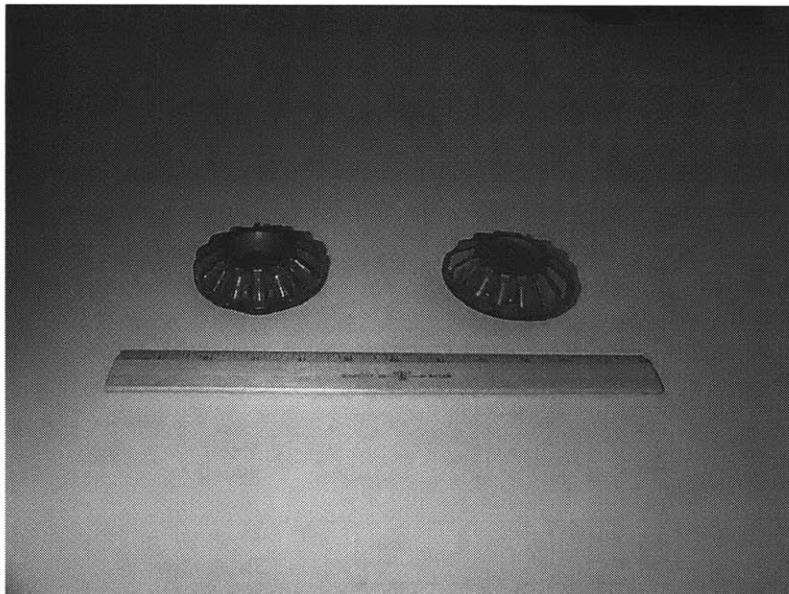At both Tonawanda Forge and the Cheektowaga Machining Facility, hourly workers are represented by unions. The International Association of Machinists (IAM) represents certain skilled trades at Tonawanda Forge and all of the hourly employees at the Cheektowaga Machining Facility. The United Auto Workers (UAW) represents the bulk of the employees at Tonawanda Forge.

4.4: Interpreting the American Axle Value Stream: Ring Gears

Instead of reviewing both the ring gear and net shape gear value stream maps, it would be more illustrative to take the time to view just one process family map and highlight the key differences to the other process map. The ring gear map was chosen because it is the simpler of the two maps and yet contains more savings opportunities. For illustrative purposes the net shape gear mapping procedure may be used to demonstrate selected concepts. The current state value stream map for ring gears, as seen by Tonawanda Forge, is shown below[22]:
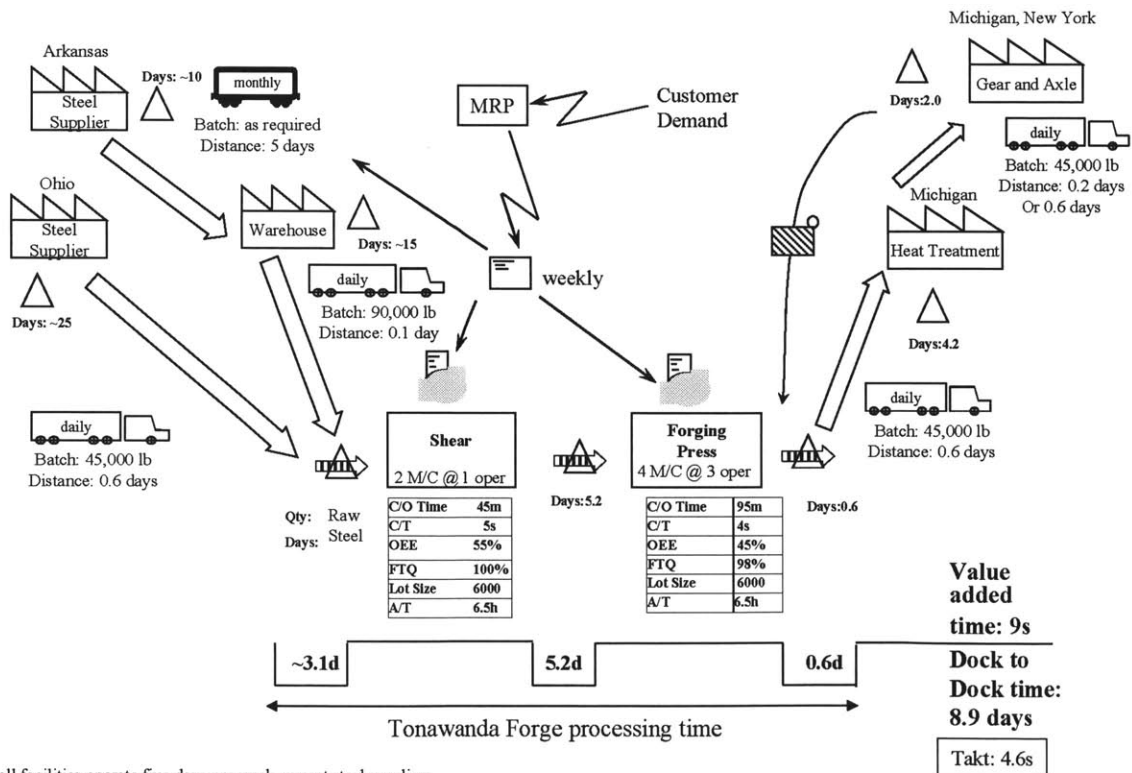
Figure 6: Current State Hybrid Rear Gear Value Stream Map

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[22] There are three products within this product family that are not sheared prior to forging. Instead the steel mill contracts with an outside supplier to pre-cut the material. The actual quantity of material in inventory is not available. For the purpose of this thesis, the separate products are not considered except in the transportation study.

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The summary statistics for the above current state map are dated August, 2003. Some improvements have been made to these statistics during the course of this research. Also, note that not all of the summary statistics illustrated in the previous chapters have been used to describe this value stream map.

Note that these summary statistics represent the average product within the product family. This is partly done to disguise the actual results and partly to allow for ease in determining the concern areas.

Before analyzing this value stream, it needs to be explained in some detail. Starting from the material movement process, going left to right, and then to the information flow process, the manufacturing system is illustrated below.

> *Steel Supply:* The steel supply base consists of all of the downstream activity required to produce steel bar (i.e. rolling mills, furnaces, etc.). There are two steel suppliers for Tonawanda Forge. One of these companies is located in Ohio and the other is in Arkansas. Steel suppliers produce product on a six to twelve week cycle and hold little safety stock. Thus, on average, the steel suppliers held three to six weeks of inventory. The steel mill in Ohio had inventory transported directly to Tonawanda Forge by truck – generally with daily deliveries. The trucks carried approximately 45,000 pound of steel each. The estimated amount of inventory in the one mill was 25 days. This value was obtained from viewing the inventory, and conversations with steel supplier personnel. The other steel mill located in Arkansas, first transported its steel to a warehouse located near to Tonawanda Forge. This transport was primarily by train. The warehouse held approximately 15 days of inventory, while the rest of the inventory, approximately 10 days of product, was held at the steel mill. These values were obtained through conversations with the steel supplier and steel supplier data.

> The steel was supplied as twenty foot long bars with diameters between 3.25 inches and 4.25 inches.

> *Steel Processing:* Steel yard attendants unloaded arriving steel trucks into holding areas. Approximately 3.1 days of inventory was kept in these holding areas. Upon request from the manufacturing department steel was transferred to the shearing process. Shearing is a rapid cutting process whereby the steel bars are cut into lengths between four inches and eight inches, depending on final ring gear product. Details of the process parameters are given in Figure 6. These short steel bars, billets as they are known, are transported in metal tubs to a holding area. When the forging presses need more raw material this material is drawn from the holding area. Forging is also a quick process, and 98% of the finished product has acceptable quality. However, product sometimes is ejected from the forging press and returned to the holding area, due to the raw billet being at an improper temperature or the forging press not being ready to process product. This led to having 5.2 days of inventory in the holding area. Little finished goods inventory was stored, 0.6 days of inventory.

Annealing: After the ring gear blank has been forged, it is transported to an annealing facility in Michigan. The ring gears are transported in approximately 42,000 pound batches. First the ring gears are annealed and then shot blasted to remove oxidation as a result of exposure to high temperatures (in the presence of oxygen). Approximately three days of inventory is kept at this facility.

Final Customer: The final customer is an AAM owned gear and axle plant. There are actually two independent plants that receive product, one in Michigan and another in New York. The final customer takes the annealed blanks and machines them into final ring gear product. The striped card in Figure 6 illustrates a material delivery signal sent from the final customer to Tonawanda Forge. The signal tells management at Tonawanda Forge to ship a given number of a certain product to the annealing facility.

Information Flow: Tonawanda Forge receives customer demand from its upstream manufacturing facilities, the gear and axle plants. The MRP system is used to determine the weekly schedule. This weekly production schedule is then used by the manufacturing group to create daily production schedules for each of the shear and forging departments. The weekly schedule is also sent, after some adjustment, to the steel suppliers. This weekly schedule also contains a fourteen week forecast for product demand. This forecast is to enable planning both internally and by the steel suppliers.

The first stage of analyzing the current state map is to obtain answers to the interview questions listed in section 3.3, *Developing Hybrid Value Stream Maps.* For the purpose of this research, the answers to these questions came from semi-structured informal interviews with different members of AAM management. This interview format, as opposed to a cross-functional team approach, was chosen for the following reasons:

a) Potential team members had responsibilities at AAM, limiting their effectiveness as team members.

b) By consolidating the question and answer information through a single person, there was only a single filter to process the information. Some of the information was qualitative in nature and filtering it through a team would take time.

c) The researcher was unbiased to the outcome of the questioning. Whereas, team members from AAM may have had hidden biases.

The following key questions, listed with their respective relevant answers, were asked[23]:

What are the major improvements that can be made to the ring gear product line or production equipment?

Management mentioned the following improvement efforts:

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[23] The answers given below are a summary of the general consensus of the people interviewed.

1) Change-over time: Reduce the amount of time it takes to change from one product to the next.

2) Press reliability: Increase the reliability of the presses through improved maintenance and new technology.

3) Ring-Rolling Technology: A new press is under construction using a technology known as ring rolling[24].

Are there any new customers targeted for ring gears? Why?

No. There are no specific new customers targeted. Ring gears are only used internally by AAM.

Are there any new suppliers targeted to supply steel for the ring gear product family? Why?

Foreign steel makers are targeted as potential suppliers of steel for the ring gear product line. Foreign steel is less expensive than local steel.

Are there any new developments product-wise for the ring gear family of products?

There are no major new types of products for the ring gear family.

What new processing technology is under development for fabricating members of this product family?

Currently, the ring gears are annealed by an outside company. There exists technology that will "slow-cool" the ring gears and eliminates the need for a separate annealing process outside Tonawanda Forge.

A new "ring-rolling" press is being implemented at Tonawanda Forge. It will eliminate some of the excess billet material required using the existing process. To operate properly the "ring-rolling" press will require billets prepared with flat ends.

The facility in Mexico has tried to saw ring gears with saws linked directly to the presses. Tonawanda Forge uses shears instead of saws and the shears are not linked to the presses.

