Implementing Lean Manufacturing Through Factory Design

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Abstract

Factory design can play an important role in the diffusion of new technologies for manufacturing. Historically, factory design impeded the electrification of factories because there were significant interrelationships between the factory infrastructure and electric manufacturing processes. These interrelationships could not be fully leveraged partly because huge investments were tied up in the old factories but more importantly it took a long time for people to understand all of the interrelationships that constituted an entirely new technological system. I explore in this thesis that the diffusion of lean manufacturing suffers the same fate as factory electrification, and therefore exploring the interrelationships that make up lean manufacturing systems, including factories, will help extend the adoption of lean manufacturing in U.S. factories.

I explore the relationships between factory design and lean manufacturing through two tools, axiomatic design and a queueing model. Axiomatic design is a process that helps the user derive the physical design parameters of the factory from the systems and functional requirements. The process helps draw out the explicit understanding of factory design and lean manufacturing and make it explicit. Axiomatic design helped me explore the essence of a lean factory, which can be summarized by the following features: independent departments through buffers and management structures, decentralized support activities to support problem solving and continuous improvement activities, and modular and scalable factory features which allow ease in continuous improvement in factory layout.

I used the queueing model to explore the relationships between the various design parameters of the lean factory and throughput performance. Throughput can be improved by shortening line segments, increasing the quantity and size of accumulation buffers, designing over-speed into upstream line segments, and allowing time to reset buffers with a two-shift policy. All of these parameters cost investment dollars and should be used only in moderation. The model also explored variation reduction through the development of a strong set of problem solving skills. Variation reduction provided the same benefit as other parameters, but required no investment costs, and is therefore a superior leverage parameter.

Finally, I explore the issue of launching the new lean factory. I discuss the risks involved in launching a lean factory, and potential mechanisms to balance the need of learning with the need for efficient production. A well-developed training plan, on-line coaching and launching organizational changes before launch can all help alleviate the risks. The issue of implementing the factory is as critical as designing the factory.

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I thank my beautiful wife Jill Triani. I dedicate this work to you, because I do not have the words to express my love, respect, and gratitude for what you bring to me and to life.

"There is a joy in manufacturing only poets are supposed to know."

- Chrysler Corporation founder Walter P. Chrysler

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Chapter 1: Introduction and Overview

Research and knowledge of lean manufacturing is readily available to any reader. The interested student can read the philosophy of Taiichi Ohno, the creator of the Toyota Production System (TPS), or detailed how-to books on specific tools within TPS. Companies trying to become lean organizations have funded careers in consulting and academics. The creation and implementation of a lean manufacturing system will often begin within the existing operations on the factory floor. As companies exceed at some level on the factory floor, they want to know '*what's next?*'

Companies must then identify complementary skills, assets, and process that will enhance their progress along the lean frontier. From a functional view of the company, many different complementary processes and organizations have been studied, with the majority of the work focusing on the human infrastructure and on product development. I propose first that factory design is not simply a part of manufacturing, and second that its role in the evolution of lean manufacturing is underestimated. This section starts by backing up this statement with some historical perspective.

Factory design and technology diffusion

Factory design can have a significant impact not just on the operation of a factory but on the evolution and diffusion of new technologies. The 'technology' of concern here is lean manufacturing. History has shown that factory design can hamper the diffusion of important performance enhancing technologies. The first industries to adopt the new technologies have been those which, for reasons such as new industry growth that are irrelevant to the technology, are building new factories. This may explain why lean manufacturing, a technology developed and optimized by the automotive concern Toyota, has been adopted in the United States more quickly by many non-automotive industries.

We can look at the early part of this century for a more developed example of how factory design may impede or enhance the diffusion of technology. While most of the manufacturing literature focuses on this era for development of mass production design and process techniques, such as those developed by Eli Whitney or Henry Ford, or the division of labor techniques of Taylor, they ignore the impact and development of factory design and electricity.

The Electric Dynamo

The central electric power station was developed in the 1880s. This would provide electrical power to factories that had historically generated their own power through mechanical systems such as water and steam. Four decades later, factories finally began to update their design and technologies to prepare for factory electrification. There were numerous advantages to electrified factories[1], including:

1. Savings in fixed capital through lighter factory construction
2. Further capital savings from the shift to building single-story factories
3. Closer attention to optimizing material handling and flexible configuration of machine placement and handling equipment to accommodate subsequent changes in product and process designs within the new structures
4. The modularity of the new system and flexibility of wiring curtails losses of production incurred during maintenance, rearrangement, and retrofitting.
5. The factories were significantly safer because power distribution within the factory was no longer through large gears and belts.

These factors were so significant that it is believed that they contributed to ½ of the total factor productivity from 1919-29. Why was industry so slow in adopting their factories to these advantages? First, these advantages were not clearly apparent to everyone, and are only well understood decades later. Second, there was a huge investment tied up in the old, mechanical factories. Third, and perhaps most important for the purposes of this thesis, is that the technological innovation of the electric dynamo, when combined with factories, constituted an entirely new technological system[2]. The innovation needed did not end with the dynamo, but extending into the brick and mortar and the process design of factories. Because the breadth of technologies and innovations that made up this new technological system was so wide, it took a significant period of time before all of the complementary innovations were in place. None of the innovators involved in the development of the electric dynamo could have possibly forecasted the impact it would have in the industrial sector. Perhaps if they had, they could have packaged and sold it differently and targeted the industrial segment in marketing efforts. Technological innovation is often, however, the result of attempting to solve a very specific problem. Once it is solved, the technological innovation has significant applications elsewhere. Lean manufacturing was 'invented' to solve problems very specific to Toyota and Japan after World War II. It turns out that it had applications to many more situations than the specific problems facing Toyota in the 1950s, including being applicable in dealing with the problems Toyota faces today.

From the lesson of the dynamo we should recognize that complementary assets such as factory design could hamper the diffusion of and realization of gains from lean manufacturing. We can reduce the delay in recognizing the gains by exploiting the complementary nature of factory design. This requires an exploration in how factory design is complementary to operations strategy, from the brick and mortar down to the process design. To explore this issue, we will examine manufacturing as a system, where many of the interrelationships exist between the physical factory and the operating patterns.

Systems theory and manufacturing

Why systems solutions?

There are many ways to explore this topic[3], but I choose to start with processes. Every result, which is what we really want, is a function of a process. A process takes a set of inputs and transforms them into the outputs, or results. Many problems we face everyday are a result of the systemic structure and not random events. The systemic structure is the pattern of interrelationships among the key components of the system, whereas the system is the collection of components, processes, and interrelationships. We therefore have more leverage in creating the results we want by understanding the underlying systemic structure as shown in Figure 1.[4] The systems are not necessarily built consciously, but are a result of the pattern of decisions made over time, both consciously and unconsciously. The system can not be analyzed by understanding the elements, whether they are human or physical. Although no one can cognitively hold the entire system, we must respect the nature of the interrelationships if we are to gain true insight into the workings of manufacturing. For the study of general manufacturing, the entire manufacturing enterprise can be defined as the system that begins from raw

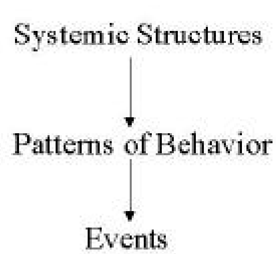


Figure 1 – Role of systems

material and the generation of ideas and extends through sales, service, and completing the entire process with recycling.

Quality is Free

The Total Quality Management movement, although not expressing this explicitly, is a great example of thinking in terms of systems and interrelationships. To put part of this movement succinctly, processes that help reduce process variation will both improve product quality and also reduce scrap, resulting in lower operating costs. Since both quality and cost improved, there is no trade-off and 'quality is free' becomes true. While the processes that are related to this movement represent only a part of the manufacturing system, many corporations witnessed significant performance improvements as a result of their adoption. I would like to point out how most companies began down this path. Both the development of the 'quality is free' tools as well as their adoption has often been a path of trial and error. Some adapters succeed and others fail, and while there are many theories no one really knows why this is the case.

This revolution elevated the role of manufacturing in the corporation from that dirty function that the company has to do, to a role where manufacturing contributes to the competitive position of the company. While companies may be able to elevate manufacturing further to a role where manufacturing contributes to the strategy of the corporation by trial and error, there is no guarantee of the same kind of success. The desire to elevate manufacturing further points to a need to develop a deeper understanding and holistic theory of manufacturing systems.

Systems theory and manufacturing

Systems theory was developed in the traditional sciences well before its application to business was appreciated. By the turn of the century, biologists were examining processes and contextual relationships as much as they were studying the pieces and components of biological systems. Applications and new understandings surfaced in fields as varied as physics and psychology[5]. Jay Forrester's work may mark the beginning of applying systems theory to industry after World War II[6]. Tools and concepts developed by Jay Forrester and others for examining systems in business, including manufacturing, have not seen significant application until the past 10 years. Today, viewing markets, businesses, and manufacturing units as systems through these tools has already brought significant insights to managers.

Managers at Toyota, particularly Taiichi Ohno, father of the Toyota Production System, developed independently their own understanding of the systems and interrelationship of manufacturing.[7] Over the span of 40 years, they developed processes and structures that balanced the relationships between customer orders, process control, material movement, process equipment, product design, and human resources. The slow, experimental development of the Toyota Production System has made Toyota the most successful and robust automotive company in the world, and a benchmark for all manufacturing organizations.

Review of manufacturing strategy theory

One of the most significant developments in manufacturing literature over the past 30 years has been in the field of manufacturing strategy. This theme of literature started when Wickham Skinner of Harvard University wrote "Manufacturing: Missing Link in Corporate Strategy" in 1969[8]. In that article, Skinner proposed that manufacturing should not just be a function which produces the products determined by the business strategy, but that manufacturing should play an integral role in developing a business strategy.

There continues to be a great deal of manufacturing strategy literature, most of which in some way is derived from Skinner's work. I believe its longevity in the business and academic press is because it provides a set of tools and frameworks that respects the system nature of manufacturing and business. My evidence for this theory can be found in the literature of manufacturing strategy (although no author, to my knowledge, has stated explicitly that manufacturing strategy is synonymous with systems theory):

1. In *Restoring Our Competitive Edge*[9], the book derived from Skinner's work by Hayes and Wheelwright, the authors present that a "pattern of structural and infrastructural decisions that constitutes the manufacturing strategy of a business unit." These decision categories are capacity, facilities, technology, vertical integration, workforce, quality, production planning / materials control, organization. They state that 'these eight decision categories are closely interrelated' and the criteria for evaluating a manufacturing strategy are its internal and external *consistency* and its *contribution* to competitive advantage. Contribution involves making trade-offs. Consistency measures how well the decisions fit and complement each other, both internal (compared to other manufacturing decisions) and external (compared to other business decisions).
2. In *Manufacturing Strategy*[10], author Miltenburg talks about the need to make decisions in the context of a manufacturing strategy because 'no single production system can provide all outputs at the highest possible level.' He adds that 'the production system used by an organization should be the one that is best able to provide the manufacturing outputs demanded by the

organization's customers.' Several different *systems* are identified as a set of consistent decisions, which he calls 'levers.' Each of these levers makes up a *sub-syst*em of the entire system in the categories of human resources, organization structure and controls, sourcing, production planning and control, process technology, and facilities.

Chapter Summary

There are two basic premises in this chapter. First, manufacturing is a system. We need to develop a general theory of manufacturing in order to raise its level of contribution in the firm, and that will only happen with system-level tools and insights. Second, factory design has played and will continue to play a major role in the diffusion of major technology changes in manufacturing. Lean manufacturing can be considered one such technology, and we should look at how factory design might impede or enhance the diffusion of lean manufacturing techniques.

Chapter 2: Lean Manufacturing at Chrysler

Before beginning to examine factory design, I should narrow the scope of lean manufacturing to the application of this case study, namely Chrysler Corporation. This chapter will review the context of lean manufacturing at Chrysler, which will help in understand latter sections of specific applications or insights.

Chrysler's Corporate Mission

Chrysler Corporation's Mission is:

To be the premier car and truck company in the world by 2000 and beyond.

What that means to the average Chrysler employee is that Chrysler does not have to be the best, to be #1, in every category. Instead, Chrysler has to be best in many categories, and 2^{nd} or 3^{rd} in most others. It also means very few last place finishes. Chrysler began this mission with the goal to become premier in North America by 1996, a goal which they believe they reached.

Chrysler has made great strides since it set out on its mission, such as numerous award-winning designs and the financial success of over $2.1 billion being returned to shareholders in stock buybacks from 1997 and at least $2 billion planned for 1998. The focus for Chrysler for the next several years will be what it can do to improve its position regarding quality, continue producing award-winning designs, and prepare itself for a future of uncertainty regarding global and market forces.

The quality issue has become very important to Chrysler in the past couple of years. Chrysler, while making significant absolute improvements in quality, still falls far behind industry leaders Toyota and Honda, and still behind domestic competitors Ford and GM. Chrysler's efforts to improve quality have almost dominated Chrysler-related press for the past couple of years. Chrysler's failure to improve its relative position in the industry regarding quality has become a significant point of criticism recently.

The Chrysler Operating System

How COS was started

The Chrysler Operating System, or COS, was born from conversations among a group of senior executives, led by Executive Vice-President of Manufacturing Dennis Pawley, asking '*how* will we become the premier car and truck company by the year 2000?' Acknowledging Toyota as the world benchmark in automotive manufacturing, if not manufacturing in general, was a start towards knowing what Chrysler needed to do to achieve its mission. From there, an extensive benchmarking and strategy building effort resulted in a plan to roll out the Chrysler Operating System as Chrysler's customized version of the famous Toyota Production System. The Chrysler Operating System represents a philosophy of manufacturing. I will use the following definition of company philosophy that I believe represents this situation[11]:

> *"The set of guiding principles, driving forces, and ingrained attitudes that help communicate goals, plans, and policies to all employees and that are reinforced through conscious and subconscious behavior at all levels of the organization."*

Balanced improvement in SQDCM

Traditionally, manufacturing organizations will manage the results of SQDCM, or Safety, Quality, Delivery, Cost, and Moral, independently of one another. Safety results will be watched by a different part of the organization (often joint union-management teams) than that which manages delivery (production control), which is different from that which manages cost (Controller's Office) or quality (engineers and quality control experts). Only the senior management of the organization or the plant is responsible for all metrics. Furthermore, depending on which metric returns poor results, extra effort will be put on improving that metric while letting the other metrics slide, assuming they won't get worse, only stop improving.

Chrysler Manufacturing wishes to break that paradigm. Chrysler can not afford to push costs down while quality slides only to turn around and spend money to improve quality. All metrics, safety, quality, delivery, cost, and morale need to be improved simultaneously. If trade-offs between cost and quality need to be made, those decisions can no longer be made without understanding the consequences on other metrics. Knowledge and responsibility for both metrics must be included in the decision process, as only high-performance results in all metrics will ensure the long-term value of the corporation. This direction comes from understanding manufacturing as a system as discussed in Chapter 1, and not a set of independent results.

Once it is recognized that the results are interrelated, we can begin examining the systems, sub-systems, and processes that define those interrelationships. Those definitions are the core of the Chrysler Operating System.

Everyone is becoming lean

There is significant evidence that lean manufacturing is not just a differentiating manufacturing strategy, but the current best thinking that everyone is trying to implement. All the domestic manufacturers are attempting to become lean. Ford has created the Ford Production System[12], while GM is simply implementing the principles of lean manufacturing[13]. Honda and Harley-Davidson have also embraced the concepts[14]. The automotive suppliers are implementing lean manufacturing, such as Freudenberg-NOK[15]. Lean concepts has even spread beyond the automotive industry to firms such as Texas Instruments, Alcoa and United Electric[16].

The point is that most firms have moved beyond the discussion of whether or not to implement a lean manufacturing strategy and into the discussion of how to implement a lean manufacturing strategy.

How COS is implemented

COS started with the insight that management was the highest leverage point in any change effort. If the principles and skills surrounding COS were entrenched in the plant managers and their staffs, there would be no reason COS would not be the focus of plant improvement efforts. The first eight courses, beginning in May 1995, that made up COS Executive Education were rolled out by the Executive Vice-President of Manufacturing teaching the course to his Vice-Presidents, those Vice-Presidents teaching their Plant Managers, and the Plant Managers teaching their staffs. The intent is that two things will happen. First, in order for each executive to teach the course they need to indoctrinate the material in their head. Second, the multiple-course, hierarchical nature of the education allowed a natural feedback mechanism so the executives would get timely, needed information on the success and value of the training and its impact on the factory floor where it really counted.

The second major component in the COS change process is that each factory would have a Learning Laboratory Line.[17] Each factory will designate a small section of the factory to developing an ideal COS production line. The line must represent normal production but not be so essential that no failures can be allowed. The line gives managers a chance to work on developing their skills regarding COS in the context of real-life production. The Learning Laboratory Line also allows the chance to experiment with what resources will be required without drawing on the entire plant. The entire exercise will deepen the line and staff managers' understanding of manufacturing as a system.

Although we have not examined COS in the light of manufacturing strategy theories presented by Skinner or Miltenburg (see Chapter 1), COS is a manufacturing strategy, and as such, demands an understanding of systems theory. In order to allow an understanding of the Chrysler Operating System to develop within manufacturing managers, a first draft of the sub-systems, processes, and tools of COS was developed. The framework containing these relationships can be seen in Appendix A. The framework is not a complete definition of COS, but it forms a basis from which managers can form a theory of operations. The four primary sub-systems of the Chrysler Operating System are as follows:

- Human Infrastructure
- Leveled and Balanced Schedules
- Value-Added Activities
- Robust, Capable, and In-Control Processes

We will review each of these sub-systems and what they mean, but will not do so in much depth.

Chrysler Operating System Sub-Systems

Human Infrastructure

From the systems perspective, we look at the human infrastructure as a set of processes and structures. This includes taking a new look at processes such as recruiting, hiring, and training. In order to achieve the results the rest of the processes in the manufacturing system are designed to achieve, a certain set of skills are required by the workforce, including management. This skill set is different than that which provided individual and corporate success for Chrysler in the past. It is not that the existing or previous skill set has been invalidated, but it is incomplete in two possible ways. First, COS requires more of people, and managers must find ways to allow the existing skills that have been stifled in the past to blossom and become integral with work on the factory floor. Second, certain skill may have to be added to the existing skill base to function-in and utilize COS as intended.

The point to understand about the human infrastructure and systems theory is that there is not necessarily a 'best' human infrastructure, but there is a human infrastructure that is most consistent and best for a certain operating system. Toyota has developed a system where the human infrastructure works harmoniously with the rest of the operating system. Some of the attributes of Toyota's human infrastructure are intensive training, rapid problem solving skills, and both teamwork and team work[18].

Leveled and Balanced Schedules

Part of both the Toyota Production System and the Chrysler Operating System is Leveled and Balanced Schedules. Production planning is designed to minimize disruption to the production process. Production is leveled in that it protects against large swings in demand with a finished product buffer allowing controlled, incremental changes in production volume. Production is balanced by assuring variations in build content are evenly distributed along the production flow.

To examine how leveled schedules interact with other parts of the system, we can look at standardized work. Standardized work can be described as a set of analysis tools that result in a set of Standard Operating Procedures (SOPs). SOPs represent the best thinking, at the time, on how to do a particular job. Toyota's continuous improvement will often be focused with standardized work processes. Toyota has become very skilled at using standardized work to determine the optimal work design to meet a given demand figure. Their ability to control and improve work design has developed over decades, and they can meet each incremental change in demand with slow-downs or speed-ups in work. As they change the takt[19] time, they can reorganize work. With demand increases they can incrementally add workers. If demand decreases, they incrementally remove workers from the assembly line, and then can lay off workers, utilize them for improvement activities, or bring in previously outsourced work. This is opposed to a North American automobile company that will meet demand increases with scheduled overtime and decreases by completely shutting the line down in 'inventory adjustments.' Both of these strategies apply more disruption to the factory floor than Toyota's strategy. Overtime puts added pressure on workers, management, and equipment. Shutting down the plant is an extreme measure, delaying future orders and interrupting the production flow from the distribution system all the way back through raw material production.

Value-Added Activities

Value-added activities embody continuous improvement and elimination of waste within the production system. This is often boiled down to the elimination of the seven wastes:[20]

- Waste from overproduction
- Waste of waiting
- Transportation waste
- Processing waste
- Inventory waste
- Waste of motion
- Waste from product defects

What is also important is that to eliminate waste is not simply a matter of focusing on the results such as inventory levels, but managing a process or system that ensures the long-term elimination of waste. COS Workshops, derived from the kaizen workshop process[21], are designed to yield the results in waste elimination. The magnitude of waste elimination will vary, and is dependant on variables such as the problem chosen, the people involved, and commitment to using the process.

Robust, Capable, and In-Control Processes

One of the less publicized aspects of the Toyota Production System is robust, capable, and in-control processes. In-control processes are more commonly associated with Total Quality Management (TQM) programs. I will not define these here but simply examine how a lack of process control impacts the other parts of the system. A manufacturing process that is out of control will continually disrupt the production process. In some manufacturing systems, this is simply accommodated by adding capacity to cover the losses of downtime and scrap while still meeting demand, which is a perfectly acceptable strategy given certain conditions. With COS, however, an out of control process can destroy the integrity of other systems.

If we consider a components operation that supplies the assembly line, the process equipment is required at the right time and must be able to produce the right quantity. Anything else will either create waste or shut down the line. The components operation will send bad parts to the line or they may not even send enough. To compensate, as required by a kanban[22] material flow system, the production line will then order more parts than originally intended. The extra orders will place extra burden on the equipment in terms of time and wear. This will have a negative reinforcing impact on process control. This vicious cycle (Figure 2) will drive process control to poor performance levels, which can then be accommodated in two ways: (1) produce enough extra inventory that the system can handle variations due to a lack of process control, which is waste, or (2) focus on maintaining an in-control process. Maintaining an in-control process is not simply a matter of choice. It requires a skill set and process established in the human infrastructure, which brings us full circle to COS being a complete manufacturing system, relying on the relationships as much as the pieces.

