A Framework For A Strategy Driven Manufacturing System Design In An Aerospace Environment – Design Beyond Factory Floor

by

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Submitted to the Department of Aeronautics and Astronautics
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ABSTRACT

Aerospace industry is approaching a phase where the manufacturing excellence seems to hold the strongest competitive advantage instead of the design excellence. This trend emphasizes the urgent need for cost minimization and focus on process improvements rather than on perfecting existing designs. Most of the aerospace companies have already invested heavily in process improvements using various tools from the Toyota Production System. It is becoming evident, however, that the existing manufacturing systems were not initially designed to account for this phase. As a result, most of the manufacturers are not in a position to take full advantage of the opportunity by competing through manufacturing excellence. The manufacturing system design framework presented here provides guidelines for designing future systems and emphasizes the need to adapt to changing business needs of the industry. The framework also describes the scope of the manufacturing system design activity based on information gathered from observations of existing facilities and discussions with industry practitioners. Based on this framework, a manufacturing system design process is also developed. Both, the framework and the process, advocate systems approach to design and improvement activities, show that the manufacturing system design extends beyond the factory floor, emphasize that the manufacturing system design should be based on a long-term strategy, provide appropriate tools for each of the steps and stress the need for continuous improvement. The framework also represents the manufacturing system design activities currently in progress in the industry and hence provides a way to gauge the extent of ones efforts in the big picture of manufacturing system design.

Thesis Supervisor: Timothy G. Gutowski
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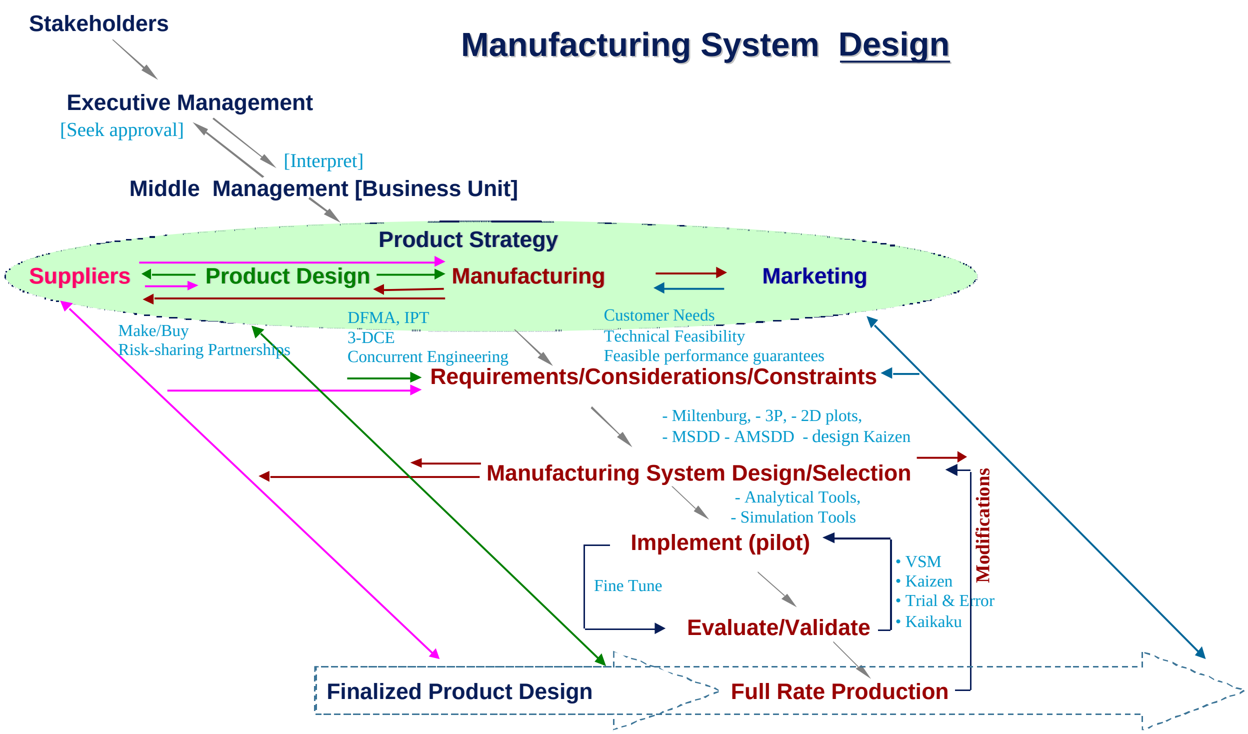
EXECUTIVE SUMMARY