Is there any production equipment or methods that have planned obsolesce at the factory level?

The ring gear billet shears are an older technology. The use of saws to cut the ring gears is under investigation at other AAM facilities.

The next step in analyzing the current state map is to answer the modified "Learning To See" style questions from section 3.3, *Developing Hybrid Value Stream Mapping*. Please note that the

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[24] The specifics of this technology will not be discussed in this thesis.

order of the questions is specific, and this is done in an attempt to guide the mapper in his or her analysis. These questions and their answers are listed below:

1. *What are the sources of uncertainty in the process and how can these be minimized?*

    The key items of uncertainty for the ring gear processes are as follows:

    a) *The customer demand*: Although there is a twelve week forecast of future customer demand, the actual demand each week can vary substantially versus the forecasted amount. Data of forecasted demand versus actual demand was examined for the months of February 2003 to June 2003. It was found that the variance between the forecast and the actual demand was as much as 40% per week. This deviation has made scheduling product exceedingly difficult. The following graph illustrates the variance between actual product shipped and planned demand, using scheduled incoming raw material as a proxy for planned demand[25]:

Supply and Demand - Ring Gears
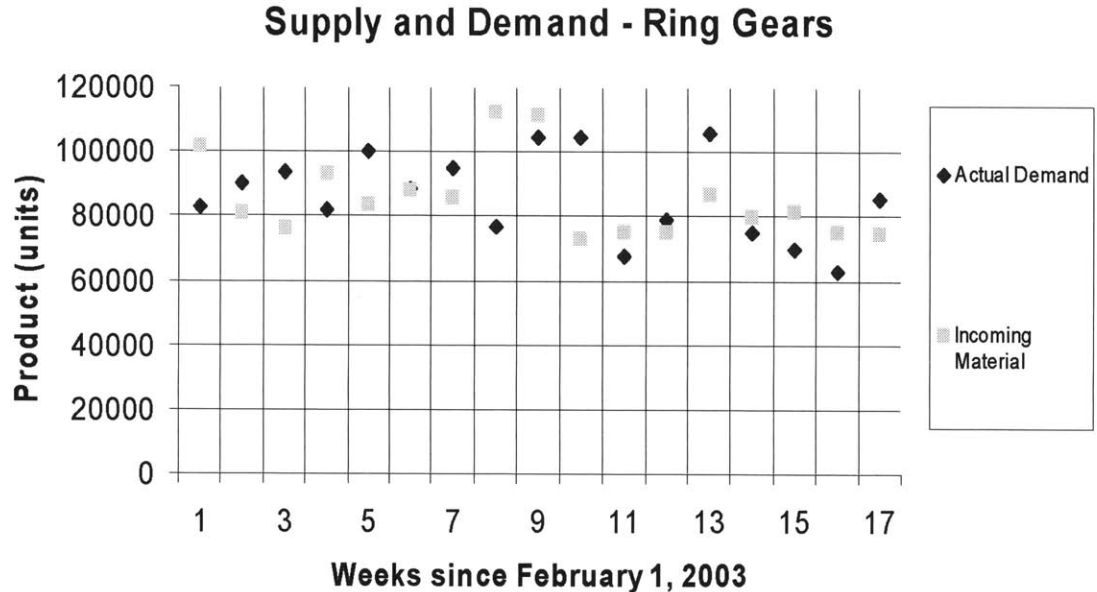
Figure 7: Supply versus Demand

    b) *The length of press downtime*: There are currently four operational presses used for forging ring gears at Tonawanda Forge. The reliability of these presses is fairly low. On average, the presses are only operating 45 percent of the scheduled operating time. The most consistent reason for this low operating time is the length of time it takes to recover from a failure, no matter how minor. When a failure occurs on the forging press, it typically takes a few minutes for the appropriate maintenance people to arrive to fix the problem. The actual problem can usually fixed quickly. However, during this time, the

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[25] Material is scheduled one week in advance of use based upon a forecast.

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machine is generally shutdown to conserve energy[26]. Upon completion of the repair, there is a restart and heat-up procedure. In total a simple fault can cause upwards of forty-five minutes of downtime. Moreover, the length of time to switch from one product to the next is on the order of one and a half hours; this time is included in the downtime.

c) *The length of time it takes a product to get through the supply chain:* Not only is the process reliability low, but the process length is quite variable. This variability tends to shift demand patterns in the supply chain.

2. *What is the process takt time?*

The maximum weekly demand is approximately 86,000 units[27]. During a standard week, there are three shifts of approximately six hours and forty-five minutes each[28] per day. Thus, to avoid overtime a product needs to be produced every 4.24 seconds[29]. The actual cycle time of the process should be less than takt time. As there is mix of products, the weighted average cycle time of the products by volume was used to determine a plant cycle time to compare to takt time. A listing of the major products used to determine the weight average cycle time is given below (figure 8):

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[26] Unless the machine is shutdown, sheared steel billets will continuously run through the machine. These billets must be returned to inventory to cool before they can be forged.

[27] This maximum was observed in August, 2003.

[28] There is a 45 minute lunch and approximately 30 minutes of breaks. Relief associates are scheduled to relieve regular production associates when they are scheduled for non-production activities. In practice, it is difficult to coordinate relief associates and their effect will not be considered.

[29] Takt Time = (5 days x 3 shifts/day x 6.75 hours/shift x 3600 min/hour) / 86000 parts = 4.24 seconds

Part #	Demand (units per week)	OEE[1]	Cycle Time (sec. per part)	Effect Cycle (sec. per part)[2]
0747	5094	53.7%	6.0	11.2
0757	340	44.2%	6.0	13.6
3709	17864	45.5%	6.7	14.7
3712	1222	44.6%	7.5	16.8
3716	4145	42.3%	7.5	17.7
3717	1331	38.3%	7.5	19.6
3720	140	35.6%	8.6	24.1
3721	3560	41.9%	8.6	20.5
3734	15960	53.5%	6.7	12.5
3735	1309	44.6%	6.7	15.0
4793	3856	50.2%	6.0	12.0
4794	4125	49.5%	6.0	12.1
4927	4261	43.0%	7.5	17.4
6450	4670	56.9%	6.7	11.7
6451	2919	50.3%	6.7	13.3
7242	8753	46.2%	6.7	14.4
7244	1075	38.3%	6.7	17.4
6006	2376	44.2%	15.0	33.9
6008	593	38.2%	15.0	39.3
Weighted Average		48.0%	7.1	15.0
Per Press		48.0%	2.0	**4.68**

[1] OEE = Actual Part Production / Expected Part Product
[2] Cycle Time divided by OEE
[3] On average 3.5 presses were available

Figure 8: Press Cycle Time

The effective cycle is 4.68 seconds per part. This was determined by taking the weighted average cycle time and dividing by the average number of presses available. As there are three crews scheduled on presses, plus suitable relief operators to operate the presses during some scheduled downtime 3.5 presses was the effective number of presses available during any given shift. The cycle time value of 4.68 seconds per part exceeds the takt time of 4.24 seconds per part. As a percentage of takt time cycle time is 110%. This result is expected, as plant management cannot produce to weekly demand without resorting to overtime most weeks. However, with no unexpected problems a ring gear should be fabricated every 2.0 seconds. Thus, the machinery is loaded to 47%[30] of potential capacity. The current AAM target is 65%. The machines are very much below target.

Using similar processes, the cycle time of the shearing and heat treating processes were analyzed. The results of this cycle time study are (figure 9):

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[30] 2.01 / 4.24 = 47%

Process	Cycle Time (sec. per part)
Shearing	3.9
Forging	4.7
Heat Treatment	3.1

Figure 9: Cycle Time Study

Note that the above cycle times are averages based upon total product range. The takt time for the products is approximately 4.2 seconds – thus forging is not fast enough and should be improved. The other processes are acceptable.

Also, the working time per process varies significantly. That is, the forging process runs on a different schedule than the heat treatment process in some cases. This situation in itself is forcing inventory. If one process works seven days per week and a downstream process works five days per week, at one point in the system, there must be two days worth of inventory, assuming the two days of production are consecutive. Matching the working times will allow for a reduction in inventory and more responsive system. A true pull system – and hence minimal inventories – cannot be achieved in this scenario. It should be noted that this problem is more pronounced in the net shape gear product family than in the ring gear product family.

3. *Will goods be stored before shipping or will they be directly shipped to the customer?*

The key factors of uncertainty (and AAM's ability to control them), combined with the strictness of the customer requirements determines AAM's ability to ship directly or the need to create a warehouse of goods before final shipping.

The major uncertainty is customer demand. High standard deviation (relative to the mean) for the average ring gear results in a highly unpredictable demand. Moreover, customers require product to be shipped within the day that a "pull signal" is transmitted to Tonawanda Forge[31]. Currently the group of presses changes product naturally approximately 1.5 times per shift[32]. Between the three manned presses this means a total of 13.5[33] changeovers per day. Usually less than thirteen different ring gear product types are made per day, but there is a high uncertainty to the amount demanded per day and on average the presses cannot kept pace, since cycle time is not fast enough. Although the variety of products might be able to be met, the total volume may not be. Also, the extra time taken changing between products to meet daily demand will result in less overall production. Product must be stored. The amount of product that must be stored to meet customer demand is developed in section 5.1, *Setting Inventory Levels.* .

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[31] A "pull signal" is an order for a standard quantity of material.
[32] See section 5.2, *Batch Sizing* for the development of this argument.
[33] 1.5 changes / machine / shift x 3 shifts x 3 operational machines = 13.5 changeovers

4. Where can continuous flow be used?
5. Where can "supermarket" pull systems be used?

The above questions are best answered together.

Continuous flow can be used when there is a natural flow of product from one process to the next. Supermarket processes are used when continuous flow is not possible. A discussion of the applicability of continuous flow and/or supermarkets to the ring gear manufacturing process is given below (for a graphical depiction of the product flow see Figure 5):

Steel Mills to Shears: Continuous flow cannot happen between the mills and the shears as steel mills batch steel production and this batching process does not match the schedule of the shears.

Supermarket processes are possible and are in development at Tonawanda Forge. Currently steel orders are placed against a blanket purchase order. This transaction is accomplished by completing a weekly order sheet for the required steel. From inventory, the steel mill then fills these weekly orders. This is a very basic, but yet not complete, pull system. The orders are not true pulls as there is not a defined loop. The information flows only one way. Moreover, the inventory in the loop is not regulated.

To properly develop the process a true pull system needs to be used and the steel mills must be made to hold some inventory to guarantee timely steel delivery. There have been steel shortages due to a lack of steel mill inventory.

Shears to Presses: Continuous flow is possible between the shears and the presses. By linking the individual shears to presses and immediately transferring cut stock to the appropriate press a near continuous flow could occur. The amount of batching that would occur between these two processes depends on the actual link type to the press, be it a continuous single piece conveyor or continuous buckets of product transferred to the shears, etc. It would be difficult to obtain true continuous flow as the current feed mechanism to the presses, a spiral feeder, requires a small batch of products upstream of itself to ensure a steady flow of products downstream. Moreover, a physical conveyor type link may be difficult to install due to the location of the presses relative to the shears. The shears sit across an aisle from the presses. This high traffic throughway has an overhead crane and thus access is required both from above and on the sides. Reworking the production area to allow easy continuous flow is an expensive proposition.