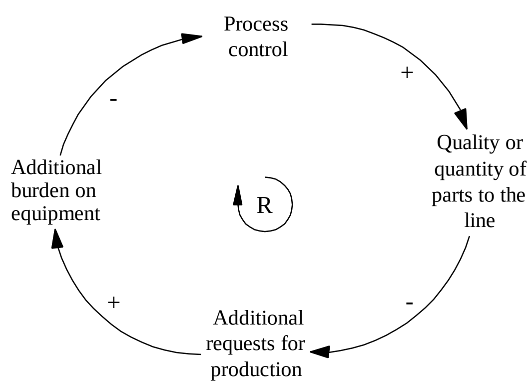


Figure 2 – System dynamics loop demonstrating the reinforcing nature of process control and production pressures.

Progress of and resistance to COS within the plants

There has been highly varied success in implementing COS into the factories. The predominant problem is sustainability. Certain practices are implemented and implemented well with management attention, but as management attention is removed or even redirected, performance in the initial success drops. I found evidence of the lack of sustained COS efforts when I walked up to a Learning Laboratory Line[23] unannounced and checked the Balanced Scorecard[24] measurements. More often than not, the measures have not been checked or utilized for weeks or even months. I found one example that was left without an update for six months.

There are two dominant reasons for the difficulty in sustainability. One is the structures, policies, and coaching performance in the factory. This thesis will not touch on the role of the plant management because they are the responsibility of the factory and not factory design. The second reason is that the support functions, such as Advance Manufacturing Engineering or Product Engineering, are producing products and processes that are not consistent with the direction the plant is trying to head, namely towards lean manufacturing.

When Toyota began their evolution towards the Toyota Production System (TPS), they designed factories not only considering what they would do in the next five years, but what they would do in the next 30 years. Chrysler facilities are currently designed for the way Chrysler historically would run its factories. Today, those designs are incompatible and insufficient to fully develop COS within the factories. The emphasis of this thesis is on what should be considered when designing a factory to meet the needs of an operating system.

Chapter Summary

This chapter reviewed Chrysler's competitive position, the origins of the Chrysler Operating System, the process for diffusing knowledge of COS, and a brief review of how that effort has performed. The Chrysler Operating System breaks down the manufacturing system into four sub-systems: human infrastructure; leveled and balanced schedules; value-added activities; and robust, capable, and in-control processes. COS recognizes that manufacturing is a system and requires system-level tools and processes. The following chapter expands on the issue of diffusion in the specifics of this case example.

Chapter 3: Diffusing Knowledge into Decision-Making

This chapter examines how knowledge of COS is diffused into the managers' minds, into decision-making processes, and how it meets up against the constraints of the organizations. We will also explore the concept of Ideal State processes for diffusing knowledge

How Advance Manufacturing Engineering impacts COS

Advance Manufacturing as a subsystem

Advance Manufacturing Engineering (AME) at Chrysler is responsible for developing facilities and tooling for all vehicle programs. As a result, responsibility for understanding how facilities and processes impact the factory's ability to implement COS falls on their shoulders. We won't actually study here the processes that AME uses to develop and deliver the factory, but focus more on the design of a factory and its result. The study of AME processes requires a longer period of time from initial concept through launch.

AME has not had to answer this question so clearly until now. With the lead-time for new Chrysler programs being around three years and COS being only two years old, most of COS has focused on what happens after AME is relieved of responsibility[25]. Here, however, the assembled team was asked to develop an Ideal State COS factory. From the Ideal State plans, a new factory can be derived given the constraints of the budget, the existing buildings, and the site. A review of this process will be included at the end of this section.

The factory system has interdependencies with the product group and with how the plant management will run the new factory, but the layout can still be optimized to meet the strategic goals of Chrysler manufacturing despite these constraints. It is important not to lose the integrity of the system, and deriving the final factory design from an Ideal State will ensure that occurs. This is a great opportunity for Chrysler and for COS.

Roles and responsibilities

Defining the roles and responsibilities of AME is important at this point because it will determine the boundaries of the subsystem. We will define AME's roles and responsibilities as follows:

- Time boundary: responsible for factory design and implementation through the launch phase
- Role boundary: responsible for the development of new processes and support to bring the processes up to required performance levels

The first factor means that we have to consider not just how the plant is designed but how it is launched. The second factor adds to that because the factory design will be new to the production management, AME is responsible to provide support functions, such as training, which will ensure production management is capable of running this new facility. This is not financial responsibility, but AME must ensure any training is capable of supporting the new requirements. While some AME managers currently get involved in aspects of the launch such as training, it is not considered part of their responsibilities. It is included here to bound what I will and will not choose to explore in the thesis, as a member of AME.

As important as what is within AME's bounds is what isn't within their bounds. AME should not try to determine the capabilities or will of production management towards implementing COS. The strategic direction of Chrysler Manufacturing is to implement COS, and AME should do everything it can to support that goal. It is common at this point to say "they won't run that way anyway," calling it impractical to design a factory system the management won't use. This excuse, however, will only guarantee that COS will never completely succeed at Chrysler. To alleviate such excuses, and Ideal State must be developed and maintained.

Developing an Ideal State process

Chrysler Manufacturing spends a great deal of time developing Ideal States. The Ideal State will be what the plant can achieve if there are no constraints that they must live with. Within the COS organizations, we could say that the COS Framework (Appendix A) is Chrysler Manufacturing's ideal state.

Executive Education involves the managers in activities on the Learning Laboratory Line. The activities include both the development of a detailed Current State and an Ideal State. The next steps will then include what the group should do, at the task level, to close the gap between Current and Ideal State.

The Ideal State has many important benefits. First, the vision to which everyone should aspire is very clear. Second, it highlights weaknesses and makes them explicit, focusing the groups attention to resolve the weaknesses. Third, it creates a documented history and vision which makes it easier to communicate to outsiders and to new insiders what the group is trying to achieve.

First, we will examine the vision. At Toyota, the Toyota Production System stands above all else as the authority in what managers should do. It determines their methods and their processes. The Toyota manager does not have the authority to ignore the Toyota Production System because they do not like it. They do have very clear bounds, however, within which the Toyota employee (manager and worker alike) is required to innovate in both an evolutionary and revolutionary nature. If you ask a Toyota manager to show you the Toyota Production System, they may find it difficult, stating that their operation is far from the ideal Toyota Production System. But they understand very well what that Ideal State is, and they will continue for many years to try to close the gap between Current State and Ideal State. An organization can set its Ideal State out for employees with this intention. This gives them a very clear structure of what they should be working towards. The Ideal State is not a bullet on their 'Goals and Objectives' for the year, but all of their 'Goals and Objectives' should be derived from that Ideal State.

Developing the Current and Ideal State documents for the organization makes weaknesses very apparent to everyone. There is very little question as to which are the biggest gaps, because they are in writing. This will remove a significant amount of the political posturing around what the group should tackle next.

If the management has documented the Ideal State, Current State, and what steps will be taken to close the gap, then outsiders or new insiders while have a significant advantage in working with the management team. Imagine if there was a new member of the management team who witnessed all the activities of the team. They would understand what the tasks were, but the manager doesn't begin each task with 'this is to help us move to the Ideal State.' The new team member will be very lost trying to put the pieces together at the task level, and the Ideal State documents will help him or her join the team in a productive manner.

The Ideal State is just what it says, ideal. No one expects the Ideal State to be achieved in six months or even in 5 years. Toyota has been working at this for over 40 years and they have still not achieved the Ideal State. One concern is that the organization will have to live with very real constraints, hampering the progress towards the Ideal State, a concept examined next.

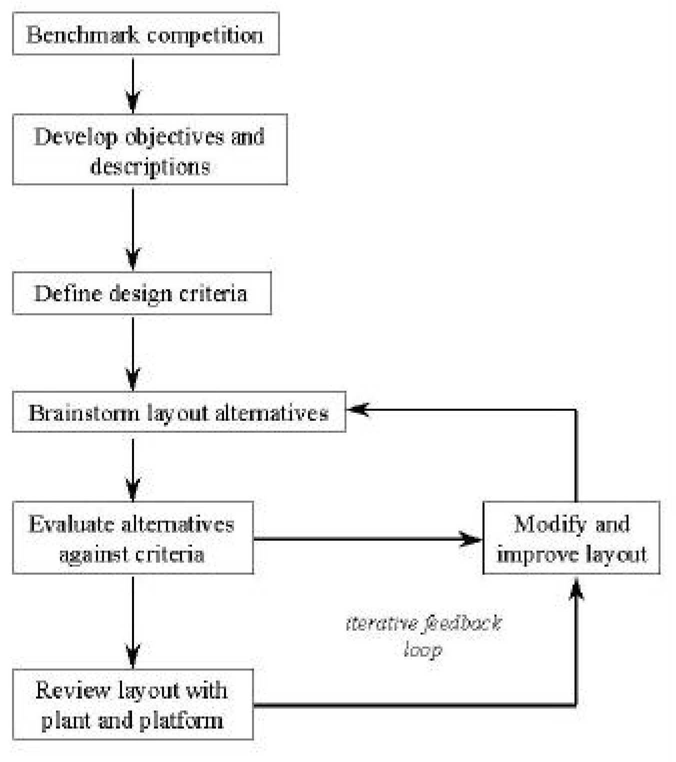
Dealing with Constraints

Constraints will always affect the actual outcome of the program or plant, but they should not affect the Ideal State; that should remain constant. Because constraints are very real, we must find ways to acknowledge them without sacrificing the Ideal State path. In this section, we will first examine the role of the time constraint on my project team to develop an Ideal State factory design, as a case study. The next section will deal with the constraint of the product, a vehicle assembly. Later in the thesis, in the section 'Utilizing What Was Learned to Design a Complete Factory' I will examine the constraints of the program such as budget and site location.

Balancing learning and action with limited time

A team was established to determine what the Ideal State plant layout should look like. This cross-functional team contained representatives from AME, Chrysler assembly plants, Material Handling Engineering, and Product Engineering. Before the group could get started, they needed to determine their own development process. Because this project needed to eventually result in an actual plant, the goal of creating the plant (*the* *action*) is just as important as the understanding behind it (*the learning*). These two objectives must be carefully balanced or the result will not meet the high-performance goals. The process, shown in Figure 3, not only balances learning, but embeds the learning within the action. That allows the group to test their knowledge and skills in the context of action. It is also important to note that this entire process was not designed before beginning. The process evolved as the knowledge developed to meet changing needs, usually in the form of unanswered questions. As different resources for learning became available, they would be utilized in different ways depending how far the lessons and design of the factory had developed.

Figure 3 - A design process to balance learning and action.



A robust design process for products and processes

While this is a process to take care of group learning needs, we should also acknowledge a process oriented towards actual design. When utilizing new knowledge in the design process, a robust process to follow is:

1. Seek new knowledge
2. Develop design characteristics
3. Model the design
4. Verify through implementation

Seeking new knowledge can be anything from benchmarking to course study, but new knowledge is useless unless put to action. For this case the new knowledge is gained through study of the Toyota Production System and COS. Developing the design is an essential part of the process, but modeling the design is one of the key steps to truly engrain the new knowledge, as is verifying the design through implementation. There is a balance between modeling and implementing design ideas, which depends mostly on their relative costs and risks. If you are learning how to shoot a basketball, the cost of implementation is negligible, and because there are more opportunities for learning, you would prefer that method of learning to modeling shooting a basketball. However, if you are building a new vehicle assembly plant as we are here, the cost of implementation is enormous. The value of modeling in the process is thus elevated.

This process can be highly iterative depending on what is being designed. In this paper we will not examine the entire context of the process but focus on the case study and the design, modeling, and implementation phases of designing a lean factory. We will extract the context-specific lessons from the design and modeling, discuss tools used to do so, and examine the process of implementation including risks and support-mechanisms such as training.

Another reason that modeling is emphasized in this case study is the time horizon. COS is a strategic endeavor, and strategy is generally used to describe activities and decisions over an 'extended time horizon, both with regard to the time it takes to carry out such activities and the time it takes to observe the impact."[26] Because of the time delay in seeing results, learning will be difficult because of the gap between action and result. Modeling can reduce that gap to near zero, allowing many more iterations and allowing better cognitive relationships between action and results.

Interrelationships between Product and Process

This section will examine the role of the product in developing the Ideal State process. One of the primary relationships is that between complexity and performance, such as cost and quality. I will spend the majority of my time examining this relationship, starting by defining complexity, and then examining the evidence behind the relationship.

Complexity and definitions

Before beginning any conversation around complexity, some definitions should be spelled out. I will use the following definitions in the realm of product complexity:

- *Design complexity*. Design complexity refers to the component and system design of the vehicle. It is independent of variety in the market. High design complexity refers to having a component, a bracket, and six bolts instead of just a component and three bolts.

- *Product variety – features.* Product variety in general refers to the position of the vehicle in the market. The features will refer to the amount of options available, such as air conditioning, right-hand drive, or diesel. The amount sold in the market is almost irrelevant because once the option is available for sale, it means more parts on the assembly line and more tooling.

- *Product variety – build combinations.* Build combinations refers to the number of available combinations of all product features or options. If no restrictions exist, the number of build combinations for vehicle assembly is (the number of colors) x (the number of engines) x (the number of wheel sets), etc. Each restriction, depending on what level they fall under, will take out sets of combinations, such as no automatic transmission with the diesel engine.

- *Another view of assembly complexity*. Another way to view complexity is presented by Fonte[27]. He creates two distinguishing spectra, that when meshed creates four categories. The first is *integrative* or *non-integrative* complexity. Integrative means the feature has tremendous impact on others parts of the vehicle, such as right-hand drive that requires different I/Ps, cowls, door panels, etc. Non-integrative is then self-explanatory, an example being decals. The other spectrum is whether the complexity is *additive* or *substitutive*. Additive complexity requires no offsetting process when the feature is absent, such as sunroof installation. The operator is installing the sunroof or doing nothing, and unless perfectly balanced leads to inefficiencies and missed operations, particularly when the operation is a low-running option. Substitutive complexity is just a matter of choosing, such as diesel or gasoline engine. Substitutive complexity keeps the operations focused on assembling the feature, but can lead to substitutive mistakes, excess floor space, and excess operating walk time.

From here on, the term *complexity* will refer to the aggregate state of all forms of complexity, used when a distinction between them is not needed.

Complexity and product quality

The product involved in this case study is somewhat but not entirely irrelevant. It obviously will matter down to the level of which processes will be included and which will not. It will not matter, however, at the level where basic features and operating patterns will be determined, which is the primary focus of this work.

The specific product is one of Chrysler's more diverse, international vehicles. It meets the needs of different regulatory, environmental, and consumer groups on every major continent. Therefore, the amount of product variety available to Chrysler's marketing and distribution divisions can be a significant source of competitive advantage[28]. This amount of product variety results in two factors to be considered here:

- Manufacturing will be more difficult due to complex product and process needs.
- The plant needs are similar to those on which the Toyota Production System was based.

This first factor is only important as we reference the issue earlier in this document regarding Chrysler's efforts to improve quality. If Chrysler wishes to make tremendous leaps in quality but will continue to design complex products (which in some part is determined by the market needs), it will need to make tremendous leaps in operating quality. That means that a half-implemented COS will be insufficient to meet Chrysler's quality needs for this product. The quality / complexity relationship deserves more explanation that this, however. Some may disagree that manufacturing is more difficult with higher complexity, citing Toyota as an example of higher complexity and higher quality. This thesis proposes, however, that quality will always decrease with increasing complexity, but that a choice in operating system can make production so robust to complexity that the marginal decrease in quality is insignificant. In Figure 4, two companies are

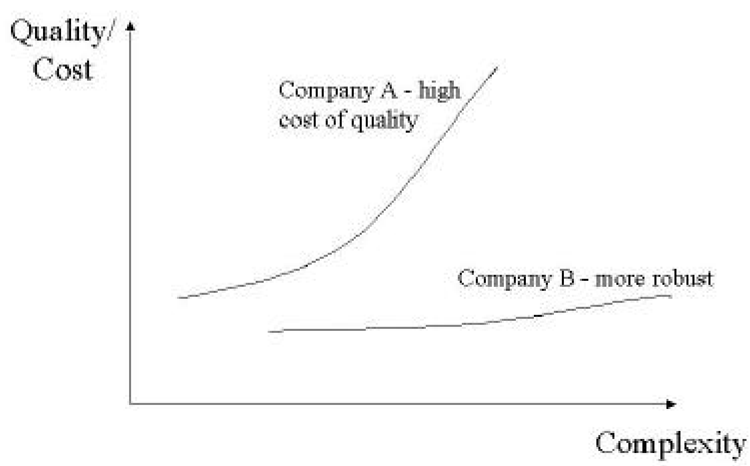


Figure 4 - Complexity / quality relationship.

compared with two different operating systems[29]. The vertical axis measures quality in terms of cost, therefore the lower the better. Company A's choices in operating system have made them more sensitive to changes in complexity. Company B's choices have made them very robust, where major shifts in complexity may hurt quality, but minor changes produce insignificant changes in quality.

This relationship can also be explored mathematically. Assume a probability of failure, q, that is greater than zero for any part, process, or selection. Assume further that quality can be measured as the overall probability of success. If the total number of parts, processes, or selections is represented as the total number of opportunities for failure, or n, then the quality level of the factory can be represented by the equation $(1-q)^n$. Notice that no matter how small q is, quality will always deteriorate with n increasing. The level of robustness can be related to how small q, the probability of failure, can be made.

I want to extend this discussion into lean manufacturing and Toyota, and dispel a commonly held myth. In studying Toyota one will hear about 'standardized work.' This is not the place to examine in-depth what standardized work is, but I can say what it is not. It is not, as some believe, to have the same product with no variety moving down the line. As a result of complexity it will be more difficult to keep costs down and quality up, but in any industry the choices in production system determine the robustness against this relationship, as was previously discussed. The Toyota Production System was created specifically to meet the need of having to produce a high level of product variety.[30] This goes against conventional wisdom, which is why it is so common to misunderstand it. Conventional wisdom presents the case of a match between the variety of the product and the process selection. As shown in the product / process matrix in

Figure 5 - Product / Process diagonal matrix.

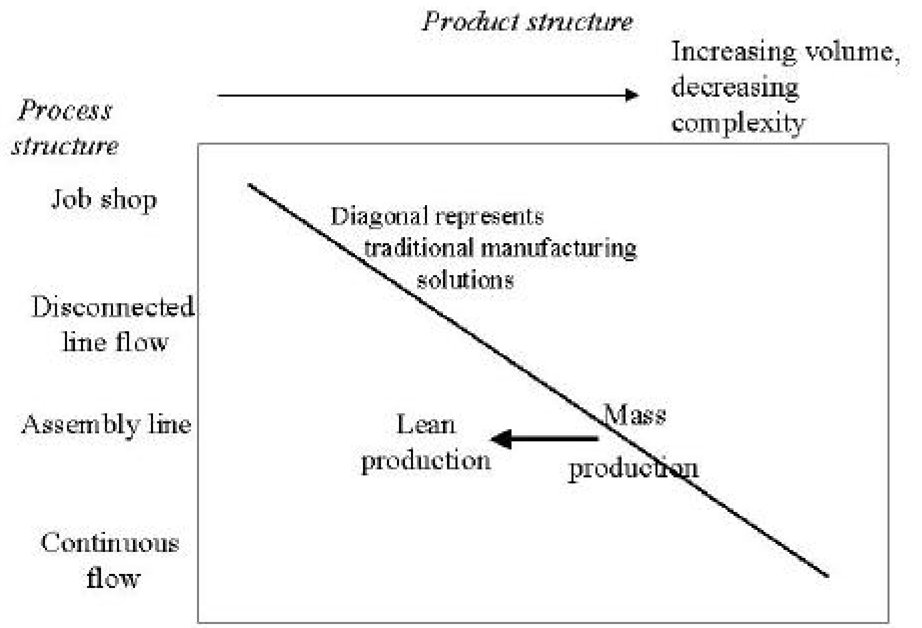


Figure 5[31], the goal would be to remain on the diagonal to maintain a consistent fit. A deviation from the diagonal represents a poor choice in process. Toyota has shown, as you see in Figure 5, that making choices in the operating system allows them to consciously deviate from diagonal providing a source of competitive advantage[32]. This break with conventional wisdom is what made it so difficult for outsiders to see the relationship between product variety at Toyota and their superior quality and cost metrics. As a result of this argument, this product's high complexity is not only a poor excuse, but is instead a reason for emphasizing the implementation of the Chrysler Operating System.

Chapter Summary

This chapter presented several important concepts. First, an Ideal State provides tremendous power in moving the organization towards lean manufacturing. It can coordinate action, find weaknesses, and communicate with new team members. Second, a process must be designed and monitored that provides a balance between learning and action throughout the design phase to handle constraints of time. Third, the choice to move towards lean manufacturing will make the production environment much more robust to high product variety, and therefore the product variety choice should enhance the argument to move to lean, not fight it.

In the next three chapters, I discuss the process of creating the Ideal State for factory design. This Ideal State can then be used as a guideline, not just for this factory, but for future new factories and redesigned factories alike.

Chapter 4: Axiomatic Design of the Factory

The stage of developing design characteristics has several alternatives. This chapter will examine the process of designing a lean factory using axiomatic design, a process developed[33] by Nam Suh at MIT, but will focus more on the content than the process.

A review of axiomatic design for the factory

This section begins by exploring what is meant by design characteristics. It is very easy for a group with years of plant design experience to jump right into the details of factory design such as where to locate such-and-such process and where to locate the air-handling unit. This skips over a higher level of detail that is often not questioned, but comes from a part of the habits and mental models of the organization. Because we are examining a new philosophy, design must start at a more abstract level than the organization is used to. Hayes and Wheelwright provide a set of decision categories that must be considered when designing a factory or a general manufacturing strategy[34]:

- **Capacity –** amount, timing, type
- **Facilities –** size, location, specialization
- **Technology –** equipment, automation, linkages
- **Vertical integration –** direction, extent, balance
- **Workforce –** skill level, wage policies, employment security
- **Quality –** defect prevention, monitoring, intervention
- **Production planning / materials control –** sourcing policies, centralization, decision rules
- **Organization –** structure, control / reward system, role of staff groups

With our design process, I will not explicitly use these decision categories, but you can see that the level of abstraction is consistent.