A project has been suggested to replace the shears with saws – this project is outlined in Appendix B. The investigation of this potential project was undertaken after noting that many people at Tonawanda Forge felt that sawing was a better technology than shearing. The details of the investigation will not be included in this thesis, but the sawing technology is a clearly superior method versus shearing technology.

The saws would either be placed at an external cutting house or internally as a replacement for the shears. The external cutting house present value to Tonawanda Forge is higher and thus it suggested that cutting should not be undertaken as continuous flow. However, the external cutting house can virtually link the saws to Tonawanda Forge by delivering small batches in a just-in-time manner, depending on its proximity to Tonawanda Forge. Due to the high present value of outsourced cutting via cold saws versus shears, and this virtual link, true continuous flow is not recommended.

Note that discussing potential projects while answering the analysis questions is discouraged. However, value stream mapping is a somewhat iterative process and at times such discussion will occur.

A supermarket pull system is the recommended link method between the external cutting house and Tonawanda Forge. Proper pull systems need to be created with signaling and monitoring included. Pull signals need to be transmitted, probably electronically, to a local cutting house and product delivered in a just-in-time manner to Tonawanda Forge.

Presses to Heat treatment: Currently the gears are heat treated (annealed) to soften the metal to enable economic machining. The existing process is to truck material to a heat treatment facility located outside of Detroit, Michigan. Obviously, continuous flow is not possible without process changes.

A process change under investigation is to install a "slow-cooling" furnace at Tonawanda Forge[34] to allow the forged parts to be slowly cooled and thus eliminate the need for outside annealing. Within AAM, technologies have also been developed for similar products to allow the complete elimination of annealing without "slow-cooling"[35]. By implementing either of these projects continuous flow could be made possible or at least this link to outside heat treatment eliminated. These projects are currently under investigation at Tonawanda Forge.

If true continuous flow cannot be developed with this technology, it may not be the case that a pull system per process is the best methodology to control flow, given that the new technology is implemented locally. By simply controlling the incoming material and the outgoing material from Tonawanda Forge, the product within Tonawanda Forge is controlled – this is similar to a CONWIP system [Marek, Elkins and Smith, 2001]. Standard supermarket type pull system may also be difficult to manage in the harsh forging environment – a paper tags can be set aflame and other visual pull systems marred or destroyed. It is suggested that if a pull type system is used, that the use of auto-id technology is investigated as a means to track containers. Alternatively, the containers themselves could be used as pull signals. An empty container indicates that it should be filled. The monitoring of the pull loop within the current forging environment may be difficult.

Heat treatment to Machining (Customer): Currently, heat treatment is located in a facility

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[34] Other technologies are also under investigation.

[35] These technologies are proprietary and will not be discussed in this thesis.

distant from the machining facility. Continuous flow is not possible in the current situation. Even if heat treatment is moved to Tonawanda Forge, the final customer is still a distance away, eliminating continuous flow as a possibility. However, the customer and the forge are linked by a virtual pull system and this can be maintained. When an order is electronically sent to Tonawanda Forge the order is forwarded to the heat treatment facility and must be filled within one day. This provides a supermarket pull type link if the heat treatment facility maintains a bank (a "supermarket") of finished goods, which is does currently.

It should be noted that until recently Tonawanda Forge did not control the inventory past the finished goods at the presses (except for a few part numbers). It has been recommended that all of the heat treatment inventory ownership be transferred from final customer to Tonawanda Forge. This change is to be complete by January 5, 2004. Prior to this date, inventory was held before heat treatment since the customer did not want product to be shipped to the heat treater (and to have to account for the inventory) without demand. The heat treater also held inventory before its furnaces to economically run the product (at least with the current furnace design). Thus there is a duplication of inventory before the furnace, one pile at Tonawanda Forge waiting to be shipped and the other at the heat treatment facility.

6. *At what point in the production chain should the production schedule be released? (More generally, how should be production process be scheduled?)*

In the current system customer data is transmitted to the Tonawanda Forge (AAM) ERP system. For ring gears this customer data comes from upstream AAM facilities forecasts. A ring gear production schedule is created from this data and from this schedule a production supervisor creates a billet cutting schedule and separate forging schedule[36]. These schedules are fairly flexible since little finished goods inventory is kept. The current system is the logical system (with some modifications):

a) Actual customer schedules, without noise, need to input into the AAM ERP system. This system will provide a forecast of demand for Tonawanda Forge. The reason for using actual customer schedules is developed by researchers such as Forrester and Taylor. [Forrester, 1958] [Taylor, 1999] The ERP system at Tonawanda Forge is currently using forecast demand that has been filtered through upstream processing.

b) Tonawanda Forge needs to have finished inventory in place ready to ship to its customers and use this inventory bank to fill immediate demand. This will help to fix the production schedules. The method to determine the inventory level is given in section 5.1, *Setting Inventory Levels*.

c) The actual production should be scheduled by the actual demand signals from the

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[36] Two products are cut outside of Tonawanda Forge. The scheduling of these products is accomplished directly in the ERP system.

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upstream customers[37]. That is, a pull-type system should be developed to schedule the production of ring gears. Pulls need to be grouped into the appropriate batch size (developed in section 5.2, *Batch Sizing*).

In the actual system a tentative schedule is created a week before the presses are required to produce products. The difficulty is predicting the appropriate demand to use. The data in the ERP system is one set of demand data. The downstream internal customer plants also produce a "gate line"[38] and this information is sent to Tonawanda Forge. It has been shown that these data sets conflict and that the supposedly firm "gateline" schedule is flexible. It is not necessary to have two sets of data – one set of correct data is required – and this data should come through the ERP system.

Moreover, the output of the ERP system at Tonawanda should be used for planning purposes and for scheduling purposes. That is, the output of the system should be used to plan preventative maintenance, allow for budget and capacity planning, and to plan long lead time items such as steel production. Moreover, the general press schedule should be set by this forecast, but the actual production schedule needs to be determined by the pull signals. The main concern with using a pull system is that demand variation will be forced into the production system as product is "pulled" out of finished goods. One method to restrict demand variation is to restrict the downstream plant in the amount that its forecast can vary.

Lastly, the current system does not have feedback and a method is needed to "close the pull loop." That is, the actual demand transmitted via pulls needs to be reconciled with the true plant production. A feedback mechanism from the shipping department to the production department would be useful to create pull like production.

The main concern with implementing the above system is stabilizing upstream demand enough to allow Tonawanda Forge to produce product at regular intervals.

7. *How can the production mix be leveled?*

The life of a die naturally creates a given batch size, as dies wear to the point of needing replacement. By producing to these batch sizes, products will be the most economically produced. This logic is explained in section 5.2, *Batch Sizing*. To schedule based upon this batch size, as orders arrive they should be queued for production. Once one batch size of product (enough orders to utilize one die-life worth of production) is required, this batch size can be produced. Inventory will be used to fulfill less-than-batch-size quantities and to provide the necessary time to fabricate product.

By examining the weekly demand forecast, the appropriate series of batches can be predicted for a given week. A forecast production schedule can then be created. The creation of this schedule is an important planning step. A means to create this schedule is

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[37] All of the current upstream customers are AAM facilities. If external customers are included in the future this scheduling method needs to incorporate the forecasts of the "external" customers.
[38] A "gateline" is defined as a firm schedule for a given time period.

developed in section 5.4, *Production Scheduling (SMRP)*.

8. *What increment of work will be consistently released?*
9. *What is the appropriate batch size for this product?*

The answer to the above two questions, for the case of Tonawanda Forge ring gear production, is the same. The appropriate batch size or increment of work to release to the floor is the economic order quantity. The economic order quantity is derived in section 5.2, *Batch Sizing*.

10. *What is the appropriate amount of raw material to receive at one time?*

All raw material is shipped to Tonawanda Forge via truck. The other potential shipping method is rail. However, the rail lines were recently removed and a road installed in their place. Thus truck is the only means to receive material.

Within New York state tractor trailers configured to optimally delivery steel will carry approximately 92,000lb of product. When the product is shipped from out-of-state, tractor trailer can only carry 50,000lb of product. Two mills currently supply Tonawanda Forge with ring gear steel, one in Ohio and another in Arkansas. The Arkansas mill maintains a warehouse in New York. This diversity has created two separate supply chains, one from the warehouse and the other directly from the mill. As these routes are distinct it is not economically possible to combine the loads of different mills onto one truck. Knowing that each truck should haul only from a single source, the next step is to determine the amount of steel that each truck should carry. Examining the cost to haul partial truckloads versus the cost to hold the inventory, it is seen that in most reasonable circumstance it is not worth obtaining trucks in partial truckloads. The table below illustrates the total weekly cost[39] to obtain or hold raw steel for production given that the product is delivered in discrete batch sizes and the product is trucked from out-of-state[40] (figure 9):

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[39] The total weekly cost is defined as the holding cost of inventory and the cost to purchase steel for one week.
[40] It is not true that the majority of product is trucked from out-of-state, but a similar result holds assuming that the product is from in-state. There is actually a mix of product.

Incoming Steel Bundle Size per week (lb)*

Production per week (lb)	9500	19000	28500	38000	47500
1000	$ 19	$ 19	$ 23	$ 28	$ 34
2000	$ 31	$ 25	$ 27	$ 31	$ 36
3000	$ 43	$ 31	$ 31	$ 34	$ 39
4000	$ 55	$ 37	$ 35	$ 37	$ 41
5000	$ 67	$ 43	$ 39	$ 40	$ 44
10000	$ 128	$ 74	$ 60	$ 56	$ 56
15000	$ 189	$ 104	$ 80	$ 71	$ 68
20000	$ 251	$ 135	$ 100	$ 86	$ 80
25000	$ 312	$ 165	$ 121	$ 101	$ 93
30000	$ 373	$ 196	$ 141	$ 117	$ 105
35000	$ 434	$ 226	$ 161	$ 132	$ 117
40000	$ 495	$ 257	$ 182	$ 147	$ 129
45000	$ 556	$ 287	$ 202	$ 163	$ 141
50000	$ 617	$ 318	$ 222	$ 178	$ 154
55000	$ 678	$ 348	$ 243	$ 193	$ 166
60000	$ 739	$ 379	$ 263	$ 208	$ 178
65000	$ 800	$ 409	$ 283	$ 224	$ 190
70000	$ 861	$ 440	$ 304	$ 239	$ 202
75000	$ 922	$ 470	$ 324	$ 254	$ 215

* Steel arrives in batches of 9500 pounds

Figure 10: Cost to hold steel

A full truck load of steel (from outside the state) is 47,500 lb. The highlighted cells show the largest volume at which it is economical to ship less than truckload quantities for a given weekly production volume. It can be seen that only when raw product is used in volumes less than 10,000 pounds per week is it potentially economical to bring less than truckload quantities of material[41,42].All ring gear raw material is used in quantities much greater than this amount. Tonawanda Forge ring gear raw material should be received in full truckload quantities when possible. A similar table with near identical results can be developed for in-state trucks (92,000 lb limit)

The nature of the raw material received is also in question – ring gear raw material comes in both 20' long black bar and as cut billets. Billetized material is pre-cut and ready for forging while the 20' black bar needs to be sheared. A study was conducted to determine the best economical method to process and receive ring gear material. A summary of that study is contained in Appendix B. The conclusion of the study is that the most economical means to process steel is to increase the bar length from 20' to 32' and employ an outside local bar processing facility to cut the bar into billets. Outside processing facilities can produce billets at a lower cost than Tonawanda Forge and 32' bars are the longest readily transportable bars available. The cut billets are to be shipped

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[41] The minimum cost is achieved at full truckload quantities only when raw material usage is above 35,000 pounds per week.
[42] Somewhere between a production volume of 5,000 and 10,000 pounds of steel per week it becomes economical to obtain steel in full truck load quantities.

to Tonawanda Forge.

11. *How can the information flow be streamlined and made highly visible in the factory?*

One of the key problem areas for Tonawanda Forge was the communication of manufacturing information (such as product volumes and product type) both internally and from its customers. There existed an information flow disconnect between the product demanded by the customer, the product manufactured at Tonawanda Forge, and the raw material on order for product creation. This disconnect manifested itself to the extent that two production forecasts were created – the "gateline" forecast mentioned above and the more traditional ERP system output. To begin streamlining information flow, one of these forecasts needs to be removed.

This disconnect resulted in rushing production parts through the system when product was demanded unusually quickly by a customer. Moreover, lack of communication caused some production to occur when demand was absent or under or over production of demanded parts to occur. To minimize these and other communication problems, a framework for communicating production requirements was created. This information flow framework can also be used to communicate with other departments the production schedule, allowing them to schedule work on production equipment. For example, preventative maintenance time was listed on these schedules. The framework for the system is a series of Excel based spreadsheets. This scheduling system is developed in more detail in section 5.5, *Scheduling Production (SMRP)*.

In addition to improving the production scheduling, the production tracking can be improved. Currently, inventory is tallied manually at the end of each shift. This leads to counting errors, poorly utilized labor (counting parts), and a slower than possible inventory count. Automatically tracking the inventory may be a viable alternative. Such a project is investigated in section 5.4, *Tracking Inventory*.

An area that has not been explored in this research, but has been an issue at Tonawanda Forge, is the identification of the state of each press. Other AAM facilities monitor the state of forging press in a real time manner. Moreover, this real time state can be displayed more visibly, maybe by using larger indicator lights or electronic display boards. It is suggested that further research be undertaken in this area.

12. *What process improvements are necessary to attain this state?*

This question has been answered by providing detailed answers to the other questions. The process improvements are also summarized in section 4.4, *A Lean Structure at American Axle (Ring Gears)*.

The next stage of analysis is to examine the questions posed in "Seeing the Whole" and the additional questions from section 3.3, *Hybrid Value Stream Mapping*. Note that these questions have been rearranged to create a logical questioning sequence. These questions and their answers are listed below:

1. *Is everyone in the entire value stream aware of the rate of customer consumption of the product at the end of the stream?*
2. *Is as little information processing as possible used with information flow? That is, is the information pure signal and no noise?*

The above two questions are best answered together.

With the current AAM information flow, Tonawanda Forge is not aware of the true end demand for ring gears to the end customer – only the immediate customer (the gear and axle plant) demand. The true demand is that of the automobile buyer purchasing the product into which the ring gear is placed. Moreover, Tonawanda Forge does not share its customer demand with downstream suppliers. Instead it shares production requirements as determined by its batched production data – this data is filtered by successive ERP systems. A better sharing of unfiltered information will enable the supply chain to be more reactive. The reasoning for this is discussed above. The answer to question six from the previous list of questions provides additional information.

3. *How can shipments be better synchronized so that inventory and processing times be reduced?*

Currently incoming raw material is ordered on a weekly basis. Orders could be placed more frequently, thus enabling faster reaction to demand changes, and the ability to reduce inventory levels. Of course, such a change cannot be made in isolation without considering the ramifications to the rest of the supply chain.

For example, steel mills process large batches of material and altering the order from nine to ten trucks in one week may not cause a delivery problem, as material may be available. However, intermediate processors may have less inventory available and not be able to react as quickly.

To synchronize its production systems AAM currently uses a supermarket pull system between suppliers. This is a web-based system that allows orders for product to be placed by simply posting the requirement to the web. This system has not yet been implemented to control steel purchases. Implementing this system and updating it more frequently than weekly will allow better synchronization between suppliers and Tonawanda Forge. However, as mentioned above, implementing this system means controlling inventory levels (and processing ability) to ensure that production schedule changes can be met – continuous rapid spikes in demand will cause problems. It is suggested that the weekly schedule still be issued as a forecast for the predicted weekly demand and that significant deviations from this schedule not be passed to downstream suppliers. Significant and rapid scheduling changes could cause downstream production problems. This is called the "bullwhip effect". See section 2.5, *Applying Extended Value Stream Mapping,* for references detailing the bullwhip effect.

4. *Are the transportation links between the production steps at a minimum?*

5. *Is the shortest possible lead time engineered into the system?*

The above two questions are best answered together.

To determine the "extra" amount of transportation within the ring gear supply chain a study was undertaken. In general, the ring gear supply chain is efficient in terms of transportation links. The following diagram (Figure 10) shows the transportation network from the raw material supplier to the final AAM customer (drive line plant):
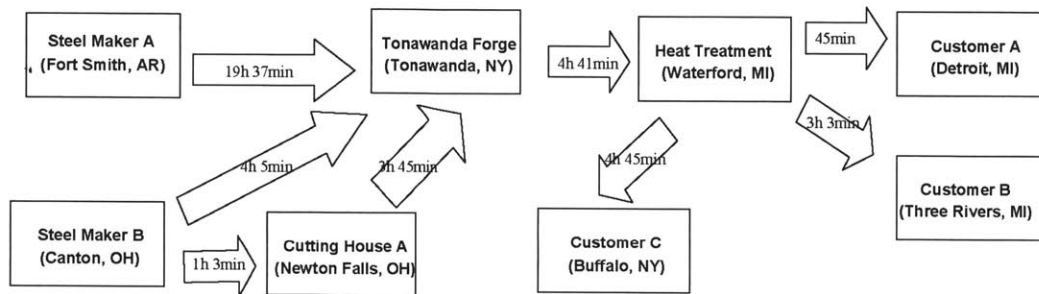

Figure 11: Transportation Network (Ring Gears)

The major transportation inefficiency occurs downstream of Tonawanda Forge. Some of the heat treated parts are sent from Tonawanda Forge to the Detroit, Michigan area and back to Buffalo, NY (near Tonawanda, NY). Thus, the product is traveling approximately 1000 miles more than needed so that it can be processed at the heat treatment facility. To rectify this problem, local heat treatment could be used or heat treatment eliminated as a process step. Processes to eliminate heat treating have been discussed above. To rectify the problem if heat treatment cannot be eliminated, the abilities of local heat treaters have been investigated. However at this time, AAM has not yet found local heat treatment facilities deemed suitable for heat treating ring gears.

The inefficiencies upstream of Tonawanda Forge are few. There is an inefficiency created by sending material to Newton Falls, OH and then to Tonawanda Forge as opposed to sending the material directly to Tonawanda Forge[43]. This inefficiency results because material is cut in Newton Falls. This situation could be rectified by locally cutting the material. Cutting could either be accomplished in house or at a local cutting facility.

It should be noted that although these supply chain alterations may save time, assuming that either new or relocated suppliers are as efficient as existing suppliers, there may still be cost increases due to different pricing from the new supply base. This increased cost needs to be weighed against the cost savings associated with reduced lead time.

Of course, more than simple end points are responsible for lead time increases. Different carriers may take different transportation routes. One must ensure that product, as it is

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[43] Note that this link is not shown in the overall value stream map (figure 6).

moved between facilities, is handled in an efficient manner. The routes of the different carriers and carrier abilities will not be discussed in depth in this thesis, but the research showed that the current carriers have similar abilities and routes and that their routes are near optimal.

6. *Is the minimum amount of inventory present in the value stream?*

   Examining the answers to the above questions, it can be seen that the minimum inventory is not in the system. This question is designed to illicit information about excess inventory not simply driven by transportation or processing times. For example, until recently there was "double" inventory between heat treatment and Tonawanda Forge finished goods. This concern is discussed in question six in the preceding section.

   Other than this obvious problem, no glaring inventory reduction items exist.

7. *Has there been an operational target(s) created that the entire supply chain is held responsible?*

   There are no system wide operational targets for the entire supply chain communicated to a single source. AAM does have supply chain metrics, such as on-time delivery, and these are maintained both at the applicable production facility and centrally at corporate headquarters. However, these metrics are only for AAM facilities. This is not to say that AAM does not track its supplier's performance, but that AAM does not track its supplier's performance for the purpose of monitoring the supply chain. Suppliers to AAM maintain their own metrics. These metrics need to be combined into a system to track the entire supply chain.

8. *Is this a natural product group for the supply chain?*

   Yes. All of the ring gears move through similar processing steps, and are fabricated from the same raw materials.

This concludes the question and answer portion of value stream mapping.

4.5: A lean structure at American Axle (Ring Gears)