Axiomatic design can be used to design anything from a toothbrush to an economic system. The process relates Customer Attributes to Functional Requirements to Design Parameters. In designing a factory system, it is the Design Parameters that are important because they become the physical attributes that plant engineers will put in place before production even begins. Axiomatic design, as a process, follows two axioms that hold true in designing anything. Those axioms are as follows[35]:

1. *The Independence Axiom*: Maintain the independence of functional requirements.
2. *The Information Axiom*: Minimize information content.

The Independence Axiom attempts to reduce the interrelational complexity of the design, improving its ease of design as well as ease of use. For example, if three design parameters all affect three functional requirements, it is not clear to the user which lever to push to get the desired result. If each design parameter affects nothing but one functional requirement, it is very easy to get the desired result by adjusting the design parameters.

The Information Axiom basically tries to minimize redundancy. A design should have no more than the minimum design parameters. This sounds like common sense, but Suh takes this axiom into consideration when he designed his axiomatic design process.

The format of the design will demonstrate linking each design parameter to its customer attribute assuring nothing is missed and it will also reveal interdependencies created by the design and repetitive features so that the designer can then work to simplify the design.

Creating explicit knowledge from tacit knowledge

It is important to create a distinction between tacit and explicit knowledge. Borrowing terminology from Nonaka and Takeuchi[36], explicit knowledge is expressed in words and numbers through hard data or codified procedures where tacit knowledge is 'deeply rooted in an individual's action or experience.' They go further to explore knowledge creation as a critical core competency for competing in the next millenium. They define knowledge creation as 'the conversion of tacit knowledge to explicit knowledge.' I do not want to explore alternative definitions or the implications of the definition, but simply explore what that statement means to the process of axiomatic design.

In our example, we are pulling together a group with different technical and experiential backgrounds. It could be argued that each has tremendous tacit knowledge in their particular expertise. Our goal in axiomatic design is then to draw out the best of the collective experience, or tacit knowledge, and codify it in terms of design parameters, or to make it explicit. Axiomatic design is therefore, based on the terminology of Nonaka and Takeuchi, a process for knowledge creation. We can now begin to explore how the process works.

The design of a factory architecture

I would like to make a distinction between the design of an architecture and the detailed design, whether it is a software package, vehicle, or factory. Karl Ulrich describes architecture as the following[37]:

1. The arrangement of functional elements
2. The mapping from functional elements to physical components
3. The specifications of the interfaces among interacting physical components

This definition is surfaced at this point because I believe it has implications for understanding how axiomatic design fits into the overall process of factory design when the design involves as much mental model shifts as lean manufacturing requires. First, it was already made clear that we are not ready to begin placing walls and conveyors, although that we must eventually complete that task as well. For an experienced group of factory designers who usually move right into the details, they may have never experienced a different level of design, which is why architecture design is important.

Axiomatic design helps primarily with step two: mapping functional elements to physical components. It also helps the designers understand the interfaces among the physical components, although it may not actually determine the specifications. An understanding of the architecture of old factories is embedded in the knowledge and information of the organization. The need to shift to a different architecture, as demanded by the move to lean manufacturing, can be threatening to an organization if they are not aware that the shift is at the level of architecture. An organization is often blind to how product architecture, even if the product is a factory, is embedded in the organization. Here, axiomatic design helps us elevate the question of architecture design so that the designers are very aware of how the architecture of a lean factory may differ from designs of today.

An example: A COS-driven factory

Ideally, the design would link Design Parameters directly to Customer Attributes, which would be the people buying the cars. That is a long, complicated path from factory

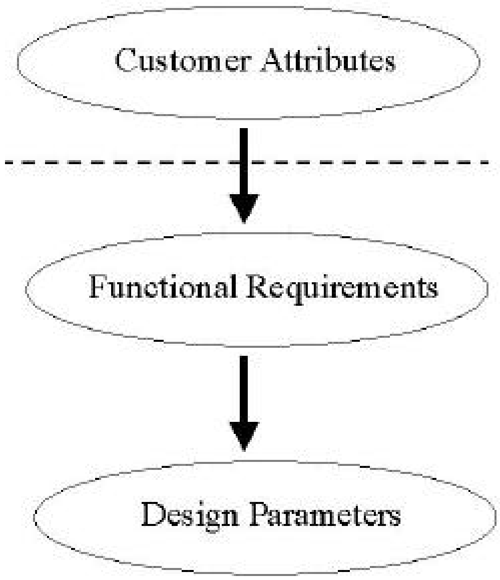


Figure 6 - Hierarchy of axiomatic design.

design to the customers, so we will assume that the Chrysler Operating System, as it was designed, will take care of customer needs and wants. We then assume COS is both strategy and customer, therefore a COS-driven design will meet the needs of Chrysler's customers. This concept is expressed through Figure 6. As shown, Customer Attributes feeds Functional Requirements feeds Design Parameters. We will assume that COS has taken into consideration the Customer Requirements, so we do not have to recreate that effort and move back to the end customer. We will maintain the hierarchy, however, by substituting the COS Sub-systems and Support Processes for Customer Attributes.

Axiomatic design allows the designer to carefully manage the process of moving from Customer Attributes (support processes of COS) to Functional Requirements (what will happen in the plant) to Design Parameters (the physical features of the plant) in a slow, deliberate, and explicit process. It will work for anything from an abstract plan down to a very detailed level. The next section includes an example of how someone might proceed to use axiomatic design to design a factory.

Axiomatic Design: Detailed Version

I developed this example of axiomatic design for a factory system with LFM Fellow Ryan Blanchette[38]. The reader may use this example to begin developing their own axiomatic design, but consider a few caveats. First, this chart was created in the context of automotive plants, and although we tried to make it generic, we did not test it against the larger set of possibilities. Second, it is far from complete. We expanded into areas that we thought needed more work, but every section here could probably be broken down into lower level detail. Third, we gained a great deal of understanding of lean manufacturing by having the conversation surrounding the development of this document. As important to us as what we did include is what we decided not to include. I propose that only by starting from scratch to apply to your own design needs will you overcome these concerns. The table follows, beginning with a legend.

- **HI** - Human Infrastructure
- **L&BS** - Leveled & Balanced Schedules
- **VAA** - Value-Added Activities
- **RCIC** - Robust, Capable, and In-Control Processes

Customer Attribute	*Functional Requirement*	*Design Parameter*
HI: Recruiting & Hiring	Manpower requirements meet factory needs.	Clear definition of manpower requirements.
	Worker skills meet factory needs.	Clear definition of worker skill requirements.
	Manning flexibility meets factory needs.	Workers can perform multiple functions.
HI: Role / Responsibility Clarity	Factory systems enhance role / responsibility clarity.	Factory systems that enhance role / responsibility clarity.
	Factory systems that provide clear communication channels.	Area is provided that displays day-to-day plant activities and responsibilities.
	Physical extend of responsibility is defined.	Physical boundaries.
	Physical extent of management responsibility is defined.	Buffers which define bounded segments which align with management structure.
	Physical extent of worker responsibility is defined.	Workstations are clearly marked and bound the line worker's responsibility.
	AME system enhances role / responsibility clarity.	A plant development system that enhances role / responsibility clarity.

HI: Performance Feedback	Factory design facilitates performance feedback.	A factory design which facilitates performance feedback.[39]
	Layout facilitates performance feedback.	Areas which allow clear communication of performance.
	Performance metrics effectively measure performance.	Performance metrics that effectively measure performance.
HI: Policy Focus & Deployment	Layout facilitates policy focus & deployment.	Area for communicating policy focus & deployment.
	AME system facilitates policy focus & deployment.	AME system that facilitates policy focus & deployment.
HI: Employee Involvement	Factory system supports employee involvement.	A factory system which supports employee involvement.
	Layout supports employee involvement.	Area which supports cross-functional team activities.
	AME system utilizes employee involvement.	An AME system which utilizes employee involvement.
	AME system utilizes plant involvement.	A process which encourages plant input at all stages of plant development.
	AME system utilizes input from all team members.	A process which involves all team members in decision making.
HI: Employee Development	Factory system supports employee development.	A factory system which supports employee development.
	Layout supports training.	Area for training near the line which supports *x* workers.
	A method for developing employees to improve explicit knowledge of the factory system.	Workshops which utilize a cross-functional team to explicitly design the factory system.
L&BS: Capacity & Process Planning	Factory system is flexible to meet unknown market needs.	A factory system which is flexible to meet unknown market needs.
	Line is flexible to meet unknown market needs.	A line which is flexible to meet unknown market needs.
	Lines are flexible to support volume changes.	A line which is capable of volume changes.
	Lines are flexible to run mixed model.	A line which is capable of running mixed model.
	Lines are flexible to change vehicles.	A line capable of building different vehicles.
	Material handling is flexible to meet unknown market needs.	A material handling system which is flexible to meet unknown market needs.

L&BS: Production Planning & Scheduling	Production planning & scheduling is capable of maintained leveled & balanced schedules.	A production planning & scheduling system which maintains a leveled & balanced schedules.
	The scheduling system can maintain leveled production.	A scheduling system which provides leveled production.
	The scheduling system maintains workload balance through product variety.	A process to develop schedules which maintain workload balance.
	The scheduling system communicates our schedule to our suppliers.	A method to communicate our schedule to suppliers.
	The scheduling system communicates our schedule to the plant floor.	A method to communicate our schedule to our plant floor.
L&BS: Material Flow Planning	Use minimal amount of material to support a factory system in the most efficient method.	A material flow which uses the minimal amount of material to support a factory system in the most efficient method.
	Material path is most efficient.	A material path which is most efficient.
	Each part's production path can be identified.	A defined path for each part from dock to line.
	Eliminate waste in part travel.	Minimal part travel distance in plant.
	Eliminate waste in material handling resources.	Minimal amount of material handling resources.
	Minimal material level to support production.	The minimal material level which can support production.
	Minimal amount of purchased material to support production.	*x* hours of purchased material at *y* location within part path.
	Minimal amount of WIP to support location.	*x* hours of WIP to *y* location.
	Material display is most efficient.	A material display method which is most efficient.
	Workstation material is clearly displayed and easily accessible.	Workstation clearly displays material.
	Eliminate waste in dunnage use.	Dunnage & use which results in minimal waste.
	Easy identification of distinct parts or features.	Plant-wide color code scheme.
VAA: Identify & Eliminate Waste	Eliminate factory system waste.	Methods for eliminating factory system waste.
	Eliminate waste of walking.	A method for eliminating waste of walking.
	Eliminate waste of processing.	A method for eliminating waste of processing.
	Eliminate unnecessary facility resources.	A method which determines appropriate facility resources

		for each operation.
VAA: Practice Sharing	Effective way to share factory system design.	A method for sharing factory system design.
VAA: Standardized Work	Factory system supports standardized work.	A factory system which supports standardized work.
	Workstations allow any process configuration.	A standard workstation design.
	Workers need to know their position within job cycle time related to takt time.	A method for indicating position within job related to takt time.
RCIC: Robust Product & Process Design	Processes need to be robust.	A method for developing robust processes.
	Process can be continuously reconfigured or improved.	Flexible process.
RCIC: Quick Problem Detection & Correction	Factory system supports quick problem detection and correction.	A factory system which supports quick problem detection and correction.
	Quality can be detected in-station.	A factory system which supports operators detecting quality problems.
	Operators have sufficient lighting to identify quality problems.	Level and location of workstation lighting.
	Facility features are quickly identified.	Factory-wide color code scheme for facility features.
	Quality can be fixed in-station without affecting throughput.	Factory system which allows quality to be fixed in-station without affecting throughput.
	Entire line does not shut down when stations are shut down.	Buffer size and location which allow stations to shut down without affecting throughput.
	Quality problems can be communicated to available resources.	Andon system.
	Quality problems can be fixed in-station quickly.	Resources which fix quality problems in-station quickly.
	Tools for replacement and repair are easily accessible.	Location and display of tools for replacement & repair.
RCIC: Total Productive Maintenance	Line stoppage due to maintenance problems is minimized.	A system which minimizes maintenance problems.
	Locations of essential systems are accessible for maintenance.	Layout designs access to essential systems.
	Maintenance is quickly notified of problems or potential problems.	Andon system.
	Maintenance is notified of	A system for tracking and

	preventive maintenance tasks.	indicating preventive maintenance tasks.
	Tools for preventive maintenance are easily accessible.	Location and display of tools for preventive maintenance.

Before Ryan and I completed this chart, the design team needed an axiomatic design. They had significant time constraints, as discussed in the previous chapter. As a result, they could not spend the time it took to develop the above chart. The team used a very simplified axiomatic design, and then in a much less structured way broke the design parameters down into more detail. To see an axiomatic design chart that has been used in the field, see Appendices B and C. Appendix B contains the high-level axiomatic design. Appendix C contains the breakdown of the final design parameters.

For more research on using axiomatic design for factory or process design, particularly for lean manufacturing, MIT Assistant Professor in Mechanical Engineering David Cochran[40] has been developing more extensive work. Cochran focused his research on cellular concepts within lean manufacturing, and uses axiomatic design as the tool to design the cells.

Chapter Summary

In this chapter we examined the use of axiomatic design for designing a lean factory. This was important because the organization was examining factory design in the light of a new operating philosophy for the first time. Axiomatic design can help us break down the philosophy into the physical design parameters that will be used to design the factory.

Chapter 5: The Essence of the Design

Once the axiomatic design is done, the designers who have gone through the process understand the essence of the design. It is difficult, however, in the detailed level of the axiomatic design document, to extract the same understanding. Therefore, this chapter attempts to extract and summarize the essence of the factory design. It is important for those involved to understand the factory design direction at this level before proceeding.

There are several concepts that form the essence of the factory design. One is to promote more autonomy on the assembly line, pushing decision making and problem solving further down the hierarchy. Another is to decentralize all activities essential to continuing operations, moving them closer to line activities and improvement activities. A third concept is to build the lines as modularly as possible, making on-going changes for continuous improvement much easier.

Independence between departments

Independence in departments attempts to push decision making further down in the hierarchy and create mini-companies within the factory. This is attained by physically promoting significantly more independent departments or line segments than a traditional assembly plant would have, as depicted in Figure 7. A line segment may consist of somewhere between 20-40 workstations. Separating each line segment is an accumulating buffer that can hold several work cycles of product. The buffers allow each of the teams to make decisions regarding stopping the line to fix problems. The buffers also increase the independence in operating metrics. These buffers seem to violate the principle of eliminating the waste of inventory, but instead this inventory, while not desirable, is necessary to eliminate a great deal of waste created by downtime. One group leader leads the team in each line segment. Under the group leader may be three or four team leaders who support teams of 6-10 team members. Both team members and the team leader are union jobs. The group leader has much more broad responsibility than in a traditional assembly plant, to the extent that they act as the president of a mini-company, with the upstream line segment as the supplier and the downstream line segment as the customer.

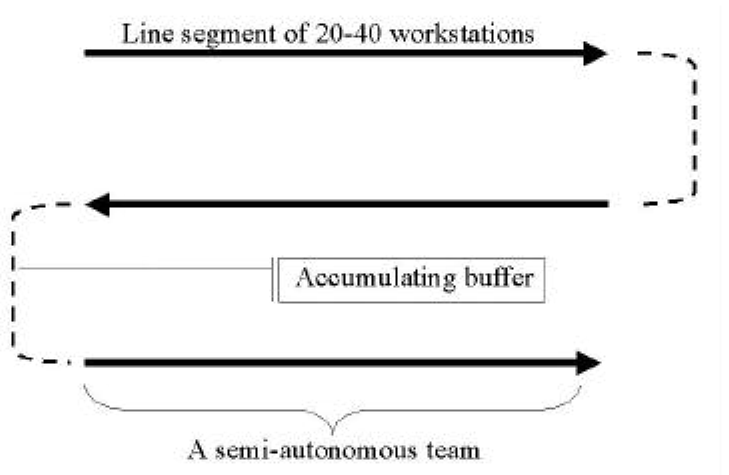


Figure 7 - Line segments and semi-autonomous teams.

Decentralized support activities

These mini-companies need the same support for their operations as any company, particularly material supply and maintenance. An additional goal of the factory design is to decentralize essential activities, moving them closer to where the decisions are being made in the line segments. This shows up as satellite maintenance cribs and decentralized material storage. Training and production meetings can also be decentralized. Team meeting areas are provided for each line segment for meetings, breaks, training, and for visual display of team performance metrics.

Modularity, Scalability, and Interchangeability

The factory design also attempts to make things as modular and common as possible. This is because the life of most vehicle assembly plants is measured in decades, and over that time process technology and product demand may change dramatically. Therefore, the easier the factory can handle change, the cheaper and smoother it will be to maintain on-going operations and continuous improvement activities. This concept can be demonstrated in many ways. All workstations are modular, and can be interchanged at will. This allows the teams freedom to redesign their work without being trapped by their existing facilities. All bays are standard, making expansion or mechanical work a standard operation by not requiring the dramatic engineering efforts often associated with new construction. So the more modular, scalable, and interchangeable the factory and process design can be made, the more the factory can handle evolutionary continuous improvement activities.

Chapter Summary

The essence of the factory can be summarized by three primary concepts. First, by dividing up the assembly line in to line segments with semi-autonomous teams, decision-making and problem solving can be pushed down the hierarchy closer to where the problems exist. Second, by decentralizing as many support functions as economically possible, we can better support decision-making, problem solving, and continuous improvement on the assembly line. Third, by making the factory and process modular, scaleable, and interchangeable, we support the evolution and continuous improvement over several product generations.

Chapter 6: Modeling the Factory

Why model the design?

Modeling the design is an important step because axiomatic design does not ensure that the design parameter will meet the customer attributes. Axiomatic design provides only a conceptual framework, without any scientific means for testing ideas and relationships. Deciding whether or not to model will depend on the costs of modeling and the cost of experimenting with actual design, as well as the confidence level in the relationship between the design parameter and customer attribute. In this case, experimenting with the actual design is very expensive, often measured in the billions of dollars for a new vehicle assembly plant. The cost of failure for a new factory is immense, and so more time, effort, and money should be invested into examining system behaviors in the modeling phase.

Modeling andon and autonomy

One of the more complicated relationships that should be examined through modeling is how line segments help create more autonomy within teams, which Chrysler refers to as 'zone control.' The problem, at its highest level, can be defined as how to maintain in-system quality control without sacrificing throughput. In a traditional automotive assembly plant, the vehicle is assembled on a continuously running chain conveyor. Because shutting down the line will often result in a direct loss of throughput, there is a great deal of pressure not to stop the conveyor. As a result, when a quality problem is identified, the vehicle is tagged and repaired after it is taken off the conveyor.

Repair processes do not have the amount of process control that an in-line workstation will, and therefore quality levels are often sub-optimal.

Toyota manages their assembly line differently, using the andon process. If any of the hundreds of workers on the assembly line encounters a problem, either with equipment or parts or processes, they pull the andon cord. This signals the team leader[41] to the workstation, who must then make a decision: can I solve the problem in the station or must it be tagged and be repaired off-line? Sometimes the problem can be fixed in a few seconds, sometimes it might require a line stop for one or two cycle times, and sometimes it may take hours. One in every six andon pulls typically results in a line stop at Toyota, all others resulting in a solution before the cycle time is completed[42]. Either way the decision goes, it does trigger the problem solving process. Furthermore, a Pareto of causes of andon cord pulls will highlight chronic problems, triggering more intense problem solving efforts.

Because the problems are unpredictable and well distributed by nature, one can reasonably assume that each workstation of the several hundred that make up an assembly plant have an equal probability distribution of shutting down. Known problem areas are either the focal point of problem solving efforts or are accommodated in other ways in the factory design. It is therefore impossible to isolate smooth operations from those that are a problem, at least from the standpoint of modeling the andon process. Having described how the andon system is intended to work, I would like to begin examining the concerns in factory design to be addressed in the modeling stage.

Relating the design parameters to throughput

If a series of processes have equal capacity, but their production varies (either within cycle times or downtime), the output will never equal capacity.[43] Said another way, the system's realized capacity, or system throughput, will always be lower than the segment's minimum theoretical capacity process. A simplified example, shown in Figure 8, shows a collection of processes in series separated by piles of WIP[44]. If the capacity of each process is 10, the output will be strictly less than 10. Its deviation from 10, or whatever the theoretical capacity is, will depend on parameters such as process-time variation, the number of processes in series, and the size of WIP buffers. I will show later how we can look at an entire line segment as the individual processes shown in Figure 8.

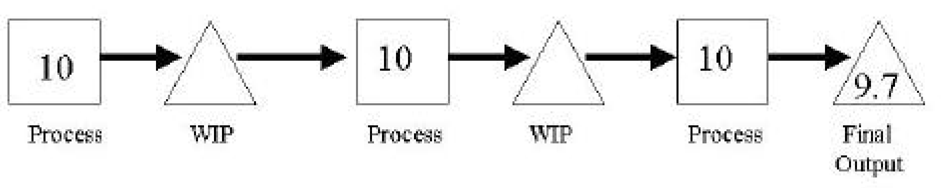


Figure 8 - An example of how the capacity of a system is less than the capacity of its components.

In order to get the desired capacity, there are three compensating techniques that can be used independently or in combination:

- Reduce processing variation
- Provide excess capacity so that realized throughput equals customer demand
- Provide decoupling buffers between processes to reduce the impact adjacent processes have on each other

Each of these solutions has other factors or trade-offs to consider. Providing buffers increases system lead-time, which in turn increases work-in-process inventory, hurts problem solving capabilities, and allows more opportunities for in-system damage. Providing excess capacity could be restated as allowing for lower plant efficiency. Excess capacity is costly both to investment and variable costs. Reducing throughput variation, which would mean both variance within cycle times and improving equipment uptime, is perhaps the least costly, but requires significant and specific skills within the organization. Although Toyota uses all three solution points to some degree, reducing throughput variation is their primary focus.

The three compensating techniques are not a complete factory design, but they do compose the strategic factory design. While the design factors exist for any factory, we need to relate them to the design of a vehicle assembly plant. Achieving strategic goals relating to variation, capacity, and buffers will be achieved through management of the following physical design features:

- Number of line segments
- Length of line segments
- Size of buffers
- Plant uptime (or over-capacity)
- Percent over-speed
- Shift structure

First we should distinguish between plant uptime and percent over-speed. It is always desirable to have 100 percent uptime, because no capital investment is wasted. We have already demonstrated that this is not possible, and so then we must decide how much downtime is acceptable and how to achieve that level. If customer demand requires an output of 10 units per hour, we will need the components of the factory to have individual process capacities greater than 10 units per hour. If we choose individual capacities equal to 11 units per hour, we could say our design parameter is 91 percent uptime[45]. If we choose 12 units per hour, our design parameter is 83 percent uptime.