By answering the above questions thoroughly and analyzing a series of potential projects a future state map for ring gears was developed. This map is shown below (figure 12):
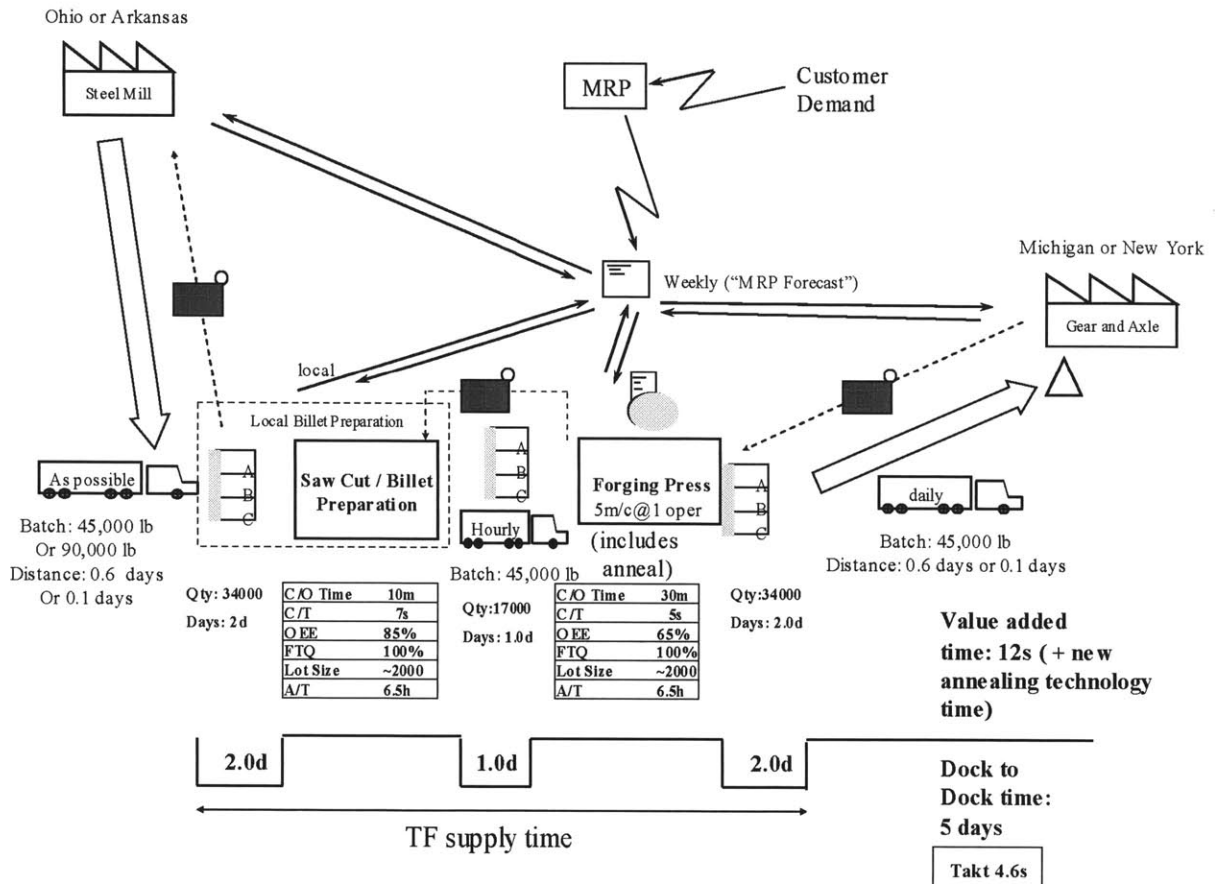

Figure 12: Future State Map - Ring Gears

The manufacturing system now works as follows:

> *Steel Supply:* There may still be two steel suppliers for Tonawanda Forge, but the entire steel supply base is represented as a single supplier. A formal pull signal is now used to call material from the supplier. This is as opposed to only a weekly forecast. Raw steel inventory should drop from 3.1 days to 2.0 days. This lower level of inventory is recommended based upon delivery times. It takes approximately 2.0 days from issuance of the pull signal to the delivery of the raw material. The material is also now delivered in longer bars, thirty to thirty-two feet, and to an external processing facility. The longer length bars reduce the amount of scrap per processed bar.

> *Steel Processing:* The first step in the steel processing is to cut the steel bars into billets. As mentioned, this activity will take place at a local processing mill. The mill will be tied

to Tonawanda Forge via a pull system. Pulls will be issued frequently to the local mill, approximately twice a day. This material will move directly to the forging press. The new "ring rolling" technology will be in place on each forging press and the presses will be equipped, either individually or in aggregate, with a means to anneal the product. On site inventory will be reduced to 1.0 days. Frequent deliveries will reduce the holding inventory significantly (to 0.5 days average) and the reprocessed inventory will be reduced due to the greater incentive to use existing inventory (add another 0.5 days for the cooling time of reprocessed inventory). A total of 2.0 days of final goods inventory was estimated using a computer model, discussed in section 5.1, *Setting Inventory Levels*.

Final Customer: The final customer is still an AAM owned gear and axle plant. Product will continue to be pulled as it was before

Information Flow: Tonawanda Forge will receive the true customer demand signal (not a filtered customer demand) and the expected demand from its upstream customers. Moreover, Tonawanda Forge will share its production plans with both its suppliers and its customers to better coordinate production. The exact coordination mechanism is still under development. Internally, schedules will be forecast using an MRP system and developed using an interactive process between the material scheduling department and production department. Moreover, a pull-type system will be used from finished goods to the forging presses. As parts are removed in finished goods inventory, the presses will be signaled to produce more of that specific good.

The economic benefits of the key improvements are illustrated in greater detail below:

o *Pull system with steel suppliers:* A supermarket pull system has been implemented. Steel suppliers receive frequent pull signals. These signals are to be answered within a specific time frame depending on the location of the steel processor and type of raw material to be delivered.

   Economic Result: Allows raw material inventory to be reduced at the forging plant. Time will also be saved when altering steel orders. Increased coordination efforts, which include this pull system, are expected to reduce raw material inventory by approximately one day of customer demand.

o *Local Billet Preparation:* The best method of preparing raw material billets for use in forging is to have them saw cut at a local cutting house. This cutting house is to be located within the vicinity[44] of Tonawanda Forge and it will replace the current shearing process. The cutting house will obtain steel from the steel suppliers using the above mentioned pull system. Tonawanda Forge will call for material using a similar supermarket pull system.

   Economic Result: The use of a local cutting house has a net present value of $3.2 million to Tonawanda Forge[45]. The value is obtained through a reduction in manpower,

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[44] The "vicinity" of Tonawanda Forge may actually be quite some distance if an inexpensive supplier is found.
[45] There is an additional $0.9 million net present value of net shape gears are prepared at this cutting house as well.

inventory, and scrap parts. Moreover, due to the improved saw-cut billet quality the forging presses will have an improved throughput and the reliability of saws is higher than that of shears. The overall equipment effectiveness of the cutting process should rise from 55% to 85%[46]. Also, the incentive to reduce WIP between the cutting operation and the forging operation increases using the cutting house approach as orders must be placed to obtain new raw material. This situation is as opposed to the current situation where production simply requests a different billet size to be cut on local production equipment.

More information about this proposal can be found in Appendix B.

o *Integrated annealing with forging press:* The annealing of ring gears will be integrated with the forging press. This eliminates the need to truck ring gears from Tonawanda Forge to near Detroit, Michigan for heat treatment. It should be noted that the ring rolling technology discussed above will also be implemented on the forging presses. Its implementation is underway at the time of the writing of this thesis.

Economic Result: The technology to be used to integrate annealing with forging is still under development, therefore estimated a present value for Tonawanda Forge is difficult. It is known that the current yearly cost to anneal ring gears is in excess of $4.5 million and that this cost will be eliminated. The simple installation of an annealing furnace on each press costs approximately $5.0 million[47].

o *Improved information flow:* Improved information flow is difficult to illustrate on a value stream map. The improved information flow will consist of the following:

a) *Improved Scheduling System:* Using the SMRP production scheduling system as outlined in section 5.4, *Production Scheduling (SMRP)*.

b) *Integrated Production Counting:* Using forklift mounted scales (or similar devices) to relay actual production information to the scheduling system. This system is detailed in section 5.3, *Ensuring Accurate Inventory*.

c) *Production based on pull signals:* Using actual customer demand to schedule production.

d) *Sharing of final customer demand data:* Relaying the true end customer demand throughout the supply chain.

Economic Result: The improved scheduling system is the only information flow improved that has been implemented. All of the information improvements, including the supplier pull system, are responsible for removing about one day of raw inventory. The present value of this inventory is $85,000. Integrated production counting may allow for additional inventory reduction and will eliminate the need for confirmatory inventory counting. Confirmatory inventory counting costs upwards of $31,000 per year.

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[46] The results is based on similar equipment installed at other AAM facilities.
[47] An estimate based on discussions with annealing furnace suppliers.

Production based on pull signals and the sharing of customer demand data will smooth the demand fluctuations within the system and allow even further inventory reduction.

o *Batch sizes matching die life*: By matching the production batch size to the life of the actual die, the number of changes between products will be minimized and the maximum economic number of changes will be had. Section 5.2, *Batch Size*, illustrate the reasoning behind matching batch size to die life.

Economic Result: By matching die life to batch size the economic production of ring gears is obtained. Finished goods inventory will be reduced by approximately 33%[48], approximately 1.5 days of inventory. The value of this inventory is $315,000. However, to maintain production at these batch sizes, raw material inventory will need to be increased, offsetting some of the gains made above.

The above systems also create a quality improvement synergy. Currently first time quality (FTQ) for processes approaches 100% for shearing and 98% for forging. The sawing technology will maintain the 100% for cutting, while the improved forging billets and ring rolling technology will improve the FTQ for forging to almost 100%.

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[48] The amount of inventory is inversely proportional to the batch size of product.

Chapter 5: Future State Modeling: Ring Gears

The following chapter contains:
- o Models to determine the appropriate values for inventory in the system.
- o A description of the implementation of these models for the ring gear product family.
- o A discussion of the importance of tracking inventory accurately and means to achieve accurate inventory values.
- o A description of a system to schedule production.

One might say that in the ultimate future state all processes are completely reliable, produce products exactly at takt time, and are co-located to eliminate transportation. But what about the non-ideal future states? In almost every future state, some inventory needs to be held and batch-production may be the most economical means of producing product. This section presents methods to determine the inventory levels, batch size, and production scheduling of the facility. To do so, it uses the information brought forth in the questions asked in Chapter four. The ring gear forging process will continue to be used as a case study.

5.1 Setting Inventory Levels

On almost any value stream map, and certainly on those found within this thesis, average inventory levels are indicated[49]. Current state inventory levels are simply found by examining the existing inventory, but future state inventory levels require vision. Most practitioners of value stream mapping promote the use of lean techniques, such as pull-loops[50] to size inventories. However, a pull-loop does not "size" an inventory - the loop only controls the inventory within it. Authors such as Monden (11 – Monden), suggest that pull loops should be sized so that the inventory within the loop is a minimum, but that adequate inventory should be provided for unforeseen events such as equipment breakdown, especially when the pull loop is first implemented.

Interpreting Monden [11- Monden] literally, one would place enough inventory at each stage to ensure that all production stages are decoupled from each other when the system begins running for the first time. Slowly, this inventory would be reduced as the system becomes more stable and those operating the line[51] gain confidence in its function. Eventually, it is hoped that no safety stock[52] needs to be held. The associates at Tonawanda Forge are using this type of methodology to size safety stocks, and as implied above, they are using a rough "experienced-based" methodology to size inventories – as they gain more confidence with the system and more "bugs" are eliminated then more excess inventory is removed.

In most real systems there is still some uncertainty and thus some need for an inventory or time buffer to enable timely deliveries to customers. In the case of ring gears at Tonawanda Forge the
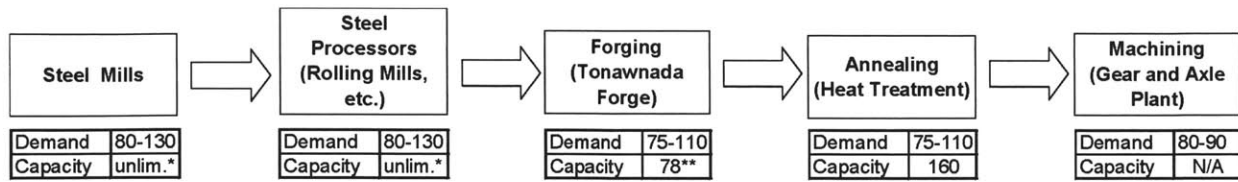
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[49] Average inventory level includes both average cycle stock and safety stock.