This example may seem clear, but I simply want to raise the point that system uptime, or system capacity divided by component capacity, is a design parameter. The uptime design parameter often is an unchecked assumption within the organization, and I want it to be reexamined here as a design parameter.

Percent over-speed applies to the relative component capacities in the system. Continuing with our previous example, a factory where all the components have a capacity of 10 units per hour will have a zero percent over-speed. As shown in Figure 9, however, when the same components have greater stand-alone capacity, that excess can be described with over-speed, in this case 20 percent over-speed.

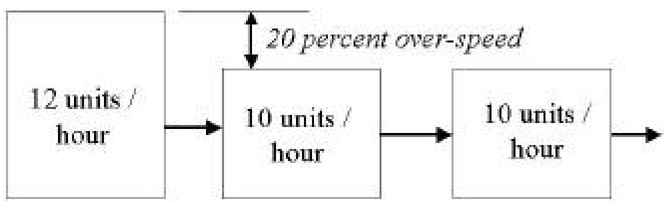


Figure 9 - Example depicting over-speed.

Shift structure doesn't fit as cleanly into the strategic choices, so to clarify, shift structure applies to whether the plant will run essentially continuously (three-shift operation) or two-shift non-continuous. A two-shift operation provides stability to throughput by:

- Providing buffers of time as overtime between shifts to absorb daily variance
- Allowing physical buffers to be reset, maintaining their effectiveness
- Allowing time for preventive maintenance that reduces variation caused by downtime.

The overall effect of the two-shift operation is that it decouples the performances of adjacent shifts.

The development of a queueing model

Understanding trade-offs

It is the job of the factory designers to manage the trade-offs between the above design parameters. Because more than just cost is involved, and even most of the cost relationships are non-linear, trying to optimize the design would not be time well spent. Instead, I believe investing time in deepening designers' insights into the relationships and trade-offs will be much more valuable. Many tools are available to gain insight into these trade-offs. Developing an analytical model is the method chosen here. The decision between simulation versus analytical solution involves more trade-offs. The benefits of an analytic solution are that it is simple, allows many iterations and solution sets to be tried because it is fast, and often provides more insight into the relationships being managed. Simulation, on the other hand, is more flexible in design, particularly in the amount of complexity it can handle, and it is usually easier for the decision-makers to understand.[46] Because gaining insight is the primary goal in this exercise, developing an analytical model is a better choice.

The analytical queueing model[47] in general models two line segments separated by a buffer. Each queueing model, as a pair of line segments, is defined by the following parameters:

- The expected number of jobs completed by workstation before an andon line stop (which represents variation)
- The number of workstations per line segment
- The number of cars per hour (or line speed)
- The number of operating hours before buffers can be reset
- The service level of the two segment interaction
- The number of line segments within the plant
- The downstream segment's starvation rate
- The size of the buffer

The model calculates the number of cars produced per day (or per shift) based on the above parameters. Before proceeding, I want to examine the assumptions of the model. First, the buffers are only designed to accommodate andon pulls and short breakdowns, but not major system breakdowns and material shortages. A major breakdown will be one that requires several times the cycle time to repair. Second, the model assume that buffers can be reset at the end of a shift. If there is not full control over buffers between shifts, such as shifts that run together, then the calculations are not entirely valid. The probability of starvation represents the probability that the buffer will be exhausted within the shift period, for example the probability that the buffer is empty and the upstream segment does not have a vehicle to supply to the downstream segment. Third, the workstations are modeled as Bernoulli random variables, and the line segments, comprised of workstations in series, are modeled as binomial random variables approximated by a normal distribution. Fourth, the model assume a first-order approximation on the impact of line segments further upstream. The impact on the n^{th} line segment from the (n-2) line segment will be from (n-2) starving (n-1). This starvation rate will be approximated by the rate at which (n-1) starves n. This is a first order approximation and second order impacts will be ignored. The second order impact will be a result from the interaction of blockage and starvation rates between non-adjacent segments.

The development of the queueing model

The analytic model of a Toyota Production System assembly line with line segments, buffers, and andon pulls will be modeled[48] as a M/M/1/c queueing model. The queueing theory notation stands for:

Distribution of inter-arrival times / Distribution of processing times / # of servers / # in system

The M stands for a markovian process[49]. The markovian process has the property that the probability distribution for the next state is only conditional on the value of the current state. The exponential distribution is the only continuous time distribution that will satisfy the definition of a markov process.

The assembly line is composed of an arrangement of workstations operating in series. The workstations are partitioned into blocks of stations that will be referred to as segments as shown in Figure 10. This is how a line segment will resemble a single process step in the model, as discussed earlier in our throughput example. In the next paragraphs, we will show how to model the segments using the M/M/1/c queueing model.

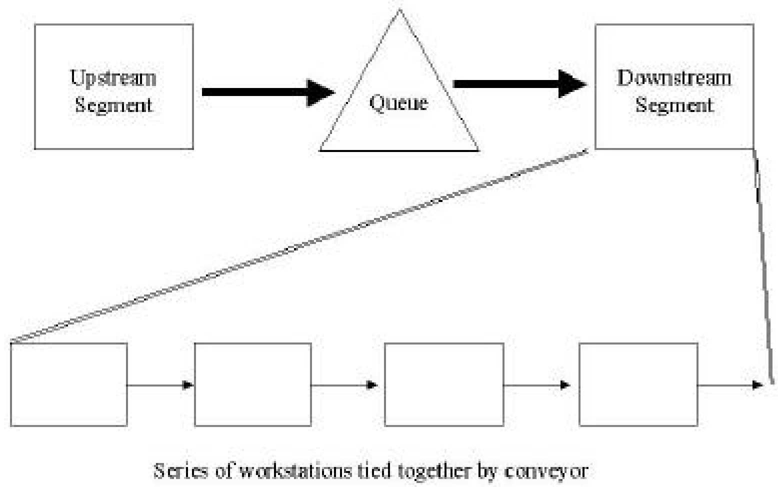


Figure 10 - Segments are broken down into a series of workstations.

A two-line-segment system can be modeled with this queueing theory model due to the following behaviors exhibited by the system. First, each line segment consists of several workstations, as shown in this diagram. In each cycle, there is a probability *(1-p)* that the workstation will fail and probability *p* it will operate correctly. Thus, each workstation can be modeled as a Bernoulli random variable.

The queueing model is represented as shown Figure 11. The downstream segment is represented as a single server. The arrival process captures the operating behavior of the upstream segment. The accumulating buffer represented by the queue that can develop in front of the server.

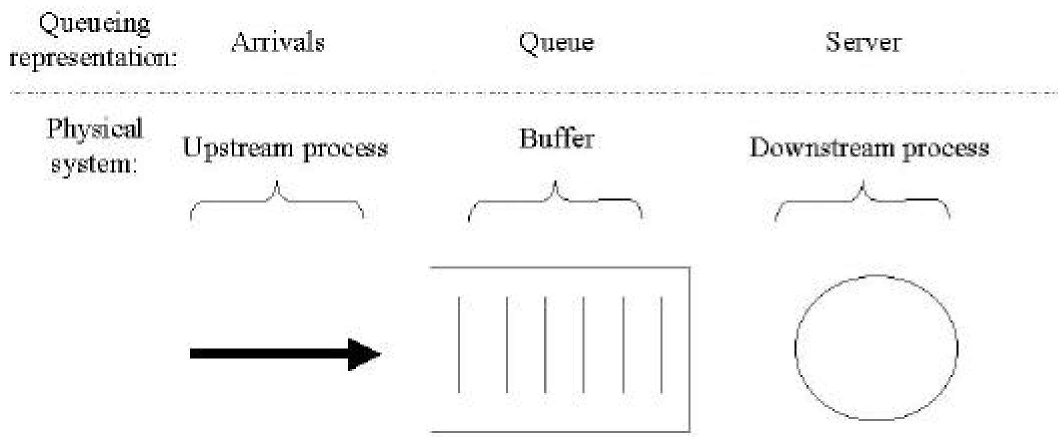


Figure 11 - Queueing model structure.

While the number of workstations per line segment is a design parameter, the entire line segment can be modeled as a binomial random variable. We do this by assuming that all *n* workstations have the same probability of success *p*. For a given cycle, the number of successes is a binomial random variable. When one or more of the *n* workstations fails, the entire line segment fails because they are all tied together through a common conveyor chain. Therefore, the line segment only succeeds when none of the workstations fail, or said another way, when all of the workstations succeed. This occurs with the probability of $(1-p)^n$. The probability of a line segment failure then becomes:

$$P(\text{line segment failure}) = 1 - (1-p)^n$$

The second behavior exhibited is that the buffer, or queue, acts consistently with the M/M/1 model in that it can only increase by 1 when the upstream segment produces a product (called an *arrival*) and decreases by 1 when the downstream segment pulls a product (call a *departure*). This is consistent with the automobile assembly line as all the vehicles are in line on the same conveyor, and therefore can only move one at a time maintaining sequence throughout the entire assembly process. This is true one-piece flow. The only departure from the simple M/M/1 queueing model is that this queue or buffer has a finite capacity, which slightly complicates the mathematics. As shown in Figure 12, the finite size of the buffer is specified as *c-1* from the notation M/M/1/c, where the one is subtracted from *c* to represent the vehicle currently being served.

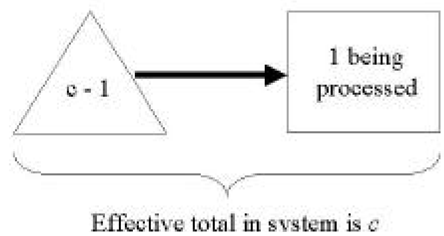


Figure 12 - Queueing theory notation shows queue size as c-1

Another assumption to take into consideration is how further upstream segments affect the immediate upstream segment. The model so far assumes that the supplying segment provides an uninterrupted flow of product at rate λ. This is not the case, because whenever that stream is starved, the 'hole' in the continuous flow of vehicles is interrupted. While determining this number exactly is not necessary for our study, the effect still should be taken into consideration. We assign a probability to the arriving flow, where probability *p'* represents the probability that the line succeeds in providing a vehicle to the queue, and probability *(1-p')* it fails, as shown in Figure 13. The upstream process will therefore provide a stream of arrivals to the queue at rate p'λ. Why is this an approximation? If we look at the upstream segment's arrival process, it is an exponential

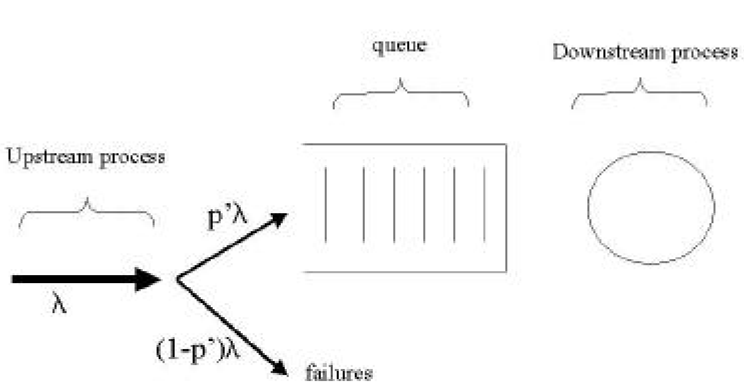


Figure 13 - Queueing model arrival assumptions.

random variable with rate p'●. Therefore, the model is treating starvation occurrences as independent events. In reality, problems, particularly those associated with breakdowns, will result in failures coming in bunches, which is a non-random behavior. Another reason why the entire M/M/1/c model is an approximation is that arrivals and departures don't move in lockstep in the model. There is not an underlying cycle time that drives the entire system, whereas in reality there is a conveyor that moves the arrivals and departures in lockstep.

The spreadsheet shown in Figure 14 makes the calculations for this model, with

Questions Being Addressed by this Spreadsheet

1. What is the expected number of completed cars per day?
2. For a given accumulator size, what is the probability that the downstream segment is starved?
3. For a given accumulator size, what is the probability that the upstream segment is blocked?
4. What are the performance characteristics (MTBF, MTTR, efficiency) of the segments?

Key Assumptions

1. Stations modeled as bernoulli random variables; stations are i.i.d.
2. Segments modeled as binomial random variables.
3. Accumulator is modeled as a M/M/1/c queue where c is the accumulator size+1
4. Shaded cells denote user-specified inputs, unshaded cells denote final or intermediate outputs

Upstream Segment		**Downstream Segment**		**Explanation**
p(station failure)	0.001818	p(station failure)	0.001818	Probability that a station experiences a minor failure during a cycle
E[# cycles until failure]	550	E[# cycles until failure]	550	Expected number of production cycles until a minor failure at station
# stations/segment	33	# stations/segment	33	The number of stations that comprise a segment
p(segment failure)	0.058287	p(segment failure)	0.058287	The probability that a segment fails during a cycle
p(segment starved)	0.07			
TAKT time (seconds/car)	100	TAKT time (seconds/car)	103	The cycle time of each station, measured in seconds
# hrs/shift	8	# hrs/shift	8	The number of hours of production per shift
# shifts/day	1	# shifts/day	1	The number of production shifts per day
Maximum # cars/day	288	Maximum # cars/day	279.6117	The maximum number of cars processed per day
MTBF	17.15651	MTBF	17.15651	Mean number of cycles between segment failures (assumes no idling)
MTTR	1	MTTR	1	Mean number of cycles required to repair segment
Stand-alone efficiency	0.944923	Stand-alone efficiency	0.944923	The efficiency of the segment independent of other line segments

Results

Accumulator size	15	The maximum number of cars that can be held in the accumulator
P(downstream seg. starved)	0.081169	The probability that the downstream stage is starved
P(upstream seg. blocked)	0.040786	The probability that the upstream stage is blocked
Expected stock level	6.057998	The expected number of cars in the accumulator
E[# finished cars/day]	241.941	The expected number of cars completed each day

Figure 14 – Sample spreadsheet of model calculations.

shaded cells being user-input cells. The first input cell, E(jobs until failure), is how many vehicles are expected to be processed before an andon pull stops the line. Many andon pulls will not result in actual line stops, but based on data on Toyota, 550 jobs before failure is a good approximation. This is the primary measure of throughput variation, and one of the three important factors that determine throughput (the others being utilization rate and buffer or queue size). The conceptual sensitivity analysis that must be considered is what is that number for Chrysler. Assuming it uses the system exactly as Toyota would, would the number be 550 or 200 jobs before failure? Then, whether or not team leaders will make line-stop decisions identical to Toyota team leaders will be another question whose answer significantly impacts the value. Another important consideration is that we are not protecting for everything; the buffers are not designed to handle major breakdowns or material failures. It may be designed to handle minor breakdowns, but that number is also not considered here because we are not seeking an exact design but instead a conceptual understanding of how this system will work and what are the tradeoffs. A minor breakdown may be defined as one that takes less than a few cycles of operations to repair. A major breakdown will require several cycles to repair, and sometimes could be an entire shift. We will not define a hard line between the two in the definition, because that is often left to the discretion of the team leader.

Does Toyota use a model?

We should also consider how Toyota might analyze the same problem. First, we should recognize that the design parameters found at Toyota assembly plants are mostly the result of decades of trial and error. History of line shut downs, success in problem solving, and general tacit knowledge of how to manage a line with small line segments and buffers all are not available for us in design. However, we can still look at how Toyota analyzes downtime and line segment speeds[50].

Consider that Toyota runs at 95 percent uptime and assume their demand is for 60 vehicles an hour, which translates into a takt time of 60 seconds. They also wish to maintain a buffer size of around ten. In a typical 8 hour shift, they will want to produce 60 jobs per hour*8 hours = 480 vehicles. Factoring in the 95 percent efficiency, Toyota should lose on average 0.05*8 hours*60 jobs per hour = 24 vehicle per shift. To account for this loss, a new takt time is calculated of 0.95*60 seconds = 57 seconds. Standardized work practices will then utilize a takt time of 57 seconds to design Standard Operating Procedures.

While Toyota's process is not very exact because it does not account for interactions between segments, nor does it take into account all the factors affecting each other, it does emphasize the importance of using takt time in Toyota.

Insights gained from the model

The model provides insights into how the andon/buffer system works. It will also provide design parameter answers that are neither exact nor off by orders of magnitude[51]. Simulation, which can handle more details and more data, can be used to validate the results from the analytic model and tweak design parameters to more exactly meet performance criteria.

Buffer Size and Line Segment Length

As the model demonstrates, buffer size and line segment length are significant design factors as determined by their impact on performance. The impact of buffer or accumulator size can be see in Figure 15. For smaller buffer sizes, increasing the size of the buffer dramatically reduces the probability of starvation, which represents lost throughput. There is a point at which adding size to the accumulator has little impact.

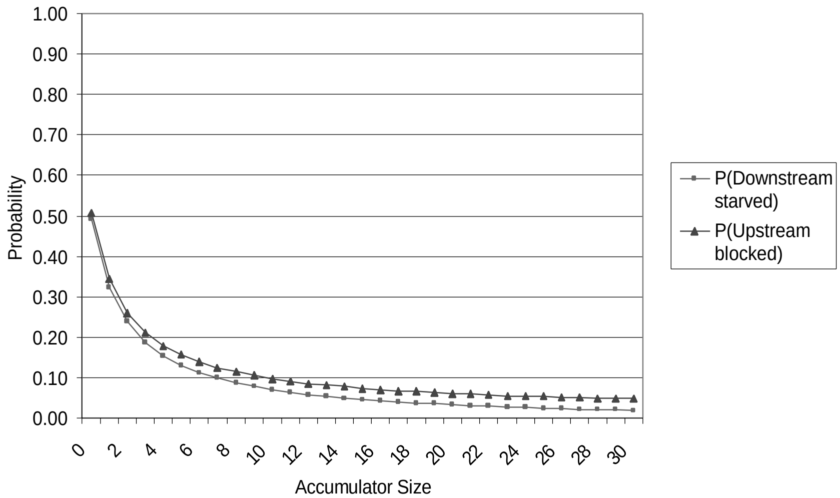


Figure 15 - Relationship between the probabilities of starvation the downstream segment and blocking the upstream falls with accumulator size, but quickly reaches diminishing returns.

There is a trade-off, however, that is not included in the model. Each additional buffer, which is increased as the line segment length decreases, involves significant investment. Increasing the total buffer size, which increases as either the buffer size or the number of buffers increases, also increases the in-system lead time. While total buffer sizing protects the plant performance from problems in production, high in-system lead-time creates its own problems such as excess inventory and high opportunities for in-system damage.

Line segment length also has a significant impact on performance. Line segment length is closely coupled with the number of buffers. Given an estimate of the number of workstations in an entire assembly plant, divide by the segment length, subtract one, and that is the number of buffers. Because the probability that a line segment successfully produces a vehicle is tied to the number of workstations in the segment, the probability of shutting down the line increases with the segment length. As the probability of failure increases and all other factors remain constant, the throughput decreases, as shown in Figure 16. The figure also demonstrates that the marginal loss in throughput caused by increasing segment length decreases as segment length approaches the total number of workstations in a factory. This is due to the nature of cumulative probabilities of failure.

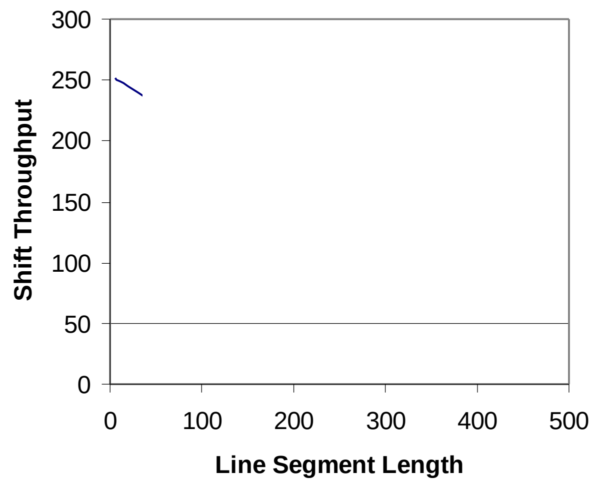


Figure 16 - Relationship between throughput and line segment length

Much more important than the declining marginal loss of throughput is the total magnitude in loss of throughput. Compared to individually buffered processes, a zero buffer factory loses 60 percent of throughput. A buffer of 10 in between each process would lead to outrageous lead times and floor space costs. I make this point that either of the extremes are undesirable, but that doesn't help us find an optimal line segment length. Due to the costs of conveyors, floor space, and lead-time, having more than 10 buffers may be cost prohibitive[52]. Based on understanding of the cost relationship, and an understanding of the numbers that Toyota have converged on, I believe a line segment length somewhere between 20 and 40 workstations is best, given a processing time of around 90 seconds. This might remain acceptable for a range of processing times from 60 seconds to 120 seconds.

Line over-speed

As shown previously in Figure 9, having an upstream line segment run faster than a downstream segment, called over-speed, is a potential design parameter. Because the upstream line segment is running faster, it can help make up for lost production and prevent starvation, although it is actually more prone to being blocked by the downstream segment. Blockage occurs when the upstream segment can not produce product because the buffer is full. There is no place for the upstream product to go so the upstream segment has to idle. Over-speed can make up for lost production that is spread out over a period of time, but it has trouble in bursts of significant losses in production or a string of downtimes. For that reason, the positive effects of over-speed are limited.

Another concern of over-speed is how expensive it is. To make the point, an upstream line segment running at 100 percent over-speed (twice as fast as the downstream segment) will require twice as many workstations to do the same amount of work than at no over-speed. While it is unlikely we would speed up that much, over-

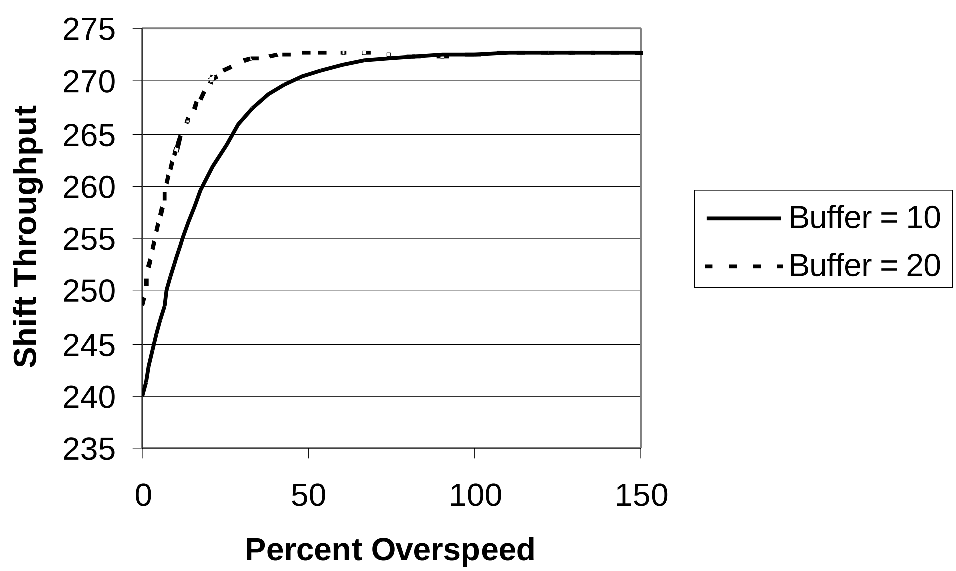


Figure 17 - Relationship between line over-speed and throughput.

speed still costs. Over-speed is also cumulative. If the solution is to be 10 line segments, each at 5 percent over-speed, the farthest upstream segment will run at 55 percent over-speed. This solution quickly moves to a very expensive assembly line.

So how much does over-speed help throughput? Figure 17 shows the relationship between over-speed and throughput. Over-speed will help significantly, but only at levels well above the costly 5 percent mark explored earlier. I also show the impact of different buffer sizes mapped onto the over-speed relationship. The relationship shows a significant gap between the buffers of 10 and 20. This brings into question whether line over-speed is a significant design advantage, and perhaps we should refocus our attention on other variables.

Before leaving the topic of line over-speed, I should acknowledge that over-speed is used as a design parameter in Toyota. My example was a little unfair, because not every line segment must have another increase in speed. In an assembly plant, Toyota may have department over-speed, which means that they may have three speeds throughout the factory[53]. Each department will run at one speed, and line segments and buffers can be found within the department. The conclusion is that over-speed can be used to some degree throughout the length of the assembly plant.

Variation reduction

As shown in Figure 14, the expected number of production cycles before a workstation experiences a failure is considered an input into the model. This is done because the variation the factory experiences is represented in this number, and the factory may experience a wide range of values in variation of failure. An increase in the number of expected cycles before failure represents the factory's problem detection and correction abilities. It is important to recognize that the factory designer can not select this value as a design parameter. The factory designer, together with the plant's eventual management, should look at this as the plant's capability that can change over time. In designing the factory, the designer should be able to evaluate and represent their current capability in problem solving. The plant management should recognize the value in increasing their problem solving capabilities in the overall design and throughput potential.

To examine the role variation reduction can have, I examine a range of capabilities of problem solving and the impact on throughput in Figure 18. The figure

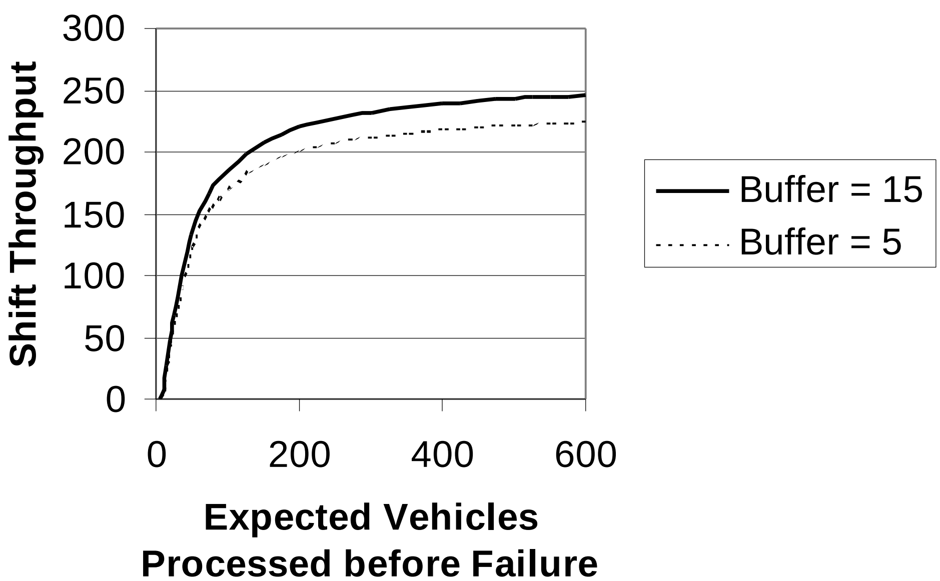


Figure 18 - Increased problem solving capabilities leads to reduced variation which leads to increased throughput.

shows a significant role for variation reduction in increased throughput. After a certain level is reached, the impact is reduced. Once the plant's improved performance levels off, it appears that variation reduction has less of an impact than other factory design parameters considered earlier. An important feature of variation reduction, however, is that it is free. It is embedded in the skills and policies of the factory, and requires no initial investment trade-off such as additional floor space.

The value considered on the x-axis of Figure 18 relies on an assumption that the plant is stopping the line to fix quality problems in-station. Because the domestic producers do not generally practice this policy, it is difficult to establish a reasonable value for the impact of problems on line-stops. Few would argue that Toyota has greater capabilities than domestic producers in this domain, but it is up to the factory designer to assume this value. Finally, I propose that Toyota has been able to achieve superior throughput while making less trade-offs with factory investment because of an emphasis on variation reduction[54]. This makes variation reduction the most powerful parameter for factory design.

Shift policy

We can also see the impact of overtime policy, or time to reset the buffers. At Toyota, assembly plants will not run three shifts. Instead, they will run two 8-hour shifts allowing time at the end of each shift to meet gaps in total output or to reset the buffers. If the plant utilization was 92 percent but the target was 95 percent, it would run overtime until the lost production was made up. Additionally, if certain line segments run worse than others and the buffers are stripped, individual departments can run overtime in order to build back up the inventory. The model creates a distribution of 'end-of-shift' inventory, from which one can calculate the probability that the downstream segment is starved. If the line is run a longer period of time before resetting the buffers, the distribution flattens and there is a larger probability of starvation during the run time. While the model breaks down if the line runs continuously, it does provide the insight that buffer sizes will have to increase significantly in order to account for the lack of reset opportunities in a three shift operation.

Solution convergence

At this point we have developed enough insight in order to begin setting the design parameters for an assembly plant, and I would propose that the solution does not diverge significantly from what is found at Toyota. We could conclude that we should just copy Toyota, but that wouldn't help us understand why we are copying Toyota. Also recognize that Toyota took decades to converge on their solution through trial-and-error, and modeling the relationships can perhaps increase the speed in converging on a factory design solution.

The convergent design is summarized by the following parameters:

- Line segments from 20-40 workstations in length.
- Buffers in the range of 10-20.
- 2-3 levels of over-speed throughout assembly.
- 2-shift operations.
- Downstream starvation probability of less than 10 percent.

For the sake of running a solution, I picked a line segment length of 33, buffer of 15, 3 percent over-speed, which yields a downstream probability of starvation of 8 percent. To close the analysis, I should remind the reader that an important parameter is the probability of workstation failure. The probability of failure was taken from data on Toyota, who has been perfecting this system for decades. There is no reason to believe that Chrysler will be able to perform at the same level at present. The next chapter will begin to examine the problems of implementation, but this probability should be a significant concern during implementation. To highlight this point, using the same design parameters given earlier but decreasing the number of cycles before failure from

550 to 300, throughput will drop by 4.5 percent. Because Chrysler has never used an andon system, there is no data available for this value, and so 300 is just an example. It is fair to speculate, however. that Toyota has greater capabilities than Chrysler. This highlights the point that reducing variation by eliminating the root causes of problems can carry very significant weight in operational performance with little trade-offs.

Chapter Summary

I would like the reader to take away from this chapter that modeling can help developing insight into any relational problem. In this case, I used a queueing theory model to develop insights and test theories around the various design parameters for a factory design. The factory designer has available these compensating techniques for developing any factory, including an assembly plant:

- Reduce processing variation
- Provide excess capacity so that reduced throughput equals customer demand
- Provide decoupling buffers between processes to reduce the impact adjacent processes have on each other

I emphasize that reducing processing variation holds the most powerful leverage, because it requires no trade-offs in the investment costs of a new factory.

Chapter 7: Moving from Design to Production

At this point we have developed an Ideal State factory design from which to guide our decision-making. We are still a long way, however, from a functional production facility. In this chapter we explore the process that was used to move from the Ideal State to the final, constrained factory design as well of some of the risks involved with launching the factory without the resources to transfer the knowledge to the management team.

Utilizing what was learned to design a complete facility

The insights and direction provided in previous activities will not result in a convergent design solution. There are thousands of factors not accounted for, among the most important the specific product, site location, and budget. The group's task must then be to design a specific factory given the learning they have just achieved. This is, of course, a very iterative process, zigzagging back and forth between the actual factory design and the framework. The group, as reported, is cross-functional in order to represent various depths of expertise, all part of the same system. This will be critical as the key to implementing this factory will be in the interrelationships between different functions.

It is critical that the group has a process to manage the factory development. Without a process, the group could get distracted by irrelevant details or lose the connection between what was learned and what they are doing. There are several processes available, but utilization of the Pugh concept selection chart was used for this application.[55] The Pugh chart allows users to compare and contrast alternative design concepts, which leads to the elimination of inferior concepts and combinations of the best features of other concepts. An example of the Pugh chart used to evaluate real alternatives is shown here:

Evaluation	*Base*	*1*	*2*	*3*	*4*	*5*	*6*	*7**	*8*	*9*	*11*
DP1: Plant is broken into segments that are naturally managed by cross-functional teams.	0	0	0	0	0	0	0	0	- (a)	+ (b)	0
DP2: Training areas and team meeting areas are near production areas.	0	0	- (c)	- (c)	- (c)	-2 (c)	0	- (c)	- (c)	0	0
DP3: Management is nearby critical production areas.	0	- (d)	- (d)	- (d)	- (d)	-2 (d)	0	- (d)	- (d)	0	- (d)
DP4: Informal and formal information flows are a visually-managed systems.	0	0	- (e)	- (e)	- (e)	-2 (e)	-2 (e)	- (e)	- (e)	-2 (e)	0
DP5: Reduce container sizes.	0	0	0	- (f)	0	- (f)	- (f)	0	0	- (f)	- (f)
DP6: Able to expand capacity with minimal cost and disruption.	0	0	0	0	0	- (g)	- (g)	- (g)	0	- (g)	0
DP7: Flexible conveyor systems.	0	0	0	0	0	- (h)	0	0	- (i)	- (h)	- (I)
DP9: Plant can be expanded for second model.	0	0	0	0	0	0	- (j)	0	+ (k)	- (j)	0
DP11: Minimal travel distance from docks-to-line.	0	- (l)	- (l)	- (l)	- (l)	- (l)	- (l)	0	- (l)	0	- (l)
DP14: Minimize system lead-time.	0	- (l)	- (l)	- (l)	- (l)	- (l)	- (l)	0	- (l)	0	- (l)
DP15: Utilize modular building construction concepts.	0	0	0	0	0	- (m)	- (m)	0	0	- (m)	0
DP16: Workstation layout and size are standard / modular.	0	0	0	0	0	- (n)	- (n)	0	0	- (n)	0
Minimizes disruption to current vehicle.	0	0	0	0	0	- (o)	- (o)	0	0	- (o)	0
Minimizes people vs. truck vs. Production vehicle traffic.	0	0	0	0	0	0	0	- (p)	0	- (p)	+
Initial costs savings	0	0	+2	+1	0	+2	+1	+4	+5	+1	+5 (s)
Operating costs - material handling	0	- (q)	- (q)	- (q)	- (q)	- (q)	- (q)	0	- (q)	- (q)	- (q)
Operating costs - overhead	0	- (r)	- (r)	- (r)	- (r)	- (r)	- (r)	- (r)	- (r)	- (r)	- (r)
TOTALS, Unweighted	**0**	**-5**	**-5**	**-7**	**-7**	**-14**	**-11**	**-2**	**-3**	**-10**	**-1**

A design matrix such as the Pugh can be used by following these process steps[56]:

1. Prepare the selection matrix.
2. Rate the concepts.
3. Rank the concepts.
4. Combine and improve the concepts.
5. Select one or more concepts.
6. Reflect on the results and the process.

The same Pugh chart is shown again, complete with all footnote documentation, in Appendix D. The Pugh chart is integrated then into the brainstorming process, constantly measuring the evolution of the design concept against the designed metrics, which came from earlier lessons. Therefore, the Pugh chart controls the zigzagging between learning and action. Although the actual chosen design cannot be shown for proprietary reasons, we can show how the Pugh helped us choose alternative 11 based on the subjective weighting of the evaluation criteria. The design metrics were essentially the design parameters determined in Appendix B, plus any quantitative data that might be available.

A group is free to customize the use of the Pugh chart to their own needs. You can see from this version that we did not add weights to the factors, although group members clearly weighted some factors more heavily than others. Our reason for this was that the tool was not primarily used to decide on a direction, but to stimulate discussion into which direction would be most desirable. The result are twofold: (1) we generated a substantially amount of alternatives in a creative, non-threatening team atmosphere and (2) the creative process led to a final design which preserved the essence of the Ideal State factory design.

Why implementation is not trivial

The hand-off to plant management

The launch of a new factory or a new product can also be defined as a handing-off of responsibility from the design groups to the production groups. Understanding and utilizing the interrelationships between different functions, which was the emphasis of the plant design, is essential in making this transition to a fully implemented production system successful. If the transition is not successful, the production group will never be able to fully utilize the efforts of the design team. The emphasis here is on human infrastructure, specifically how do we prepare thousands of people who have spent careers operating one way to suddenly change and operate a different way? I do not know the answer, but I believe it lies in part in how the transition period is managed, how the people are trained, and what resources are available to them as they take over responsibility. In the remainder of this chapter I will review an example of how this hand-off in implementation can break down and limit the success of this new factory by looking at the dynamics of starting up the andon process.

An example: the dynamics of andon and its success

The andon process is dynamic in nature, affecting other variables and activities in the plant, which in return affect it. Awareness of some of this dynamic behavior will help focus attention on high-leverage variables, increasing the probability of success of andon and therefore of the overall manufacturing strategy[57].

Figure 19 will help tell a dynamic story. It is not a complete story, and is not intended to show all variables affecting and affected by other variables. Instead, the story will help us gain insight into the dynamics, providing opportunities to take high-leverage actions.

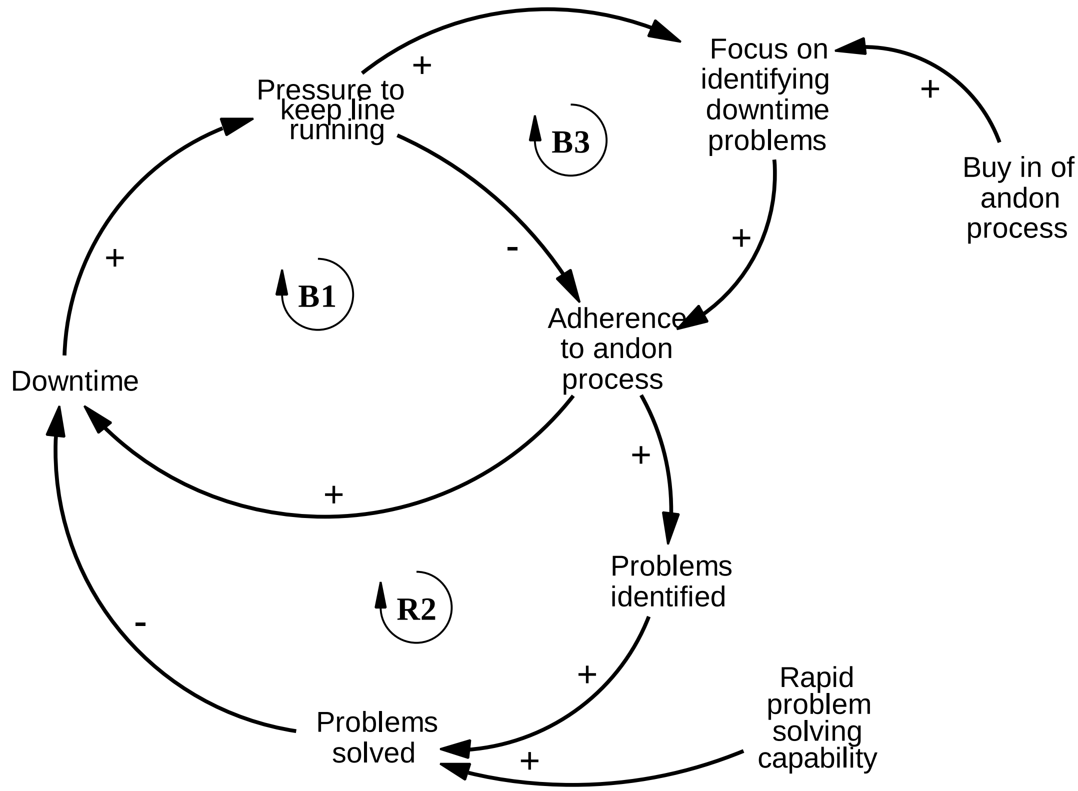


Figure 19 – This systems dynamics model captures the dynamics between andon, downtime, and human behavior. The balancing loop B1 represents the tendency for team leaders to stop using the andon the first time it increases downtime. The reinforcing loop R2 represents how andon interactions with problem solving as a mechanism to eliminate the root causes of downtime. Balancing loop B3 represents how acceptance of the andon process helps maintain its use as a problem solving mechanism and keeps downtime at a new low level.

Any manufacturing system will have an equilibrium downtime value that will not be zero. Factors affecting it include among others the age of machines, the quality of the product, and preventive maintenance adherence, but to understand the story we will hold all of these factors constant. Downtime will therefore be assumed stable under the current no-andon policy.

Pressure to stop using andon

Assume we then launch the andon process. If we consider a very short time frame, say 15 minutes or even a couple of days, downtime will increase. That is because we are now stopping the line for problems that were once fixed off-line. This extra downtime will increase pressure to reduce downtime and return to the previous equilibrium. The fastest way to do that, again in the short time frame, is to stop the andon system. The production line will then return to its previous equilibrium. This is shown in the diagram as B1, or Balancing Loop 1, which wants to keeps andon adherence at zero and downtime at its previous equilibrium value. This can also be seen as the smaller dotted line on the time graph in Figure 20. Without andon, the system is in

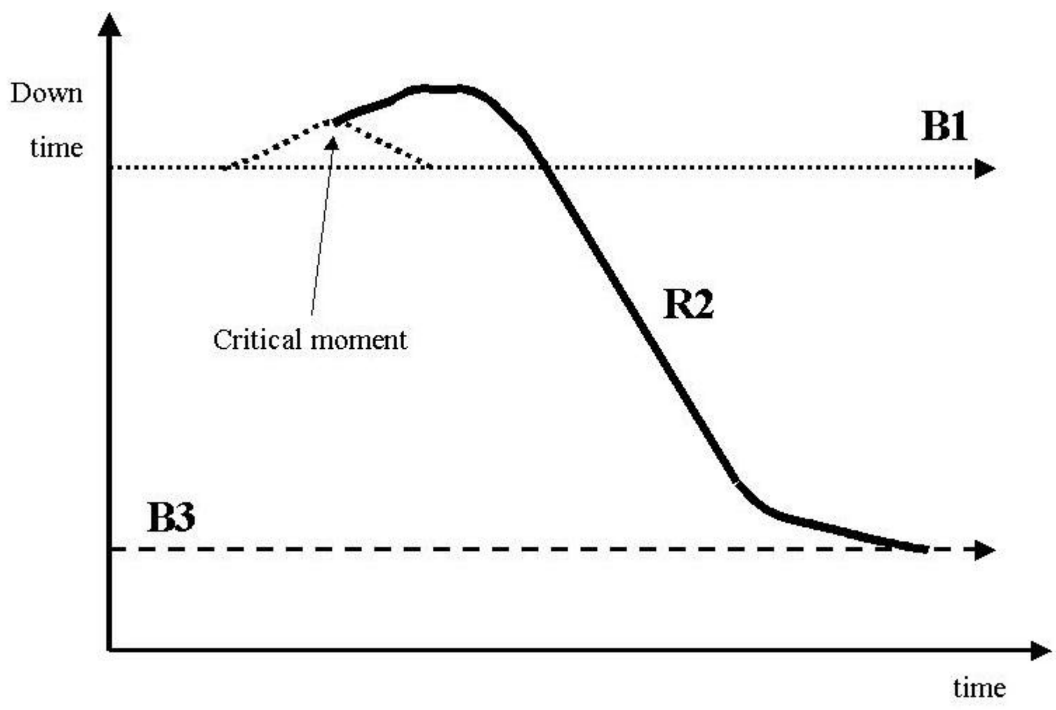


Figure 20 - The behavior over time diagram shows how the dynamics of Figure 15 affects downtime as time progresses. The two balancing loops try to maintain downtime at its current level, whether the level is at B1 under the undeveloped system or the lower downtime B3 under a developed system. R2 is how the team can transition from the old to new equilibrium.

equilibrium on line B1. Then as andon is initiated, there is upward pressure on downtime. At the 'critical moment' loop B1 is dominating and downtime returns to its previous equilibrium of B1 by eliminating the use of andon.

Adherence to andon brings success

If we adopt a longer time frame, we can see the improvement we expected when designing the andon system in R2, or Reinforcing Loop 2. Adhering to the andon process helps us identify problems, which after a delay, are solved. Because those problems no longer contribute to downtime, by themselves or through the lack of andon pulls, downtime is then reduced, pressure is alleviated, and adherence to the system is reinforced. This new effort in solving downtime related problems can be seen in the Figure 20 as the downward sloping solid line. Because there is a delay, however, before the effects of this reinforcing loop actually reduce downtime, the downtime problem gets worse before it gets better. This is because at the critical moment, the reinforcing loop is dominant, recognizing the need to wait for success to come.