[50] Pull-loops are controlled sets of inventory whereby a signal device prevents inventory from exceeding a maximum amount and causes new product to be ordered or created when finished product exits the loop.

[51] A line is a set of grouped equipment. In this case it is assumed that the line comprises a set of grouped pull-loops.

[52] Safety stock is inventory held to protect against uncertainty in the system.

main uncertainty is customer demand. Before examining the other key parameters affecting the Tonawanda Forge supply chain, the chain itself should be reviewed. A simplified version of the value chain is shown below (Figure 13):

Steel Mills		Steel Processors (Rolling Mills, etc.)		Forging (Tonawnada Forge)		Annealing (Heat Treatment)		Machining (Gear and Axle Plant)
Demand 80-130		Demand 80-130		Demand 75-110		Demand 75-110		Demand 80-90
Capacity unlim.*		Capacity unlim.*		Capacity 78**		Capacity 160		Capacity N/A

Demand: The total number of ring gear unit equivalents (in thousands) requested from the facility in one week
Capacity: The total number of ring gear unit equivalents (in thousands) that can be processed in a five day week.

* With sufficient notice, the capacity is essentially unlimited in comparision to the downstream operations
** The capacity is determined for a five day week. Overtime is used to produce above capacity. Total capacity for a seven day week is 110.

Figure 13: Simplified Process Map

The following are key characteristics of the production system:

o *Serial network:* The value stream is a serial system with no parallel operations.

o *Demand uncertainty:* There exists substantial demand uncertainty. The value stream map analysis, from Chapter 4, shows that demand uncertainty is the major uncertainty in the system.

o *Ample machine capacity (in most cases):* In a given production week, assuming that there are no major equipment failures, the production of ring gears is not constrained by machine capacity. In the case of Forging overtime is used when sufficient machine capacity is not available.

Two other interesting aspects of the production system are:

o *End customer demands product quickly:* The demand uncertainty is amplified since end customers demand their product quickly. Customers downstream of Tonawanda Forge require the shipment of product within one day of order.

o *Deterministic setup times:* Within reason, production equipment can begin producing the required part within a known time frame.

The inventory problem faced by Tonawanda Forge is at which locations in its production process should safety stock be located? This problem can be formulated as a linear program.

Simpson [Simpson, 1958] attempted to solve this problem. He formulated it as such:

$$\min \sum_{i=1}^{N} h_i I_i$$

s.t.

$$I_i = k\sigma\sqrt{S_{i-1} + T_i - S_i} \qquad i = 1...N$$

$$0 \leq S_i \leq S_{i-1} + T_i \qquad i = 1...N$$

where

h_i	inventory holding cost for stage i of the value chain.
I_i	safety stock inventory held at stage i of the value chain.
k	factory of safety to ensure that the safety stock is not depleted when demand is higher than average
σ	standard deviation of the end customer demand.
S_i	the amount of time required to provide a product from stage i to stage $i+1$.
T_i	the production lead time of stage i.
N	is the number of stages in the value chain.

Note that this problem formulation makes additional assumptions to those listed above. These assumptions are:

o *Demand for each period is a normally-distributed random variable.* The assumption of normality was examined for rear gear demand data and normality was a reasonable assumption.

o *Final customer gets product instantly.* As opposed to only quickly demanding product, Simpson assumed that the customer instantly receives product.

The above optimization problem was solved using five months of ring gear weekly demand data for all of the major ring gear products. Using Excel Solver™ to find the optimum solution for each major ring gear product, it was found that the value of safety stock is minimized by placing all of the safety stock as finished goods after forging[53]. Note that this result should be independent of any of the inventory control structure suggested in Chapter four[54]. That is, the safety stock model is only concerned with the minimum cost to the system. Good management practice is needed to ensure that a system wide optimum is beneficial for Tonawanda Forge.

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[53] This is true for the average ring gear. The values shown do not represent a specific product, but an aggregation of products.
[54] Placement of goods after forging occurred because Tonawanda Forge management was not authorized to place goods further downstream. On January 4, 2004 management received authorization to place inventory downstream of annealing and this location became the optimal placement of safety stock.

Note that the above model is mathematically fairly simple. If the network is not purely serial, however, modeling the problem is more difficult. Graves and Willems [Graves and Willems, 2000] address this problem.

Not surprisingly the statement that all safety stock should be kept as finished goods fits within the lean framework. Companies fully embracing TPS keep finished goods as safety stock to allow quick response to customer demand [Monden, 1998]. From the above equations one can see that the amount of safety stock to be held at Tonawanda Forge will be based upon the following formulation:

$$ SS = k\sigma\sqrt{L} $$

where

SS   The amount of safety stock

k   A scaling factor to ensure an adequate amount of safety stock

σ The standard deviation of the order quantity

L   The lead time to satisfy demand

From the above formulation was estimated that Tonawanda Forge needed approximately 1.5 days of inventory as safety stock. The value of k was chosen to be 95%, σ was modeled based on historical demand, and L was estimated from previous data. For more discussion on placing safety stocks in manufacturing systems see Stephen Graves paper, *Safety Stocks in Manufacturing Systems* [Graves, 1988].

5.2 Batch Sizing

In above section the amount of safety stock in the system was determined, but the production plan to create cycle stock has not yet been discussed. In a perfectly lean world – one requiring no time to change from one product to another – a product would best be made using one-piece flow[55]. However, when the time (or cost) to switch between products is significant when compared to the time (or cost) taken to manufacture a product, single piece flow becomes increasingly uneconomical. For example, a representative time to forge a product is four seconds. However, to change a forging press from one product type to another takes on the order of sixty minutes. Assuming different products for each batch run, only 23 different forged products could be produced per press per day using a batch size of one[56]. However, assuming that only one part type was made per day and thus no forging dies need to be changed, a total of 21,600 parts can be produced[57]. But, this means that storage resources are required to hold the

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[55] One-piece flow describes a system in which products are made with a batch size of one.

[56] Producing one product in this manner requires 3604 seconds per part. There are 86400 seconds in one day. Dividing 86400 by 3604 gives 23.97 or 23 parts in one day.

[57] Without part type change one can use the full 86,400 seconds for producing parts (86400 / 4 = 21600). We are also assuming that a forging die will not wear during the production of the 21,600 parts.

products for sale if the entire 21,600 parts are not sold as they are produced. Thus, there is large trade-off between the productivity of a process and the cost to hold the product produced.

It is evident that by holding inventory one can increase the productivity of a press. Another alternative is to right-size the equipment to produce to takt time, and thus create special equipment to produce product. Special equipment usually comes at a premium price. Considering the economics of the situation for a given takt time, there is a trade-off between capital investment and the amount of inventory held for a given press type.

The purpose of this discussion is to illustrate that although the lean enterprise may be ideal, the amount of product produced can be duplicated by using a batch and queue structure (and possibly at a lower price). It may be uneconomical to attain the ideal lean situation. Of course, if economics permit, one should strive for the ideal lean state. In the time between achieving the lean ideal (if it can be achieved) and the current state how should batch size be determined?

It should be noted at this point that batch sizing, in and of itself, has not been considered part of value stream mapping in past research. Standard pack sizes have been discussed in *Learning to See*, but these amounts may not be the actual batch sizes used in production.

The standard method to determine batch size is to determine the economic production quantity. This quantity is a trade-off between the costs to undertake a production run and those required to hold inventory between production runs. Building on this basic methodology, economic run sizes for Tonawanda Forge can be determined.

Before undertaking an economic lot size calculation, the physics of the forging process needs to be understood. It must be noted that each die has a finite life[58]. That is, for the most part after a certain production quantity, all of the parts produced by that die are not of sufficient quality. Producing past die life would never be considered economically viable. Thus, any production run size calculation is only valid when the quantity produced is less than the die life.

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[58] In the case of ring gears, there are actually six different dies within the forging press at any one time. However, the "finishing die" has a die life substantially less than the others, and can be treated as the die-life of the entire package of dies.

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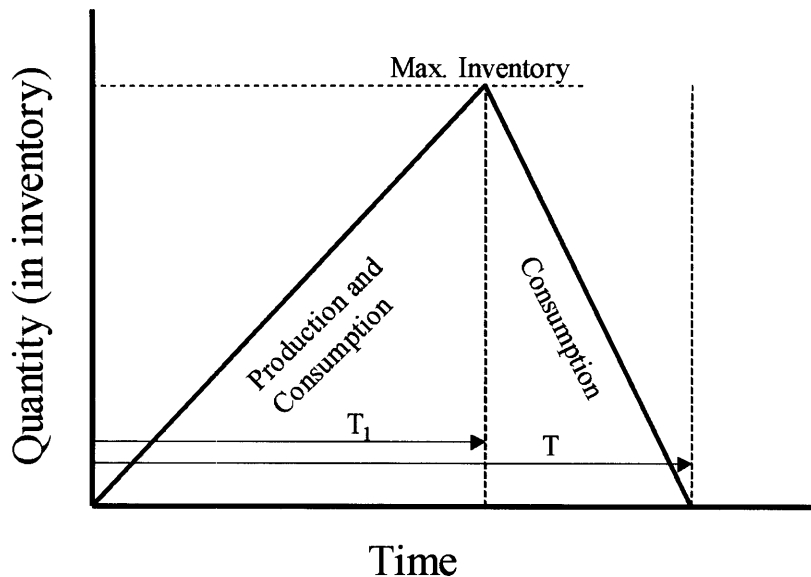A typical production / consumption run of product is shown below:

Figure 14: Typical Production Run

Examining the inventory pattern of the system shown above (Figure 14) the beginning of a saw tooth pattern is observed. The tooth illustrated above repeats itself as production continues. This is assuming that goods are produced at steady rate, and products are consumed at a steady rate. Both of these assumptions are generally valid for Tonawanda Forge. To determine the average inventory, let Q be the size of a production run and let T be the period between production runs. If goods are consumed at a rate, L, then,

$$Q = LT$$

However, goods are not produced for the entire production period, T. Let the amount of the period during which goods are produced to be T_1. During T_1, goods are consumed at a rate L, and produced at another rate, P. Since goods are only produced during period T_1, the quantity produced must also be,

$$Q = PT_1$$

To determine the long run average holding cost, note that during time period T_1, goods are being consumed at a rate L and a produced at a rate P. Thus the accumulation rate of the goods is P-L. It can thus be said that,

$$Max(Inventory) = (P - L)T_1$$

If inventory is neither decreasing nor increasing during the time period T, then the average inventory held during that period is half of the maximum inventory. Thus we can write that the average holding cost of inventory is:

$$C = \frac{K}{T} + h\frac{(P-L)T_1}{2} = \frac{KL}{Q} + h\frac{Q}{2}(1 - L/P) \qquad for \quad Q < D$$

where

C   is the average production cost during time period T
h   is the linear holding cost of inventory
D   is the die life.
K   is the set-up cost for a production run.

Elementary calculus can be used to determine where C is a minimum with respect to Q:

$$C' = \frac{-KL}{2Q^2} + \frac{h}{2}(1 - L/P) \qquad Q < D$$

$$C'' = KL/6Q^3 \qquad\qquad Q < D$$

Noting that the second derivative is always greater than zero (as Q is always positive), it can be said that the optimum obtained is a minimum. That optimum is:

$$Q = \sqrt{\frac{2KL}{h(1 - L/P)}} \quad Q \le D, \quad or \quad Q = D$$

For the average ring gear, die life is approximately 2000 pieces. Using reasonable approximations for the other parameters it was found that unless less than 50 units of production are required per day then the economic production quantity is die life. Since almost no products have such low demand, die life is considered the optimum batch size. Reasonable values for Tonawanda Forge were obtained by deriving Q using reasonable minimum and maximum values for all of the above parameters. For additional discussion about deciding on the optimal order quantity see Nahmias [Nahmias, 2001].

Before continuing, it should be noted that this equation, as derived, applies to a single product only. That is, for a given machine that produces only a single product, it is optimum to produce in batches as noted in the last equation shown above. The capacity of multiple machines producing multiple products, as it occurring at Tonawanda Forge, has not been considered. Given the current operating conditions of Tonawanda Forge, it is assumed that multiple products can be produced in the recommended batch sizes since these batch sizes occur naturally. Tonawanda Forge press operators are trained to recognize this poor quality and request dies to be changed when dies are worn. Thus, the same number of die changes occurring currently will be occurring in the future – the production volume for a given period divided by the die life is the number of changes to that product. Since sufficient product can be produced currently, and

production demand satisfied[59], the above optimum number of die changes is already in force. Now, instead of simply replacing worn dies, dies for a new product will be installed. However,

However, there is mindset at Tonawanda Forge that larger batches are more efficient. Thus, product is produced that is not immediately required for period T, the optimum production period length. This increases holding cost. Tonawanda Forge management is claiming that there is a cost to manage the die change from one part type to another part type. However, the author could find no evidence of a cost to change to a different part type versus maintaining the same part type.

Quantifying the actual inventory drop due to decreased batch sizes is difficult in practice. As the product produced needs to be matched to the product demanded, unless the correct ring gear part is produced inventory will not decrease in proportion to the batch size drop. However, in the ideal future state, a drop in finished goods inventory of a specific part will signal the production of that part. Thus one could say that in this case there will be an inventory drop. In this case as batch sizes are currently on the order of 6000 parts, and will drop to around 2000 parts, cycle stock should be reduce to one-third of its current amount. Assuming no change in safety stock, cycle stock will drop by approximately 18000 parts[60]. Weekly production is approximately 85,000 units and thus one day of finished goods inventory could be eliminated. This amount conservatively represents $156,000 in inventory.

5.3 Ensuring Accurate Inventory

Assuming that the optimum inventory has been established at Tonawanda Forge, the inventory still needs to be monitored so that production decisions can be made. That is, the amount of inventory in raw material, work-in-process (WIP), and finished goods needs to be monitored to determine the amount of material to order and process.

The need for accurate inventory increases as the amount of inventory decreases. When a facility is "fat" with inventory, errors in computing the actual amount of inventory do not immediately translate into a missed customer order. In a lean facility, miscalculating the amount of inventory can immediately translate into a lack of required product. Without an accurate count of the actual inventory in a production system, a truly lean production system cannot be attained.

It is best to evaluate the inventory of product as close to the production operation as possible. That is, as one form of inventory is transformed into another form of inventory, evaluating the change in inventory type as soon as it happens provides the most real-time (and hence accurate) inventory control. Taking this as self-evident, the best method to monitor a forging production process is to evaluate the quality of a part (scrap, rework required, or good part) and count the part at the forging press. For almost any new installation, the extra work required to install a sensor (or two) to monitor the part and determine quality is probably justified. As an alternative to monitoring at the press, monitoring as the product is removed from the press is possible.

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[59] Weekend production is required, as the cycle time of the process does not meet takt time, and it is assumed that it will continue on an as needed basis.

[60] There are nine major parts. Current average cycle stock is 6000/2 x 9 parts = 27000 parts. New average cycle stock is 2000/2 x 9 parts = 9000 parts. The difference is 18000 parts.

However, as the time between the change in inventory state and recording the inventory state increases, the accuracy of the physical inventory in the plant decreases.

Tonawanda Forge chose to seriously investigate monitoring the product inventory state as the product is removed from the press. That is, when a basket of inventory is taken from the press, inventory in that basket is counted as produced at that point in time. By equipping the forklift with onboard scales, the weight of the product could be used to determine the number of pieces produced. After a short study, it was deemed that equipping a few forklifts with scales was less expensive than installing sensors on a myriad of presses to count the parts.

To summarize the study, a total of five forklifts (plus one spare) require scales to track inventory as it is removed from the press compared with a total of 41 presses requiring sensors[61] to track inventory as it is created at the press. Moreover, the "traveling" scale located on the forklift provides additional flexibility. The cost to equipping one forklift[62] is on the order of $15,200[63], for a total project cost of approximately $91,200. The cost to equip a single press is conservatively low at $4,350[64]. Assuming that each machine is connected to a large scale data monitoring system (to centrally record the information) the total cost is $178,350. The operational cost of a press mounted system is assumed to be similar to that of a forklift mounted system. It should be noted that as an alternate to the forklift mounted scales, fixed in-ground scales could be used. The cost of such a scale is approximately $4,000 and installation approximately $2,000. It is estimated that approximately six scales would be required. Although this is only a cost of $36,000, the operational costs of this system are high. Drivers must move material to the scale, and wait when the scale is occupied. Moreover, these scales take floor space. Properly positioning the scales uses excessive floor space[65]. The effective cost of installing fixed scales greater than that of installing forklift mounted scales.

As a permanent solution Tonawanda Forge management is considering using forklift mounted scales where possible. This will allow the accurate monitoring of product as it is removed from the press.

It is difficult to calculate the savings of implementing this policy. However, to maintain inventory accuracy at Tonawanda Forge weekly inventory counts are taken. These are mostly done on the weekends and at an overtime rate. These counts are taken approximately once every two weeks and an average four people are involved per count. These people are paid for approximately six hours each counting period. The cost to undertake one count is $1248. Yearly cost is $31,200. This cost could be eliminated by implementing the above mentioned systems.

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[61] The machines are: Twenty 2.5"-3" upsetters, Three 6" upsetters, Six presses, Six shears, two cold headers, and four cleaning machines.

[62] A class IV forklift to be outfitted with a commercially available forklift scale.

[63] A cost breakdown: $10,000 for scale and indicator, $1000 for the bar code scanner, $2000 for the hardware associated with capturing the part number (1/6 of $12,000), $1000 for the forklift indicator programming, and $1200 for installation of the scale hardware.

[64] A cost breakdown: $3000 for electrical installation labor, $400 for electrical installation supplies, $150 each for two sensors, $150 each for two sensors mounting brackets, and $15,000/41 for ERP programming and PLC programming.

[65] Assuming that approximately 10' x 10' is required per scale and that the floor space is valued at $100 per square foot, a total of $10,000 is "used" each time a scale is installed.

Additional manpower is used in interpreting the count results. Moreover, some inventory could be eliminated with better tracking.

5.4 Scheduling Production (SMRP)

Even once accurate inventories are set and the general operational methodology established the entire system still needs to be coordinated. The incoming raw material, transformation of this raw material into finished goods and the shipping of the finished goods needs to be synchronized with the manufacture of product. This should be done using the fewest possible resources.

At a high level most large companies accomplish this coordination with some form of Materials Resource Planning (MRP) software or Enterprise Resource Planning (ERP) software. The purpose of this software is to account for the existing inventory, required product shipments, and production capacity. Although seemingly simple, as the variety of products increase, properly allocating raw material to finished orders becomes increasingly complex.

To limit the complexity of the traditional MRP system and to create a simple communications tool, the SMRP tool was developed. SMRP (Steve's Material Resource Planner), provides a communication tool for Production Schedulers to allocate production requirements to individual machines for a set amount of time. This is not to say that the existing MRP software could not perform the current SMRP function, but that SMRP has the following advantages:

o SMRP is built using Microsoft Excel® and the Production Schedulers (and Production personnel) at Tonawanda Forge understand that software and can alter SMRP if required. This is as opposed to the existing MRP software that requires specialized programmers to alter.

o SMRP allows for easy electronic communications between the various concerned parties. SMRP "sheets" can be emailed or made accessible to different parties via a local area network. Although the existing MRP data can be transmitted, it is most easily accomplished with paper copies.

o Currently SMRP allows the user to schedule machines by product and by shift. The existing MRP software schedules product only weekly. The MRP software can be made to schedule similarly to the SMRP software, but the complex interactions within the MRP software may take excessive time.

o SMRP functionality has been confirmed by its users. The MRP package is commercially available and could not be configured, without excessive reprogramming, to have the same functionality as SMRP.

The key advantage of SMRP over the existing MRP system is ease of use. This factor is important since it functions as a communications tool between the various parties at Tonawanda Forge to allow them to schedule certain activities. SMRP is used in the following manner:

1. The Production Scheduler allocates the weekly MRP schedule to machines by shift. This forecast is communicated to Production using the SMRP entry sheet. Time for preventative maintenance or other required downtime is also scheduled.

2. Production personnel comment on the schedule and the schedule is revised as appropriate. As required, meetings and discussions are held until a firm schedule is developed.

3. The final SMRP schedule for each machine is posted. This schedule is made available to every Tonawanda Forge associate by placing it on the local area network.

4. Finally a module within SMRP creates a master production file. From this master production file, the steel requirements each shift are calculated. This facilitates the timely ordering of steel. By reviewing this steel requirement, the correct amount of steel per unit time can be ordered.

This production scheduling routine increases the communication between both the raw material purchasers and users. Moreover, as it is a simple tool, it has been fairly easy to implement.

SMRP has been a very useful tool for planning production. Since the implementation of SMRP raw steel inventory for all products has dropped approximately $2.0 million. The use of SMRP has allowed inventory reduction through better production communication. It is difficult to estimate the percentage of this inventory reduction that was actually due to SMRP, but it may be conservative to say that 5%[66] of the improvement was due to SMRP.

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[66] An estimate by the author.

Chapter 6: Concluding Thoughts

The following chapter contains:
- o Evaluating Hybrid Value Stream Mapping
- o Areas for further study

6.1 Evaluation of Hybrid Value Stream Mapping

Value stream mapping is a visual technique allowing the user to graphically illustrate a manufacturing system. This illustration is a telling picture. However, it takes skill and an understanding of manufacturing systems to properly interpret a value stream map and to derive an improved future state. Most value stream mapping techniques only illustrate the weaknesses of a production system.

Both traditional and extended value stream mapping techniques are powerful tools and by combining them synergies between the supply chain and the manufacturing processes were illustrated. For example, the use of sawing technology was investigated as both an internal-to-facility option and as one to be provided by an external supplier. Also improved information flow was investigated both internally and externally.

The addition of explicitly investigating the strategic objectives of the firm allows for focus in determining a future state. By understanding the current strategy of the organization the production system can be designed to support this strategy. Of course, the production strategy needs to support the ultimate firm goal of making profit.