New equilibrium with andon

Downtime will never be reduced to zero. There will always be problems. A new, lower downtime equilibrium will exist. This is because as downtime increases, pressure to reduce downtime increases, but now that leads to focusing on identifying downtime causes through the andon system. That only reinforces the use of the andon system, and the system will behave as designed over a long period of time. This new equilibrium is shown in B3, or Balancing Loop 3. The new equilibrium line is maintained in Figure 20. A part of the system not shown here is another balancing loop that may control the introduction of new downtime problems into the system. Recognizing this is sufficient, however, and so I choose to limit the detail of the model to the insights gained in the above description and the following review.

High-leverage management points

We understand from this story that the critical moment is just as the andon system is introduced. Will B1 dominate, keeping andon out of the factory and downtime at its old equilibrium, or will R2 and B3 dominate, making the benefits of an andon system a permanent part of the performance metrics? This will depend on the development of a few high-leverage variables. The strength of R2 will depend on two factors:

1. Developing the factory's capability in rapid problem solving.
2. Having a long-term focus, and reducing pressure to keep the line running, allowing the andon to take its roots before returning to the pressure.

The strength of B3 will depend primarily on buy-in of the value and benefit of the andon process. This will depend, in part, on training and coaching which will be discussed later in this section.

Chapter Summary

This chapter reviewed some of the challenge from moving from an Ideal State factory design to production. First, there must be a process that can help the team manage the relationship between the Ideal State and the constraints of the current real project. We used the Pugh chart to help manage bouncing between the two, but there are many alternatives. Second, there is a significant risk in launching a factory that was designed to run under a different system than current management is used to. I presented the dynamics of the andon process as an example of how the failure might take place.

The following chapter will attempt to alleviate some of this risk by managing the launch of the new factory.

Chapter 8: Balancing the Needs of Production and Learning

This chapter will review some of the challenges in launching the new factory, balancing the need to ramp-up to full volume production quickly with the need to promote learning within the factory. The chapter will also present some opportunities for managing this balance, enhancing the probability of success of the new factory and its operating system.

Learning new operating relationships

Operating in semi-autonomous teams

The new factory, as discussed in depth in earlier sections, is designed to allow the plant to be controlled by semi-autonomous operating teams consisting of operators, team leaders, and group leaders. While we will not discuss the intricacies of how teams function, we should investigate the critical interrelationships between the factory design and the team function.

Creating semi-autonomous teams was one of the primary goals of the factory design. Autonomy means freedom of choice and comes in the form of self-direction and self-control, but there are also defined limits to that freedom.[58] In the factory, we want each team in control of how their area operates, but within certain boundaries regarding both results and process. The team can choose to shut down the line to solve a quality problem, but only if they are still meeting their demand quotas. The team can choose which problems they must focus attention on, but they must follow plant guidelines regarding measuring the problem and what processes they will use to guide problem-solving. This is what I mean by semi-autonomous, because the teams have more self-direction and self-control than more traditional models, but they still must operate within certain pre-determined and communicated boundaries.

Achieving semi-autonomy is much easier in factories that have distinct, separated manufacturing processes, such as a job shop, than in an assembly plant because the assembly plant conveyor inherently makes the teams interrelated, taking away from some of their autonomy. How the assembly plant is designed, as seen in previous sections, has considerable impact on recreating that desired autonomy.

Managing the line

Assuming the factory is designed as we have designated, how will teams have to adjust their operating practices in order to successfully interface with this new technology? Here are a few factors that will be new to the team:

- *The team and team-leaders makes decisions on delivery*. Teams never had the opportunity to stop the line to fix quality in station. They will need to develop confidence and decision criteria around why and when to stop the line, and what response the team should take when it does stop. The parameters they must make these decisions within are set by other functions in the plant, and include how many they deliver each day and even in what order they are delivered.
- *The team manages interfaces upstream and downstream*. Teams never had to worry about their downstream customer because they were rarely affected by what they did. Repair workstations were periodically placed to fix problems. Now, the team has to worry about the delivery of a high-quality on-time product to the next team, and to receive one from the previous team. Managing those hand-offs will be a new variable on the plant floor.
- *The team is responsible for the performance* of the line segment, not just completing a job within a given time. That means they will need new skills in managing improvement and learning all the jobs in the area, and will be responsible for safety, quality, delivery, cost, and morale of the area, not just delivery.
- *The team*, in managing the entire line, *must take the lead in problem solving*. The best opportunity to find and solve a problem is on the production line as the problem occurs. That requires new skills for the team in identifying problems, beginning the problem solving process, and harnessing available resources in completing the implementation of a solution.

- *These line segments and buffers must be managed by quantity control*. That means that the same quantity is produced each day, and the department does not leave until that quantity is produced. It also allows departments to maintain their buffers, so that if an unusual day strips the buffers, the final line will go home and the other departments will work overtime to rebuild the buffers so that normal operating conditions can resume on the following shift.

These are things that the operating team must learn how to handle. They can not fully appreciate the difference in practice until the plant launches, but they are also expected to begin production under normal performance requirements. How the factory can handle this dilemma will be discussed in the following sections. The solution set is by no means complete, but does provide some insight into how the problem can be handled.

The launch acceleration curve

Product and process launch is a critical time for a factory. The speed with which they can get up to volume quantity and quality is the critical factor in beginning the revenue stream from selling products in the market. At the same time, the plant is learning about new processes, and in this case, an entire new factory. Taking the time to learn will ensure the long-term success of the factory in terms of safety, quality, delivery, and cost, but that may restrict the early revenue which can be critical to the long-term profitability of a product. Managing the balance between these trade-offs is not a trivial decision.

The launch acceleration curve, usually measured in days, is the rate at which the factory is required to go from the first sales vehicle to full production. MIT faculty member Marcie Tyre[59] reports on the difficulties of learning within the production environment, especially when efficiency is emphasized. She says that the cognitive processes under which individuals are able to adjust their mental models are in conflict with the automatic process of managing efficient production.

I consider this concept as two different 'rhythms' that exist within the plant, the *production rhythm* and the *learning / problem-solving rhythm*. These two rhythms are at odds with one other. The key is how to ensure both rhythms are given their required space. This will be especially true for the learning / problem-solving rhythm when a new factory with a new operating system is being launched simultaneously to the product launch.

Toyota recognizes this dilemma, although perhaps not using the same framework, and has made decisions that ensure space exist for both sets of activities. First, depending on the magnitude of the learning that will be required during launch, Toyota will slow down the launch acceleration curve. They know that if the learning isn't allowed to exist chronic problems will plague the factory for the life of its processes. An example is the recent Sienna minivan launch in Georgetown, Kentucky. The minivan was a new product for the factory used to building sedans. As a result, Toyota slowed the launch to 45 days from the 30 required for the previous Camry sedan launch[60]. This allowed Toyota operators and managers to learn how to process the minivan and to find solutions to new problems posed by minivan processing. The question then remains: how fast can Chrysler launch when they not only have to learn a new product but a new factory and operating system?

Toyota will also provide more resources to support learning. In the case of the Sienna, they began building prototypes several months before launch on the intended production line while current production was taking place. This allowed them to resolve problems in processing where the sedan and minivan processes were at odds with each other. They also spent a significant period of time visiting other minivan plants, particularly Chrysler's, in order to learn how their competitors process minivans[61].

Organizational changes

Launching organizational changes early

In order to reduce the load on the launch period, the factory can focus its efforts from now until the factory comes online on launching any organization changes that do not require the factory be built first. The following are organizational changes that will have to exist in order to make the new factory work successfully, but do not require the factory before they can be started:

- Operating in teams
- Simultaneous safety, quality, delivery, cost, and moral responsibility
- Rapid problem solving

While the system of line segments and buffers will require the plant to run with autonomous teams in the future, today's factory, or really any factory, can be run by teams. Teams will not have the magnitude of autonomy they will in the future, but they can begin exploring how their relationships, roles, and responsibilities will change as they are organized in teams.

The teams can also be given responsibility for the simultaneous improvement of safety, quality, delivery, cost, and morale. While they can not have the impact that they will when the new factory launches, they can begin understanding how they are interrelated, how to measure them, and what resources will be required to improve.

This will, in turn, require that factory resources be organized for rapid problem solving. Rapid does not mean to attack problems with band-aids, however. It will still require the teams get to the root cause of the problem. Focusing on the systematic improvement of this skill set will be critical for management when it tries to launch the new factory.

Creating space for learning

These shifts in operating patterns should occur interspersed over a period of years, following a cycle between rapid change and stabilization. This also recognizes the need to create space for both cognitive / learning rhythms and efficient / production rhythms. The need for efficient production space is key, because without it, problem identification is more difficult. As much time should be spent on problem identification as problem solving.

The reason these spaces for learning are important is that learning does not occur naturally in the production environment. Marcie Tyre[62] presents these sources of conflict:

- The direct and indirect costs of problem solving in the manufacturing environment.
- Opportunity costs associated with problem solving.
- Managerial decisions about the way production is carried out.
- Uncertainty of payoffs from problem solving.
- The cognitive demands of problem solving compared to those of 'business-as-usual.'

Creating short bursts of learning space deals with some of these conflicts in the following ways:

- Creates a time-based shift in cognitive patterns between production and learning.
- Allows a focusing and increase in resources available.

- Allows a break from on-going measures to put in more experimental, exploratory metrics.
- Allows management to 'forgive' lapses in performance, making it safe to learn and experiment.

This process of short bursts of learning while implementing organizational changes will increase the probability that these changes will take hold in the factory. Making sure these organizational changes are no longer performance gaps for the factory management will significantly ease the burden of launching a new factory and operating system.

Training

Developing training plans

Training is usually the first means considered when an organization requires new skills. Training is a very valuable use of time but often is limited to passing on information. Gathering new information will not be enough if the organization is to change, but that does not mean it is not valuable. First, we will distinguish training from coaching. Coaching will be considered later and is different in that the knowledge is more tacit where in training the knowledge can and should be made explicit. Coaching is also different because when the coaching engagement begins, the problem or need often will not be known.

Training is more important than before given the new structure of the factory. As the teams begin operating more autonomously, their capabilities must grow. Meyer concurs: "The key deliverable of team development is to increase the capability of each team to manage itself and become a learning organization."[63] We will consider two factors in the discussion on training. First, what skills and knowledge are needed and at what level of the organization. Second, how is that tied to the timing of activities and to performance.

A matrix has been developed to express the training needs to support the launch of this new plant. It not only lists a set of skills or topical areas in which training is needed, but it also describes the different levels or types of training required for each level. The training level scheme is derived from a review of types of skills and how they relate to performance in multi-skilled teams[64]. The following notation will be used, followed by the actual matrix:

◆ – Policy-setting level
❒ – Expert level
♓ – Functional level

Topic	*Plant Manager*	*Operations Manager*	*Support Staff Manager*	*Area Manager*	*Supervisor*	*Line Opera-tor*	*Skilled Trades*	*Support Staff*
Lean manufacturing	◆ ❒	◆ ❒	◆	◆ ♓	♓	♓	♓	♓
Standardized work	◆	◆		◆	❒ ♓	♓	♓	
Preventive maintenance	◆	◆	◆	♓	♓	♓	♓	♓
Andon	◆	◆		◆ ♓	♓	♓		
Rapid problem solving	◆	◆	◆	♓	♓	♓	♓	♓
Part processing	◆	◆	◆	♓	♓	♓	♓	❒
SPC	◆	◆		♓	♓	♓		❒
5 S's	◆	◆		◆ ♓	♓	♓		
Balanced scorecard and measurement	◆ ♓	◆ ♓		♓	♓	♓		❒
Kaizen or continuous improvement workshops	◆	◆ ♓		♓	❒ ♓	♓		
. . .								

To explore the distinction between the different levels, we can explore the needs of Standardized Work as an example. The policy-setting level would consider factors such as how standardized work fits into a larger system and strategy, what resources will be required to make standardized work successful, and how to recognize successful or unsuccessful standardized work. The expert level must have the capability to design, coach, and improve processes related to the topic. An expert could be someone in a line position, such as a supervisor, but often will be in a support role. The expert in standardized work should be able to design processes to support standardized work. They should be able to coach users, and take feedback from users and improve the standardized work processes. The functional level is where the policies and processes are set into motion. The team members who need only functional understanding need to know how to carry out the process as well as how that relates to the other parts of their job, but do not have to understand how it relates to strategy or policies. The team members on the line and the supervisors need to be able to analyze a work process using standardized work methods, then redesign and optimize the process. Not every team member will be required to deeply understand how the process fits into the strategy of lean manufacturing or how to redesign the process using information technology. They do need, however, to know how to relate it to the rest of their job so that they can give effective feedback to others based on what is and is not working.

As you review the chart, it will be very clear that the plant manager and his or her staff will require more of the strategic and policy-setting knowledge and supervisors and operators will require more of the functional knowledge. The part that will not be as easy to fit is who will require the expert knowledge. There may not be a clear fit, but it is a required role to be filled for the factory team. In this case, the plant must identify someone who either is or who can become the expert. It might be a supervisor who can coach other supervisors on that specific topic. It might be someone in the support staff, or it might be an external source. It does not necessarily have to be related to their position, but instead rely on balancing roles and responsibilities as well as utilizing an existing skill base. If not clear, the chart will not automatically assign an expert, but be aware of that case and make sure the expert knowledge is not missing.

Roles, responsibilities, and training

The training matrix should be very closely linked to the roles and responsibilities within the factory. One of the explicit goals of the Chrysler Operating System is to increase the clarity of roles and responsibilities in the factory, and use of the matrix can help accomplish this goal. For example, if it is the *role* of the operator to use standardized work methods, they probably only require a functional understanding of standardized work. To contrast, if it is the team leader's *responsibility* to implement standardized work and utilize it to improve the operations within their area, they may require an expert-level understanding of standardized work. This is similar to the plant manager's responsibility to implement lean manufacturing. The plant manager will then require an in-depth, expert-level understanding of lean manufacturing. The team leader's responsibility is not to implement lean manufacturing, but to play a role in doing so, and therefore only requires a functional understanding of lean manufacturing.

To further explore the distinctions between the three levels of skill and knowledge, I will examine the concerns and process involved in creating the training matrix. This matrix is not intended to be complete, and will be different for each factory depending on their needs and existing skills. Therefore, a team comprised of factory members must create their own training matrix. The three levels of knowledge must be represented in creating the matrix. The plant senior management level must be represented at the strategic level. This is to utilize knowledge of the future of the factory, its goals and plans, and an understanding of how the many levels of the plant function together. Representation of the functional level will also improve the matrix design. The functional level would be those who may be involved in conducting the training as well as those who will participate in the training, and who understand the functions of the factory floor. Again, the expert level must not be ignored. The expert level must contain expertise on the subject matter but more importantly, expertise on designing training programs. Only in all three knowledge levels being represented will an effective training matrix be complete.

Implementation of training

Implementing the training is not a trivial matter either. Who will do the training, when will it be done, and how will it relate to the on going performance of the plant are all matters that must be considered.

The first question is who will do the training. Sometimes this will relate to who is the expert. If the topic affects many different levels of the line organization, or if significant depth of understanding is required at upper levels, cascade training is a good idea. Cascade training is where the plant manager will train his staff, the staff will train the area managers, and the area managers will train the supervisors who will then train the operators. Outside trainers should only be used if the plant will not be developing expertise within their own ranks. A plant certainly does not need to develop expertise for every area, but it must carefully choose what it will not be developing expertise in.

When the training is done is also important. Training during launch is not good due to the other extreme pressures on time and attention. For physical process training, one should only wait until launch if the training must take place with an up and running process. In this case, as much training should be done before launch as possible. This pre-launch training would also be well utilized if focused on changes in operations and performance. I find that training, at least for skills difficult to establish, is most effective if presented in stages, with participants moving in and out of training and in and out of action. This allows trainees to give feedback to the trainers, and training can be adjusted for what is working and what is failing.

Tying training to action and performance can be a good step forward for an organization, but it still assumes the knowledge to be applied is known, identifiable, and pre-packaged. That will not always be the case, particularly during the depth and breadth of change required by this plan. Installing coaches into the organization will be critical to deal with the unknown training needs.

On-line coaching

The role and skill of coaching

Having coaches available for this organization will be critical to fill the following gaps:

- The gap between the goal (Toyota Production System) and current reality is significant and how to close the gap is not clear
- For individuals, what to do next will not always be clear
- For individuals, what capabilities need to be developed may not be clear
- The knowledge that needs to be captured is largely tacit
- Existing mental models block performance regardless of training

Coaches can help supplement training efforts by working with managers in the moment. They can do everything from correct simple technical misunderstandings at meetings, to helping team leaders determine when to stop the line to fix quality problems and when not to. They can also help identify gaps in performance that individuals within the system cannot identify for themselves. These roles are critical to fill when the goals are as ambitious as they are here. We will derive our coaching model from the following definition:

> *"Coaching is unlocking a person's potential to maximize their own performance. It is helping them to learn rather than teaching them."*[65]

Many people can be coaches without being experts in what they are coaching. How this is possible will be discussed later, but we do not want to ignore the value of expertise when the depth of knowledge required surpasses what could be included in off-line training. The topic required here is the Toyota Production System, which is complex in its intricacies, but simple in its tacit clarity and consistency. An understanding of the Toyota Production System deep enough to be a coach could only be acquired by working within it. Hiring former Toyota production managers to coach everyone from the plant manager to the supervisor will be a valuable resource for this plant.

As we examine the skills of a coach as determined by our definition, high-quality inquiry skills will emerge as one of the most important skills. Because our definition focuses attention on the coachee, the coach must be able to inquire into the coachee's assumptions and blocks. *The Fifth Discipline Fieldbook* presents to following protocols for inquiry[66]:

- Gently walk others down the ladder of inference and find out what data they are operating from.

- Use unaggressive language, particularly with people who are not familiar with these skills. Ask in a way that does not provoke defensiveness or 'lead the witness.'
- Draw out their reasoning. Find out as much as you can about why they are saying what they're saying.
- Explain your reasoning for inquiring, and how your inquiry relates to your own concerns, hopes, and needs.
- Test what they say by asking for broader contexts, or for examples.
- Check your understanding of what they have said.
- Listen for the new understanding they may emerge. Don't concentrate on preparing to destroy the other person's argument or promote your own agenda.

A model of partnership coaching

Careful use of the skill of inquiry often shows immediate results, but the structure of the coaching session can have a significant impact on the results. Figure 21 shows the GROW model[67] for structuring coaching sessions, which stands for Goal, Reality, Options, Wrap-up. The process is designed to be highly fluid and iterative, but generally

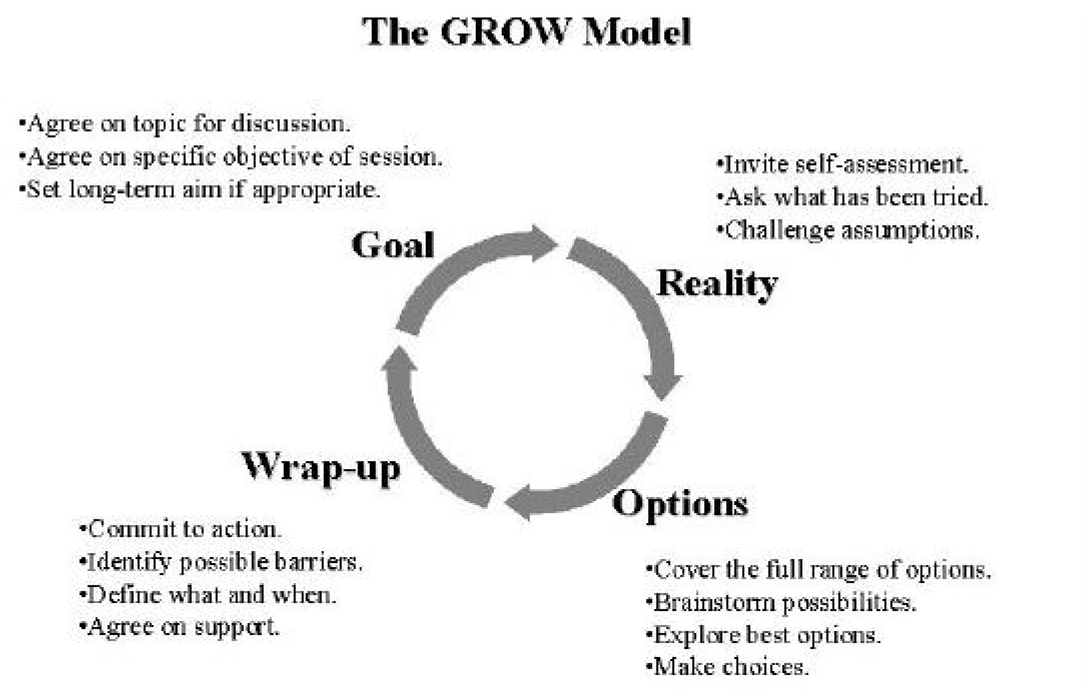


Figure 21 – The GROW partnership coaching model.

follows the process shown in Figure 21.

Coaching is a skill or topic just as standardized work, and so returning to our training matrix, it is important to have an expert on coaching available to help with those who are acting as on-line coaches. One possibility is for the plant to hire former Toyota employees for their expertise of the Toyota Production System, but before introducing them to the plant, they will be more effective having been through intensive training on their coaching skills. The GROW model is effective even if the coach is not an expert in the subject matter. The reason is the coachee is responsible for many of the factors leading to their lack of performance, especially with the difficulty in seeing current reality. The GROW model focuses on the notion that removing the coachee's internal interference, performance will immediately improve without having to gather new knowledge. This is demonstrated in the capacity model shown in Figure 22, where the capacity is measured in the ability to take effective action[68]. The coach helps the coachee remove interference by using the GROW model, increasing the individual's capacity.