The use of net present value as an evaluation technique for different future state strategies proved useful. It allowed the different sawing strategies to be evaluated systematically and to determine which strategy was the most profitable. Moreover, the value of undertaking improvement efforts could be weighed against the cost of implementing them.

In summary, hybrid value stream mapping did achieve its objective of integrating traditional and extended value stream mapping. The addition of a strategic evaluation and a financial evaluation of the alternative projects aided in decision making. However, hybrid value stream mapping is not yet a cohesive process. Some of the questions asked may be redundant. This may have led to extra work in evaluating the current state.

6.2 Additional Research

Hybrid value stream mapping does not systematically guarantee an improved manufacturing flow. The current system used to examine a current state map does not provide a definitive improvement strategy. Although a definitive strategy for improvement is probably not possible given the extreme variation of different manufacturing systems, it may be possible to improve the examination methodology. This thesis integrated the common existing approaches used to evaluate value stream maps in an attempt to capture all of the possible improvements. Hybrid value stream mapping needs to be evaluated against other techniques to refine this new mapping technique.

During the analysis phase, determining the inventory requirements was a key step to determine the value of an improvement methodology. A systematic way to determine the required inventory in a production system allows one to determine the base inventory required to run the system in its current state. From this point, the effect on inventory of improvements to the production system can be determined. By evaluating improvements against each other, the future state map providing the highest present value can be chosen. Inventory evaluation techniques need to be even better integrated into value stream mapping.

The material flow processes were easily analyzed using the existing icons and summary information, but the information flow analysis techniques needed to be developed. A systematic means to evaluate information flow, however, has not yet been developed, but some techniques and principles of good information flow were discovered. An improved method to determine the future state information flow needs to be determined.

6.3 A Final Lesson

Constructing a manufacturing system is a complex task. There is no one way in which a product can be created. Every individual manufacturing system will have its benefits and costs. The objective of the manufacturing systems designer is to evaluate the costs and benefits of a variety of systems to determine the best system for a given product.

This is not to say that there are not principles for the design of good manufacturing systems. Whether one uses value stream mapping or other techniques, the questions upon which the analysis of value stream maps is based provide a good illustration of the key principles in designing manufacturing systems. The designer of a good manufacturing system will be able to answer all of the questions.

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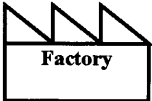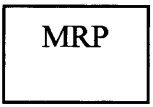
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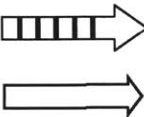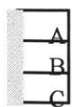
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Appendix A: List of Icons used in Value Stream Mapping (in this thesis)

Factory	**External Manufacturing Process.** This process is performed at a facility at which the mapper does not have authority. The word "factory" is to be replaced with the name of the process that takes place in this location. The manufacturing process may only be one of having the parts sit, in this case making the process storage.
Process	**Internal Manufacturing Process.** The process contained within this box is under the direct control of the mapper. The word "process" is to be replaced with the name of the process that takes place in this location.
	Enclosure Box. This symbol represents a set of processes located away from the facility being mapped but under the control of the mapping facility. A satellite processing facility a few miles away from the main facility would have its processes enclosed in this box.
MRP	**Scheduling System.** This box represents the scheduling system. The text within the box is to represent the scheduling system. Typical scheduling systems are MRP or Manual. The box to the right of the scheduling system represents the rate that the scheduling system is updated. Note: This system is a modified version of the information flow icons commonly used.
C/O Time 95m C/T 4s OEE 45% FTQ 98% Lot Size 350 A/T 6.5h	**Process Summary Box.** Within this box the key process summary statistics are placed. The terms within the box will be process specific. The statistics listed in box to the right are used in this thesis. They are defined as: *C/O Time*: The change-over time. The time from the last good part produced during the former run to the first good part produced by the next run. *C/T*: Cycle time. The average time to produce a single part. *OEE*: The overall equipment effectiveness. The percentage of time that a piece of equipment is producing good parts when it is scheduled to be operating. *FTQ*: First Time Quality. The percentage of parts produced at a given process that have acceptable first run quality. First run quality is a quality party that does not rework. *Lot size*: The batch size of production run. A/T: Active time. The amount of time that a machine is run per day.

daily Batch: 45k lb Distanace: 1.0 days	**Delivery Truck**. A truck represents the mode of transportation from one facility to the next facility. Within the trailer of the truck the frequency of arrival is noted. Note that if the delivery is by rail, boat, etc. the appropriate icon should be used. The moniker, Batch, refers to the amount that the truck can carry and the label, Distance, is used to indicate the travel time between two way points.
	Information Flow Arrows. The jagged arrow represents an electronic transfer of information, while the straight arrow represents a manual transfer of information. These arrows can be further expanded by explaining the actual means of transfer, such as by phone or fax. The information flow to the process to communicate the required production and the information flow from the process to illustrate actual production are both to be shown.
	Material Flow Arrows. The striped arrow represents a push system. A push system is one in which goods are transferred to the next process without the next process calling for the goods by some means. The clear arrow represents external travel to another facility.
weekly	**Schedule.** A production schedule generated by the scheduling system. Usually information flow icons are used to illustrate the flow of the schedule from the scheduling system. The schedule icon is to illustrate how often the schedule is issued to the production process.
21,000pcs (2.1 days)	**Inventory.** Inventory between processes and facilities. This symbol represents work-in-process or finished goods inventory. The amount of inventory and the time to process it (based on takt time) is also to be shown. If inventory is well organized and its amount controlled the supermarket icon should be used. Note that sometimes a "hat" symbol is used to represent inventory.
	Kanban Card. The kanban card is used to represent a pull loop, a control processing or inventory loop. The arrow under the card icon is wrapped around the processes which encompass the loop.
	Look and See Scheduling. When a central scheduling system is not employed process scheduling may be undertaking directly at the production process. This is called look and see scheduling and it is represented by the glasses symbol.
A B C	**Supermarket (Organized Inventory)**. The supermarket icon is used to represent organized and controlled inventory. Inventory is controlled by controlled the amount of inventory that may be at this location.

Appendix B: Saws versus Shears

<u>Description</u>: This document contains a summary of billet preparation study that was completed by Steve King. This study took place between September 20, 2003 and October 31, 2003.

<u>Key Options</u>: The following are three best-case scenarios:

Option 1:   Local External Billet Preparation Facility

Using an outside processor set-up an external billet preparation facility within the vicinity of Tonawanda Forge. This processor will receive black bar for all net shape gears and all ring gears. The processor will have the following capabilities: straightening (1.5" – 4.5"), peeling (1.5" – 2.5"), polishing (1.5" – 2.5"), NDT testing (eddy current and ultrasonic), and saw cutting (1" – 4.25"). External suppliers are interested, but some type of agreement is required to induce a company to relocate.

<u>Financial Assessment</u>: Excellent
NPV: $4.1 million   IRR: N/A (assumes no initial investment)
Investment: $0 (actual total depends on inducements)

<u>Opinion:</u>
The above option is the best long-term allocation of resources. A low cost ring gear supply chain can be designed and the high cost net shape gear supply chain redesigned. The option entails outsourcing of all ring gear cut stock and a re-sourcing of all net shape gear cut stock to a single supplier. This eases management of the supply chain and allows bars to be lengthened from 20' to 32' to reduce scrap losses (by properly designing the new facility). For the ring gears, the economic benefits of saw cutting for the conventional presses ($981,000 / yr) are attained while minimizing the cost to achieve them. For net shape gears, the existing supply chain is consolidated (saving $310,000 / yr) and scrap is reduced ($71,000 / yr). For Tonawanda Forge, valuable floor space is freed and existing cutting associates may be assigned to higher value-adding tasks. A local outside cutting house also reduces the lead time required to produce product (approximately a two day reduction for net shape gears)

Moreover, the upcoming ring rolling process requires saw cut billets and currently predicted pricing is more than $0.82 per billet (loss of $3,116,000 / yr if all forging are "ring rolled") above predicted market price. This option is a means to attain market price (or below market price).

The drawback of this option is that it requires work to be outsourced from Tonawanda Forge and for Tonawanda Forge to design the appropriate partnership with an outside cutting facility. There is at least one bar processor interested in partnering with Tonawanda Forge, Bar Processing. The initial investigation highlighted Bar Processing as a good match – the company has $3,000,000 in underutilized assets it is willing to redeploys, it has undertaken a similar partnership with North star Steel, and it is a current supplier to Tonawanda Forge.

Option 2:   Internal Sawing of Ring Gears

Replace the existing Shear #5 and Shear #6 with circular saws. The shears can be replaced on a one-to-one basis if the larger Lansing style saws are used. To feed the saws, pre-straightened

material is required to be shipped to Tonawanda Forge. Increase the bar length from 20' to 32' to maximize the savings from this project.

Financial Assessment: Good
NPV: $1.8 million   IRR: 55.1%
Investment: $1,200,000

Opinion:
The above investment simply replaces one asset with a more economically productive asset. The intention is to only cut ring gear stock on these saws and to not cut net shape gear material. Additional saws could be installed if net shape gear processing was desired, but the overall savings is marginal.

Economically, this project captures the potential conventional ring gear press savings ($981,000 / yr) and the saws can be installed to handle 32' bars. This project also eliminates the current over-pricing of externally obtained ring gear billets.

The main drawback of this option is that it does not eliminate the excess costs in the net shape gear supply chain ($310,000 / yr supply chain + $71,000 / yr less scrap) and that it adds a step in the ring gear supply chain – the bar needs to be straightened. Also, during the change-over period between installing the saws and removing the shears there is an external cutting cost.

However, this process change could be easily sold to the UAW. In doing it though, a chance to permanently rework the supply chain may be missed.

Option 3:   Internal Sawing of Ring Gears and Net Shape Gears

Erect a small structure on the Tonawanda Forge property to house enough saws to cut both the ring gears and the net shape gears. This facility would only cut product and not straighten, peel or polish. The facility would cover approximately 17,500 sq ft. – the size is due to the need to store peeled bar undercover.

Financial Assessment: Good
NPV: $1.8 million   IRR: 24.4%
Investment: $4,730,000

Opinion:
The above project is a "good" compromise between an improved supply chain and a high return project. All of the ring gear savings ($981,000 / yr) and the net shape gear savings ($381,000 / yr) are captured, but the cost to obtain them is high.

However, this project creates additional jobs at Tonawanda Forge and may obtain support from the UAW. It may also be possible to restructure the floor space at Tonawanda Forge and place the saws in an area to free floor space for potential press additions. In doing so, the start-up cost of removing the shears and being without cutting ability is avoided.

Conclusion:

The best option is Option #1, Local External Billet Preparation Facility. A local facility requires minimal investment and all the benefits of saw cutting and creating excellent supply chains are

obtained. However, there may be resistance to outsourcing of work and constructing the actual "contract" may require some negotiation.

As an alternative, replacing the current ring gear shears with saws provides a high return on investment and is not a controversial proposal. An even less controversial proposal from the UAW perspective is to add jobs by insourcing the cutting of net shape gears.