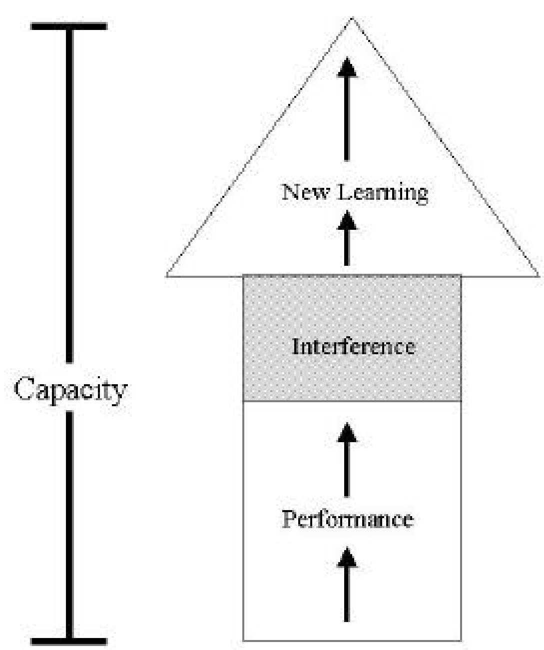


Figure 22 – The capacity model of performance improvement

This approach can then be combined with the coach's expertise, which may help in inquiring into the right topic, to help see current reality more clearly, or to help in brainstorming. Coaching in the GROW model usually starts with the coachee being frustrated, unable to get the performance or result that he or she wants. Given the unfamiliarity with the Toyota Production System, this realization may not come so easily. In this situation, the coach's role extends to before the coaching session even begins. The coach must first help to identify gaps between potential and current reality.

Finally, the better integrated the coaches can be to the organization, the better the organization will perform. Being part of the organization will help the coach identify problem areas and will make coachees more comfortable with the coach's role.

Chapter Summary

This chapter explored the difficulties of launching a factory under performance constraints while balancing the need to create space for real learning. I presented the concept of the learning rhythm at conflict with the production rhythm, and that we must create space for the learning to take place. Three possible solutions were presented as a subset from a much larger menu of possibilities. First, short burst of organizational change and learning before the plant launches will help to off-load the huge learning requirement that exists during launch. Second, the training needs must be planned, focused, and tied to the performance requirements of the teams. Third, on-line partnership coaching can help bring in needed expertise and guide team members through their own learning experiences. These opportunities can be combined with many others to tackle the daunting challenge of balancing learning with production.

Chapter 9: Summary and Conclusion

Lessons extracted from thesis research

Factory design's role in technology diffusion

I proposed in this thesis that factory design plays a very significant role in the diffusion of technology in manufacturing. The historical example provided is that it took 40 years from the installation of the electric dynamo for the electrification of factories to take place by overcoming the barriers of the mental models of factory designers as well as the tied-up investments in current plants. This lag in new factories hampered productivity growth. This lesson extends to the diffusion of effective lean manufacturing, and that a focus on factory design might be a critical missing step in realizing the gains inherent in lean manufacturing.

Systems theory in manufacturing

Great insight and leverage into manufacturing performance can be gained by viewing manufacturing as a system. As a system, the important insights are gained at the level of processes and interrelationships. Understanding how one part of the system affects another part will be critical if a manager is to construct a competitive and consistent manufacturing strategy.

This thesis only examined the interrelationships between the physical factory and the operating system, and how they both relate to learning, product, and launch activities. Establishing a physical factory system that is consistent in design with the operating system goals will enhance the performance of both activities. Establishing learning and launch activities that highlight these interrelationships will also be critical to ensuring the consistency. There are many other interrelationships that must be examined and understood that are not included in the scope of this thesis. I would also suggest that the theories of manufacturing strategy respect the systems within manufacturing and try to create more consistent decisions for manufacturing managers.

The Ideal State to guide decision-making

To diffuse a new concept into a large manufacturing organization has been the focus of a great deal of research in recent years. I propose that the Ideal State concept, inherent at Toyota and explicit at Chrysler Corporation, is one effective method of dealing with that problem. An Ideal State of manufacturing has several benefits. Two major benefits are that it moves the largely tacit understanding of manufacturing systems into a more explicit and documented body of knowledge. Perhaps the most important benefit is that it shifts the conversation from '*what* the organization should do' to '*how* it should achieve it.' This can help liberate an organization by aligning it with a common vision that is the Ideal State.

Choose an operating system that is robust to product variety

This thesis presented the argument that manufacturing is more difficult with more complexity in the product. I tried to distinguish different types of complexity, and proposed that product variety means the most to the company's competitive advantage. With increasing product variety, manufacturing performance will corrode, particularly in quality and cost metrics. The manager's choices in operating systems, however, can have a significant impact on how sensitive manufacturing is to product variety. This argument is concluded with an observation that lean manufacturing not only is more robust to product variety, but that its creation at Toyota came from a need to produce low quantities of a high variety of product.

Axiomatic design can help you shape the essence of the factory

Axiomatic design, a design process developed by MIT's Nam Suh, can help the factory design derive the physical features of the factory based on customer requirements or manufacturing principles. This process has a significant advantage in that in group design situations, it helps draw out the multi-dimensional tacit understanding of manufacturing and facilities and derive a more explicit set of relationships and design parameters. Axiomatic design helped us shape an understanding of the essence of the factory design. The essence of the factory was summarize by three principles:

1. Establishing *independent departments* with physical line segments will preserve throughput while pushing decision-making and problem solving further down the hierarchy close to the root causes of manufacturing problems.
2. *Decentralizing* essential manufacturing support activities will make them more responsive to on-going production, problem-solving, and continuous improvement activities on the assembly line.
3. *Modular, scalable, and interchangeable* physical processes, tools, and facilities will allow the facility to evolve with the roll-over of new products and continuous improvement activities without significant penalties to costs or downtime.

Utilizing a queueing model to analyze the production system

This thesis also presented the utilization of a basic queueing model to analyze production systems, particularly the application of the andon process to our factory. The queueing model provides us the opportunity to analyze relationships and push the relationships to extremes, which is not possible or is cost prohibitive in design iterations. The queueing model helps us understand throughput of any factory system by managing the trade-offs between (1) reducing individual process throughput variation, (2) establishing excess process capacity, and (3) reduction of variation interaction through buffering.

Focus on variation reduction to increase throughput

Through the use of a queueing model, I explored the trade-offs in various design parameters for factory design. Most of the parameters improved throughput significantly, but could only be used in moderation because of their significant investment costs such as additional conveyors or floor space. The model showed that variation reduction can have the same affect on improving throughput as other leverage points such as accumulating buffers, but variation reduction also requires no trade-offs with investment costs. Variation reduction will often be embedded in the skills of the factory's human resources, particularly in quick problem detection and correction. These problem-solving skills may focus on breakdowns or purchase parts quality or process variation because they all will contribute to downtime reduction under a policy of fixing quality in-station. I propose that factory management emphasize developing a skill set for variation reduction because it can contribute significantly to increasing throughput without trade-offs in the investment cost of the factory.

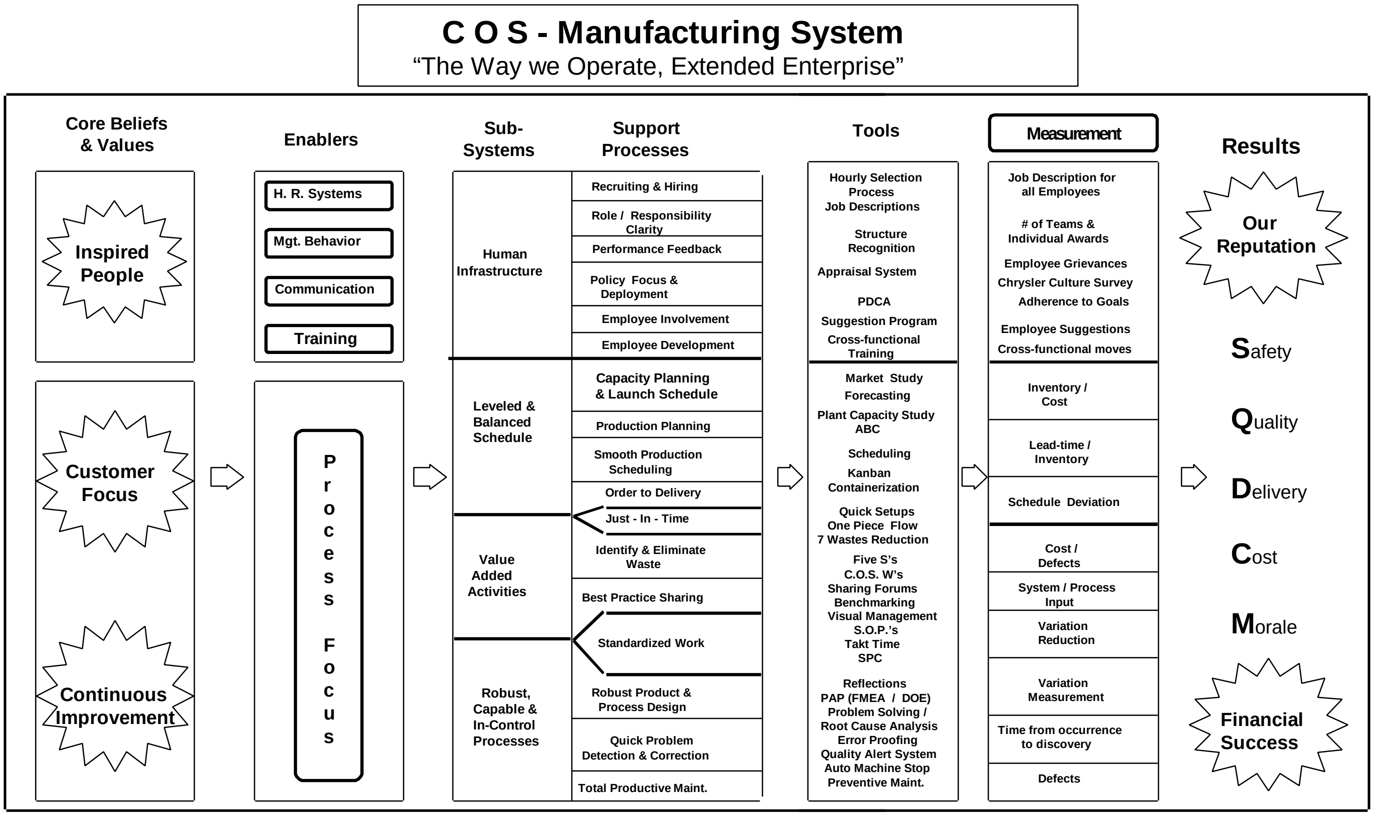
Resolving the conflict between learning and production rhythms

This thesis also presented the concept that different rhythms exist within manufacturing. One must strike a balance between the efficient, automatic *production rhythm* and the cognitive, problem-solving *learning rhythm*. Neither rhythm is more important than the other, but we must relate the balance to the needs of the individual project. We are faced with ambitious learning goals, and therefore need to think carefully about creating a safe space for learning to occur. I present three possible support-mechanisms to help support the learning needs. First, the factory can reduce the learning loaded into the launch situation by creating short burst of learning by implementing several organizational changes that complement the new factory before the launch phase begins. Second, a training plan can be developed which identifies the topical learning needs, but also distinguishes between the different knowledge levels of strategic, expert, and functional. Third, on-line partnership coaching can help identify learning needs and coach participants in their real production environment. This coaching would be designed to further develop the individuals internal capacity to perform, as opposed to teaching him or her new knowledge.

Future research

I believe the concept of factory design and its role in the diffusion of technologies such as lean manufacturing has been fairly well established in this thesis. I believe there are three areas of this research that should be extended much further. First, the thesis only examines the relationships between factory design and operating system in the context of a lean automobile assembly plant. This same relationship, in order to be better understood, must be examined in a broader context of examples, such as a craft machine tool builder or a continuous process chemical manufacturer. Second, there are many other levels of interrelationships that must be examined other than factory system and operating system. Some other examples are the interrelationships between product design and process design; product/process design and the operating system; supply chain management and the operating system; and the human infrastructure and the operating system. Developing better understandings between these many subsystems will be essential to developing cohesive strategies for manufacturing organizations. Third, I only began to explore how the organization can manage the balance between the learning and production rhythms under the pressure of launching and new factory and product. I believe more research must be done into why these two rhythms are in such conflict, and what mechanisms can be put in place to alleviate the conflict.

Appendix A – COS Framework



The Chrysler Operating System Framework shown here is a basic map from values through systems and into results. The Framework is Core Beliefs and Values that determine the Enablers, then Sub-systems, Support Processes, Tools, Measurement, and Results. There are two important points related to this map. First, it shows how lean production is much more than simply implementing a couple of tools like kanban or 5S's; it is a system of interrelationships. Second, the framework is only a beginning, a work-in-process, probably never to be completed. It's use it not to be a manual for implementing lean production, but to help users understand COS as a system and to provide a new language for that system.

Appendix B – Axiomatic Design: High-Level

The purpose of this chart is to stimulate inquiry into alternative new plant layout concepts. The structure exists to ensure there is a balanced representation of the system that is neither dominated by one component nor ignores certain components altogether. The level of the system for this set is factory system design or concept development; a derivative of this set could be developed for use in selecting individual processes. This process would usually begin with 'customer requirements'; for Chrysler's use, however, we can assume that analysis of customer requirements was considered in the design of the Chrysler Operating System Framework (Appendix A), and therefore meeting COS requirements will ensure meeting customer requirements.

HI - Human Infrastructure; L&BS - Leveled & Balanced Schedules; VAA - Value-Added Activities; RCIC - Robust, Capable, and In-Control Processes

COS Subsystem & Support Process	***Functional Requirement (FR)***	***Design Parameter (DP)***	***Process Variable***
HI - Employee involvement	Cross-functional, autonomous teams throughout the plant. (FR1)	Plant is broken into segments that are naturally managed by cross-functional teams. (DP1)	- natural team size -# of support functions that are not part of the team
HI - Employee development	Infrastructure supports training activity. (FR2)	Training areas and team meeting areas near production areas. (DP2)	-maximum distance to a training area -maximum distance to a meeting area
HI - Policy Focus & Performance Feedback	Management is available as support for production areas. (FR3)	Management is nearby critical production areas. (DP3)	-distance from administration building to body, paint, Trim/Chassis/Final final lines
HI - Performance Feedback	Performance measures are clearly owned and actionable. (FR4)	Plant is broken into segments that are naturally managed by cross-functional teams. (DP1)	-natural team size -aggregation of metrics -# of information flows

HI - Clear communication channels (role clarity and performance feedback)	Visual management techniques designed-in. (FR5)	Informal and formal information flows are a visually-managed system. (DP4)	-% of information flows presented visually
L&BS - Just-in-time	Containers can be moved at the time needed in the amount needed. (FR6)	Reduce container sizes. (DP5)	-new average container size / old average container size
L&BS - Capacity Planning: Volume Change	Plant is flexible to meet future growth in demand. (FR7)	Able to expand capacity with minimal cost and disruption. (DP6)	-investment cost -expected downtime
L&BS - Capacity Planning: Model Change	Minimize model change downtime. (FR8)	Flexible conveyor systems. (DP7)	-# of days downtime due to model change
L&BS - Capacity Planning: Multiple Models	Can run the plant with a second model with minimal impact to uptime and cost. (FR9)	Current line can run a second model. (DP8) Plant can be expanded for second line. (DP9)	-cost of adding a 2nd model / line -downtime for adding 2nd model
L&BS - Maximize potential throughput	System is robust to segment downtime and operator slow-load. (FR10)	Buffers large and frequent enough to minimize impact of downtime and slow-load. (DP10)	- system uptime / component uptime (%/%)
L&BS / VAA - Material Flow Planning	Dock-to-line material flow is short and clear. (FR11)	Minimal travel distance from docks-to-line. (DP11)	-average dock-to-line distance in feet
VAA - Eliminate waste: overproduction	Produce only the amount needed when it is needed. (FR12)	System is stopped when correct quantity is produced. (DP12)	-number of excess units that can be produced before shutting down the line
VAA - Eliminate waste: waiting	Maximize worker utilization. (FR13)	Standardized work developed for balanced line. (DP13)	-average utilization (%) -% of process w/ Standard Operating Procedures

VAA - Eliminate waste: inventory	Minimize system inventory. (FR14)	Reduce container sizes. (DP5) Minimize system lead time. (DP14)	-inventory turns at design stage
VAA - Eliminate waste: Non-standard adjustments	Building design should be easy to design, construct, and modify. (FR15)	Utilize modular building construction concepts. (DP15)	-# of non-standard bays -$/sq.ft modular / $ / sq.ft. non-modular
VAA - COS Workshops	COS Workshops support continuous elimination of waste. (FR16)	Training areas and team meeting areas near production areas. (DP2)	-number of workshops that can be supported at once
VAA / RCIC - Standardized Work	Work stations can be standardized. (FR17)	Workstation layout and size are standard / modular. (DP16)	-# of deviations
RCIC - Quick problem detection	Minimize time from defect creation to detection. (FR18)	Minimize system lead time. (DP14)	-system enter to exit time
RCIC - Robust process design	Minimize operator decisions. (FR19)	Reduce in-station complexity. (DP17)	-number of decisions within a station -total number of product permutations
RCIC - Auto machine stop	Reduce errors with machine monitoring and automatic shut-off. (FR20)	Link machine error-detection to line for automatic shut-off. (DP18)	-# of machines with autonomation controls

Appendix C – Utilizing the Axiomatic Design

This document will reference Appendix B. All Design Parameters (DPs) were derived in that document. This document demonstrates how that knowledge is utilized in the detailed design process.

Design Parameter	***COS Ideal State T/C/F Layout***
DP1: Plant is broken into segments that are naturally managed by cross-functional teams.	-provided a facility that would allow for zone control -28-33 stations per segment; less than 40 maximum originally stated as possible range -cross-functional: assembler, team leader, supervisor, maintenance (value-added people) -not certain if we meet levels above supervision; depends on management structure -no place to stack cars up; can't hide problems -might need help in how easily Final / Inspection / Certification is managed; purpose needs more clarity and agreement
DP2: Training areas and team meetings areas near production areas.	-modular areas along the side of the line -process holes -two per line right now -sizing and number depends on process and product -could simultaneously support one COS Workshop per line segment -some training in Pilot area which would be centrally located
DP3: Management is nearby critical production areas.	-use modular offices at the end of the line segment for group leader -area manager and center manager reside in centrally located office that can see all zones -maintenance manager in center office
DP4: Informal and formal information flows are a visually-managed system.	-marquee, one per line, at center of each line -control room in center of plant and near main offices -lines are straight so that you can see the marquee from any point on the line -post line specific measures in team meeting area -need to add a central area for measuring / meeting / training on continuous improvement (attendance to COS Workshops)
DP5: Reduce container sizes.	-Central Material Area (CMA) and satellite CMAs -docks near line will help reduce WIP and facilitate small containers -station layout to be driven by process, not container sizes

DP6: Able to expand capacity with minimal cost and disruption.	-final line near wall can be shared with new T/C on other side -add conveyor spurs to allow for pilots to be pulled off -start without white space; create it through CI (6% yearly task) -modular building concept is more easily expanded -depends on architecture of complex (BIW / Paint); need 3-sides of green space
DP7: Flexible conveyor systems.	-accumulating conveyors; decoupled at end of line segments -expandable in length, reconfigurable -proven technology in conveyor systems; low risk
DP8: Current line can run a second model.	-if both unit bodies, yes; same architecture -small lots should allow ample parts display -second model should share commodities (engines) -a plan should be developed to deal with this; what needs to happen, what processes need to be the same
DP9: Plant can be expanded for second production line.	-expansion can occur on the other side of fixed line
DP10: Buffers large and frequent enough to minimize impact of component downtime.	-should be expandable for Alternate Work Schedule considerations -needs to be modeled to determine optimal line length and buffer sizes -paint / trim buffer protects for: transit -TCF buffers protect for: andon pulls, automation stop-and-go, slow-loads, nearby material shortages; not for breakdowns or long material shortages
DP11: Minimal travel distance from docks-to-line.	-dedicated docks for large items -CMA for small parts -CMA is centrally located -central docks to CMA which feeds length of line -minimal travel distance to secondary storage when necessary -create plan for every part which includes distance traveled measure and flow chart
DP12: System is stopped when correct quantity is produced.	-nothing reflected in layout at this point
DP 13: All components of material movement from dock to vehicle are minimized.	-no unnecessary bending or movement by operator to reach material line side -minimized walk distance to retrieve material -efficient delivery routes based on pull system -material storage must be FIFO (to reduce time in system) -all part locations must be labeled to prevent waste searching for parts or parts getting lost; 5S's done pre-launch
DP14: Standardized work developed for balanced line.	-requires predictable / balanced schedule -man-assign according to gateline constraints -need to consider how workstation footprint will accommodate changes -concern: some pillars may limit line display on one side of the line
DP15: Minimize system lead time.	-limit what we size buffers to protect for -broadcast point is at the end of paint -Paint deals with buffers in their system; we minimize distance from end of paint - in-plant conveyor distances minimized

DP16: Utilize modular building construction concepts.	-Ideal state layout will be changed to incorporate modular bays -reduces cost of construction and future modifications
DP17: Workstation layout and size are standard / modular.	-same line drop, for example air drop and lighting -workstation size is not driven by material display requirements -workstation can only hold prescribed amount of material
DP18: Reduce in-station complexity.	-Sequential Part Delivery parts will eliminate large in-station selection -same walk point to all parts; helped by modular workstations, line balancing, and small containers
DP19: Link machine error-detection to line for automatic shut-off.	-Automatic Line Stop (ALS) linked to marquees

Appendix F – Pugh Concept Selection Chart

Evaluation	*Base*	*1*	*2*	*3*	*4*	*5*	*6*	*7**	*8*	*9*	*11*
DP1: Plant is broken into segments that are naturally managed by cross-functional teams.	0	0	0	0	0	0	0	0	- (a)	+ (b)	0
DP2: Training areas and team meeting areas are near production areas.	0	0	- (c)	- (c)	- (c)	-2 (c)	0	- (c)	- (c)	0	0
DP3: Management is nearby critical production areas.	0	- (d)	- (d)	- (d)	- (d)	-2 (d)	0	- (d)	- (d)	0	- (d)
DP4: Informal and formal information flows are a visually-managed systems.	0	0	- (e)	- (e)	- (e)	-2 (e)	-2 (e)	- (e)	- (e)	-2 (e)	0
DP5: Reduce container sizes.	0	0	0	- (f)	0	- (f)	- (f)	0	0	- (f)	- (f)
DP6: Able to expand capacity with minimal cost and disruption.	0	0	0	0	0	- (g)	- (g)	- (g)	0	- (g)	0
DP7: Flexible conveyor systems.	0	0	0	0	0	- (h)	0	0	- (i)	- (h)	- (I)
DP9: Plant can be expanded for second model.	0	0	0	0	0	0	- (j)	0	+ (k)	- (j)	0
DP11: Minimal travel distance from docks-to-line.	0	- (l)	- (l)	- (l)	- (l)	- (l)	- (l)	0	- (l)	0	- (l)
DP14: Minimize system lead-time.	0	- (l)	- (l)	- (l)	- (l)	- (l)	- (l)	0	- (l)	0	- (l)
DP15: Utilize modular building construction concepts.	0	0	0	0	0	- (m)	- (m)	0	0	- (m)	0
DP16: Workstation layout and size are standard / modular.	0	0	0	0	0	- (n)	- (n)	0	0	- (n)	0
Minimizes disruption to current vehicle.	0	0	0	0	0	- (o)	- (o)	0	0	- (o)	0
Minimizes people vs. truck vs. Production vehicle traffic.	0	0	0	0	0	0	0	- (p)	0	- (p)	+
Initial costs savings	0	0	+2	+1	0	+2	+1	+4	+5	+1	+5 (s)
Operating costs - material handling	0	- (q)	- (q)	- (q)	- (q)	- (q)	- (q)	0	- (q)	- (q)	- (q)
Operating costs - overhead	0	- (r)	- (r)	- (r)	- (r)	- (r)	- (r)	- (r)	- (r)	- (r)	- (r)
TOTALS, Unweighted	**0**	**-5**	**-5**	**-7**	**-7**	**-14**	**-11**	**-2**	**-3**	**-10**	**-1**

* - Not feasible on site.

(a) Longer line segments have a greater negative impact on plant throughput when a single station is shut down.
(b) Shorter lines facilitate shutting down the line to address quality in-station.
(c) Having team meeting and management areas in two different buildings makes management more difficult. The more operations are separated the worse the situation.
(d) Managing operations in two different buildings is more difficult than one building.
(e) The more marquees that can not be seen from a 2^{nd}-floor Center Office, visual management will be harder.
(f) Extra space in existing building may provide access for Integrated Logistics Center (ILC) activities, helping to reduce container sizes on line.
(g) More difficult to extent line segments.
(h) Closed-end line segments in existing building are more difficult to add buffers or expand.
(i) Longer line segments are more difficult to expand without having a negative impact on quality or throughput.
(j) Limited areas to put additional production facilities considering traffic patterns and existing vehicle
(k) Leaves more room to the north for expansion.
(l) WIP amounts are driven by building configuration, not sized by analysis and design. This applies to both vehicle and subassemblies such as engine or tire & wheel.
(m) The more operations are in existing building, the more difficult and expensive future modifications will be without utilizing the modular building concept.
(n) Smaller bays in existing building than in new construction makes maintaining standard workstations more difficult.
(o) More construction in or to existing building will have a greater impact on existing operations.
(p) New building up against existing building leaves little room for truck traffic, and makes production vehicle and people traffic more difficult.
(q) Inefficiencies driven by using existing building facilities (aisles, docks, etc.).
(r) Cost of patching in systems to existing building (MIS, etc.) plus excess work of support staff working between two buildings.
(s) Estimated as same as Proposal #8.

Notes

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[1] For a study on the electric dynamo and its impact on factory, see David, Paul A. 'The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox.' *American Economic Review*, Vol. 80(2), 1990, pp. 355-361.

[2] Nathan Rosenberg's writing has had a significant impact on my thinking of technology development and diffusion. For an excellent review on the barriers of technological diffusion, see Rosenberg, Nathan. *Uncertainty and Technological Change.* Prepared for the Conference on Growth and Development: The Economics of the 21st Century, organized by the Center for Economic Policy Research of Stanford University, June 3-4, 1994.

[3] For a review of systems theory see F. Capra's *The Web of Life* or *The Turning Point*. These works follow the development of systems theory from the turn of the century and through the fundamental sciences such as biology, physics, and mathematics.

[4] For more explanation on this, see Senge, Peter. *The Fifth Discipline: The Art and Practice of the Learning Organization*. Doubleday-Currency, 1990 or Senge, Peter; Kleiner, Art; Roberts, Charlotte; Ross, Richard; and Smith, Bryan. *The Fifth Discipline Fieldbook: Strategies and Tools for Building a Learning Organization*. Currency Doubleday, 1994.

[5] Again, see F. Capra's *The Web of Life*, 1997.

[6] For a review of modeling and systems dynamics for business see Jay Forrester's *Industrial Dynamics*, Productivity Press, 1964.

[7] For a review of the development of the Toyota Production System and how it relates to an understanding of systems, see the text written by the system's founder: Ohno, Taiichi. *Toyota Production System: Beyond Large-Scale Production.* Productivity Press, 1988.

[8] Skinner, Wickham. "Manufacturing: Missing Link in Corporate Strategy." *Harvard Business Review*, Issue 3, 1969, pp. 136-144.

[9] Hayes, Robert H., and Wheelwright, Steven C. *Restoring Our Competitive Edge: Competing Through Manufacturing.* John Wiley & Sons, Inc., 1984.

[10] Miltenburg, John. *Manufacturing Strategy: How to Formulate and Implement a Winning Plan*. Productivity Press, 1995.

[11] Hayes, Robert, and Wheelwright, Steven. *Restoring Our Competitive Edge: Competing Through Manufacturing.* John Wiley & Sons, 1984.

[12] Kowalski, Joseph S. *An Evaluation of the Design of Manufacturing Measurables for the Ford Production System*. MIT LFM Thesis, 1996.

[13] *Lean Manufacturing: A GM Perspective.* A presentation at the 2nd Annual Conference on Lean Manufacturing at the University of Michigan, May 14-15, 1996.

[14] While working at Harley-Davidson in 1992, I was working in their Material-As-Needed system, which is based on lean just-in-time principles. Harley learned most of what it knows about lean manufacturing from Honda's U.S.-based plants, and Honda had learned it from Toyota.

[15] Vasilash, Gary. 'Lean – and Beyond.' *Automotive Production.* January, 1996, pp. 60-63.

[16] The Texas Instruments example is from 'JIT and Lean Production' in *Production*, August, 1995 by William Congdon and Robert Rapone. Congdon is the Operations Manager, Precision Controls Department, Materials and Controls Group for Texas Instruments. The Alcoa example is in reference to the Alcoa Business System, or ABS, which was started after a benchmarking tour which included Chrysler Corporation's COS. I learned about it at a presentation to MIT at Alcoa in January, 1997. The United Electric example is from United Electric Controls, Harvard Business School case N9-697-006, December 19, 1996. The case was prepared by Professors Jody Hoffer Gittell and Kent Bowen and Research Associate Sylvie Rychebusch.

[17] Green, Jeff. 'One Line at a Time: Chrysler's Operating System must capture workers' hearts and minds.' *Ward's Auto World.* August, 1997, pp. 32-33.

[18] Teamwork v team work. Team work is work that a team must accomplish. Teamwork, on the other hand, is the ability of team members to reinforce and support each others' tasks, which is exemplified through attributes such as trust and open communication.

[19] Takt time is roughly calculated as the available time in a day divided by the daily demand. Takt time is the pace at which all production activities are determined. It can be adjusted based on factors such as expected downtime.

[20] For a simple review of the seven wastes, see Suzaki, Kiyoshi. *The New Manufacturing Challenge: Techniques for Continuous Improvement.* The Free Press, 1987.

[21] Kaizen is a Japanese term that means continuous improvement. In Japan, it can show up in many ways, from QC circles to Total Productive Management. It involves workers and management, it involves groups and individuals, and it always involves a designed process. In North America, however, the kaizen workshop is the most practiced under the kaizen umbrella. It is often a 4-5 day workshop bringing people together to eliminate waste. For more on the history and practice of kaizen in North America, see Jeanne Lee Goehle-Sternbergh's MIT Management of Technology thesis, *Episodic Kaizen: A Temporal-Based Approach to Manufacturing System Improvement*, May 1995. For more on kaizen as a concept and a process, see Imai, Masaaki. *Kaizen: The Key to Japan's Competitive Success.* McGraw Hill, 1986.

[22] *Kanban* – Kanban is a material control system commonly confused with Just-in-Time or the Toyota Production System. Kanban is one tool utilized by the Toyota Production System. Signals, or kanbans, control production and material movement. When a downstream process uses a batch of material, it sends a signal to an upstream process that triggers production of that part. The upstream process may not start production until signal, thus controlling the level of inventory and contributing to the Just-in-Time philosophy of the Toyota Production System. The frequency of signals and the batch size are critical variables in this system. Attempting to increase the frequency and decrease the batch size will bring the process towards its goal of one-piece-flow.

[23] The Learning Laboratory Line (LLL) is similar to the learning lab concept developed by MIT's Center for Organizational Learning. The LLL is a chance for managers to experiment in a situation that is similar in its complexity to real life situations but does not have the risk associated with a full factory nor the time lags with a full-scale roll-out. The LLL provides managers with real-time feedback and learning opportunities in how to implement lean manufacturing.

[24] The Balanced Scorecard is a tool utilized within COS. On the plant floor, the scorecard balances metrics of safety, quality, delivery, cost, and morale. It also tries to utilize process-driven metrics as opposed to output-driven metrics.

[25] Ideally, AME will never be relieved of responsibility, but will shift to a support function in the continuous improvement of existing manufacturing processes. This is how Toyota operates. While Chrysler's current state is perhaps somewhere in between, in spirit the design is much closer to the situation described here. This is one of many dimensions that Chrysler is trying to improve upon.

[26] Hayes, Robert, and Wheelwright, Steven. *Restoring Our Competitive Edge: Competing Through Manufacturing.* John Wiley & Sons, 1984.

[27] Fonte, William G. *A De-Proliferation Methodology for the Automotive Industry*. MIT LFM Thesis, 1994.

[28] The remainder of this section is devoted to the relationship between manufacturing and complexity. For a review of product variety in light of market strategies, human infrastructure, and product cost structures, see Fisher, Marshall; Jain, Anjani; and MacDuffie, John Paul. *Strategies for Product Variety: Lessons from the Auto Industry.* Massachusetts Institute of Technology, International Motor Vehicle Program, June 1994.

[29] This relationship is from an example in Steven C. Wheelwright and Kim B. Clark's *Revolutionizing Product Development: Quantum Leaps in Speed, Efficiency, and Quality* (Free Press, 1992). Wheelwright and Clark study two real companies, neither of which are in the automotive industry, over a period of time. Their research shows that (1) there is a positive relationship between complexity and

falling quality for both companies but (2) for the more robust production system, as complexity increased the gap between the performances of the two companies widened providing a competitive advantage for the more robust production system.

[30] This is a commonly misunderstood word about Toyota. Because standardized work is a strong component of the Toyota Production System, people often extrapolate the word 'standardized' to apply to the product, believing that Toyota builds closer to the Henry Ford model of 'you can have any color you want as long as it's black.' This is opposite from the intended design and strategic direction of the Toyota Production System. The Toyota Production System is designed to be robust against high product variety, in part due to market conditions for the company while the system was evolving. Evidence of this can be found in Ohno, Taiichi. *Toyota Production System: Beyond Large-Scale Production*. Productivity Press, 1988; Suzaki, Kiyoshi. *The New Manufacturing Challenge: Techniques for Continuous Improvement*. The Free Press, 1987; and Womack, James P., Jones, Daniel T., and Roos, Daniel. *The Machine That Changed The World.* Rawson Associates, 1990.

[31] For a review of the product / process relationship matrix, see Hayes, Robert, and Wheelwright, Steven. *Restoring Our Competitive Edge: Competing Through Manufacturing*. John Wiley & Sons, 1984

[32] With Toyota, we are discussing product mix flexibility. I would like to be careful about this. Flexibility can and does come in many forms, among them flexibility in mix, volume, new products, and delivery time. This framework and its implication for performance is presented in *Flexibility and Performance: A Literature Critique and Strategic Framework* by Suarez, Fernando F.; Cusumano Michael A.; and Fine Charles H. (Massachusetts Institute of Technology, International Motor Vehicle Program, November 1991). I bring this point up because I believe the impact of product variety and other forms of complexity on manufacturing, and the issue of how manufacturing should deal with it, deserves considerable more research and thought.

[33] For a detailed review of axiomatic design, see Suh, Nam P. *The Principles of Design*. New York, Oxford University Press, 1990.

[34] Hayes, Robert, and Wheelwright, Steven. *Restoring Our Competitive Edge: Competing Through Manufacturing.* John Wiley & Sons, 1984.

[35] From a talk on axiomatic design given by Nam Suh at MIT.

[36] Ikujiro Nonaka and Hirotaka Takeuchi explore the concept, process, and management of knowledge creation, converting tacit knowledge into explicit knowledge, in their 1995 book *The Knowledge-Creating Company: How Japanese Companies Create the Dynamics of Innovation* (Oxford University Press).

[37] For a classic journal article on product architecture, see MIT's Karl Ulrich, 'The role of product architecture in the manufacturing firm.' *Research Policy* 24. 1995, pp. 419-440.

[38] This document was created in cooperation with LFM Fellow Ryan Blanchette, Class of 1998. An additional benefit of working with this model is the quantity and quality of inquiry into the relationships which comprise the system. This level of conversation was very valuable in deepening our intuition and understanding of the Chrysler Operating System and the Toyota Production System.

[39] Relationship such as these may appear forced to the reader. It should be noted that when the design parameter looks exactly like the functional requirement, it is a sign that the parameter must be broken down into lower level components. This is, however, largely to the discretion of the designer.

[40] For a review of David Cochran's research or information on contacting him, see his web page at me.mit.edu/people/dcochran.html

[41] Toyota hierarchy: Toyota is run with a hierarchy that starts with two union jobs, the line operator and the team leader. The team leader may support around 8 line operators. A group leader will support 3-4 team leaders. Group leaders will report to the head of the operations who reports to the plant manager.

[42] This data is taken from the case study Mishina, Kazuhiro. *Toyota Motor Manufacturing, U.S.A., Inc.* Harvard Business School Case 9-693-019, September 5, 1995 and confirmed with conversations from ex-managers from Toyota.

[43] For more explanation and proof of this relationship, including a simple simulation, see Jud Graham's MIT LFM Thesis, 1998, forthcoming.

[44] WIP stands for Work-in-process, and represents all of the inventory from the factory's raw material to the factory's finished product. In our case of a vehicle assembly plant, it would represent all inventory from the sheet metal being assembled into a vehicle body through final inspection.

[45] It is not essential in making my point, but to be careful for modeling, the values for theoretical component capacity can be looked at either as the bottleneck process capacity or assuming that all processes have equal capacities.

[46] For a compare and contrast review between simulation and analytic models, see Strosser, Catherine M. *Diagnosis of Production Shortfall in a Transfer Line by Means of Analytic and Simulation Methods*. MIT LFM Thesis, 1991. An additional point to consider is how simulation would be used even though it will not be here. Because simulation can absorb large amounts of data, probably more than the modelers can gather, does not mean all the data must be used. A simulation that includes every downtime profile, every inch of conveyor, every drive speed, will overwhelm the decision maker with so much complexity that the model will be useless if the goal is to gain insight into relationships. If the goal is deepening understanding, consider the simplest simulation first, and only add layers after lessons are extracted from the simple model.

[47] An early use of queueing models to explore a serial production line can be found in the work by Gordon C. Hunt for a thesis in Mechanical Engineering at MIT, explained in 'Sequential Arrays of Waiting Lines.' *Operations Research*, December, 1956, pp. 674-683. There was a significant evolution to this work by Frederick S. Hillier and Ronald W. Boling. An example of their work can be found in an article by the authors, 'The Effect of Some Design Factors on the Efficiency of Production Lines with Variable Operation Times.' *Journal of Industrial Engineering*, 17(12), 1966, pp. 651-658. I believe the work in this thesis takes the use of queueing models for production lines a significant step closer towards a useful tool for factory designers.

[48] This model was developed in large part due to the work of Sean Willems, Ph.D. MIT with guidance from MIT Professor Steve Graves. An Excel version of the model can be requested by sending email to lfmrq3-www@mit.edu.

[49] For an explanation of queueing theory, notation, or proofs of the equations, see either Hopp, Wallace J., and Spearman, Mark L. *Factory Physics: Foundations of Manufacturing Management*. Irwin, 1996 or Nahmias, Steven. *Production and Operations Analysis*. Irwin, 1993.

[50] I developed this deeper understanding of takt time mathematics through conversations with Mark Tussey, a former Toyota manager, who now consults through RWD in Maryland.

[51] This means that if the correct buffer size would be 10, the model may return 8 or 12 and is therefore not exact. It will not, however, return answers orders-of-magnitude off such as 100.

[52] Included with this analysis was a detailed cost analysis of each design alternative. Discussion of investment cost carry heavy weight, but cost data is considered proprietary and therefore is not included in this thesis.

[53] Toyota's assembly plants, like most automotive companies, are divided into trim, chassis, and final departments. This means that each department may run at a different speed. Final, at the end, would be the slowest. Chassis and trim would be incrementally faster. Within each department, there will still be line segments and buffers.

[54] I have checked this insight with many ex-Toyota managers and engineers. Toyota emphasizes their problem solving and variation reduction capabilities for exactly this reason.

[55] For further information on Pugh concept selection charts, such as alternative processes for using them or how they are integrated into the broader picture of product/process development, see Ulrich, Karl T., and Eppinger, Steven D. *Product Design and Development*. McGraw-Hill, 1995. The origins of the Pugh concept can be found in Stuart Pugh's *Total Design*. Addison-Wesley, 1990.

[56] From Ulrich and Eppinger's *Product Design and Development*.

[57] For more in-depth research of understanding the dynamics of improvement programs in the manufacturing environment, see the research of MIT's Nelson Reppenning and John Sterman. Some examples of the work include Reppenning, Nelson P., and Sterman, John D. *Getting Quality the Old-Fashioned Way: Self-Confirming Attributions in the Dynamics of Process Improvement*, Sloan School of Management, Systems Dynamics Program, April 1997; and Sterman, John; Reppenning, Nelson; and Kofman, Fred. *Unanticipated Side Effects of Successful Quality Programs: Exploring a Paradox of Organizational Improvement.* Sloan School of Management, Systems Dynamics Program, August 1994.

[58] Klein, Janice A. 'A Reexamination of Autonomy in Light of New Manufacturing Processes.' *Human Relations.* Vol. 44, No. 1, 1991, pp. 21-38.

[59] Tyre, Marcie J. *Managing Innovation in the Manufacturing Environment: Creating Forums for Change on the Factory Floor*. MIT Working Paper #3005-89-BPS. December, 1989.

[60] See Flinchbaugh, Jamie. *Launch Plan and Review.* Chrysler Corporation. November, 1997.

[61] For specifics on Sienna, see previous listing. For a more generic and in-depth review of how industry leaders Toyota and Honda prepare to launch vehicles and the reasons behind their success, see Clark, Kim B., and Fujimoto, Takahiro. *Product Development Performance: Strategy, Organization, and Management in the World Auto Industry*. Harvard Business School Press, 1991.

[62] Much of the exploration into the topic of learning in a production environment, its pitfalls and solutions, took place with the help and guidance of MIT's Marcie Tyre, both in readings and in conversation. For further reading on this subject, see Tyre, Marcie J. *Managing Innovation in the Manufacturing Environment: Creating Forums for Change on the Factory Floor*. MIT Working Paper #3005-89-BPS. December, 1989; Tyre, Marcie J., and Hauptman, Oscar. 'Effectiveness of Organizational Responses to Technological Change in the Production Process.' *Organizational Science*. August, 1992, pp. 301-320; Tyre, Marcie J., and Orlikowski, Wanda J. 'Exploiting Opportunities for Technological Improvement in Organizations.' *Sloan Management Review*, Fall 1993, pp. 13-26; Tyre, Marcie J., Leslie Perlow, Nancy Staudenmayer, and Christina Wasson. 'Time as a Trigger for Organizational Change.' *MIT*

Working Paper #157-97. August 1996; and Tyre, Marcie J. and von Hippel, Eric. 'The Situated Nature of Adaptive Learning in Organizations.' *Organizational Science*. January-February 1997, pp. 71-83.

[63] Meyer, Christopher. *Fast Cycle Time: How to Align Purpose, Strategy, and Structure for Speed*. The Free Press, 1993.

[64] This training level scheme was derived from a review of different types of skills and knowledge in Klein, Janice A. 'Maintaining Expertise in Multi-Skilled Teams.' *Advances in Interdisciplinary Studies of Work Teams*, Volume 1, 1994, pp. 145-165.

[65] Whitmore, John. *Coaching for Performance: A Practical Guide to Growing Your Own Skills*. Nicholas Brealey Publishing, 1992. Whitmore's business coaching model is based on individual coaching work for sports developed by Tim Gallwey whose books include *Inner Skiing*, *The Inner Game of Golf*, and *The Inner Game of Tennis*.

[66] Senge, Peter; Kleiner, Art; Roberts, Charlotte; Ross, Richard; and Smith, Bryan. *The Fifth Discipline Fieldbook: Strategies and Tools for Building a Learning Organization*. Currency Doubleday, 1994. While here we are focused on inquiry, good inquiry must be balanced by good advocacy. Good advocacy is not being a good 'salesman.' Instead, just as good inquiry helps you uncover the mental models behind the other persons reasoning, good advocacy will allow you to expose your mental models to others. Good advocacy on your part promotes good inquiry from others.

[67] Model is derived from two very similar GROW models. One is from Rebecca Bivens and John Whitemore. Bivens is a corporate coach focusing on partnership coaching. Rebecca Bivens can be reached at Beckcoach@aol.com. The other version is documented from Landsberg, Max. *The Tao of Coaching: Boost Your Effectiveness by Inspiring Those Around You.* Knowledge Exchange, 1997.

[68] Both the GROW model and the Capacity model are derived from the work of Tim Gallwey. See Gallwey, Tim. 'The Inner Game of Work: Building Capability in the Workplace.' *The Systems Thinker*. Volume 8, Number 6, August 1997, pp. 1-5.