Since the end of the cold war, the defense aerospace contractors and the commercial aerospace manufacturers are focusing on product affordability as well as best life cycle value. The aerospace industry as a whole appears to be approaching a phase where the manufacturing excellence seems to hold the strongest competitive advantage instead of design excellence. This trend emphasizes the urgent need for cost minimization and focus on process improvements rather perfecting existing product designs. Most of the aerospace companies have already invested heavily in process improvements using various tools from the Toyota Production System. It is becoming evident, however, that the existing manufacturing systems were not initially designed to provide the manufacturing capability needed in this phase. The companies with already "mature" manufacturing capabilities are benefiting from this situation compared to the ones who are struggling to catch up. The current challenge should be an incentive enough to start preparing for the next such phase in the industry dynamics.

In this thesis, the manufacturing capability is treated as a strong competitive weapon. To structure the manufacturing system as a competitive advantage, it is recommended that the manufacturing system must be based on a long-term strategy. Two closely related options to achieve this level of manufacturing capability are discussed. First, it is recommended that, given the opportunity, a new manufacturing system should be <u>designed</u> with considerations to the changing business needs of different phases of the industry life cycle. Second, the existing and the new manufacturing systems should be continuously improved to build capability to compete in the future. While designing a new manufacturing system or redesigning an existing system might be the fastest way to structure manufacturing as a competitive advantage, this might not be possible due to business consequences. However, the second option of continuously improving the system to attain the capability needed in the future is entirely practical and should be highly considered. Thus, the system is continuously adapted to the meet the present business needs of the industry. Therefore, the design of a new system or the modification of an existing system should be based on specific goals (a strategy) to help succeed in the future.

The scope of manufacturing system design is presented in the form of a framework. A design process is also presented based on this framework. The framework is an excellent visual tool to understand the extent of the manufacturing system and its importance to the corporation in achieving corporate objectives. Because of the impact the manufacturing capability has on the success of the corporation, it is important to recognize that the manufacturing system is larger than a factory and the system design process extends beyond the factory floor. The framework clearly shows this view by representing the stakeholders, executive management, and middle management, product designers, suppliers, marketing and factory floor as part of the design environment. The framework emphasizes holistic thinking by supporting system level design and system level improvements as opposed to local improvements.

The system design is explored in terms of infrastructural design (decision and strategy components) and structural design (detailed factory floor design). The structural design begins only after a ***Product Strategy*** has been formulated, which indicates completion of the infrastructural design. A product strategy is a plan where all of the core competencies of a company work collaboratively to offer the best solution possible. The major components of this strategy are product design, manufacturing, suppliers, and marketing. The strategy also reflects the needs of the corporation and provides a long-term plan for the manufacturing organization. ***It stressed here that the manufacturing system should be designed based on a strategy and not just on a product design since the product is just one part of the product strategy***. The product strategy should take into account the dynamics of product lifecycle and industry life cycle such that the manufacturing system can be designed to adapt to these dynamics. This continuous adaptation in the form of continuous improvements to build manufacturing capability for the future is also emphasized in the framework. The framework is a tool of many tools. It recommends use of existing strategy concepts and manufacturing system design tools where they can make a meaningful contribution. A manufacturing system design process is recommended based on the insights gained during the framework development exercise. The process not only provides a way to think about manufacturing system design but also serves as a quick guide to understand the scope of the design. The framework is shown below:



ACKNOWLEDGEMENTS

Working at the Lean Aerospace Initiative (LAI) has been a very rewarding experience for me. I am very grateful to LAI for providing me with the funding and an opportunity to study the topic of my interest. The LAI researchers, professors, team leads and the industry practitioners have been a great resource. LAI is the best place to prepare a graduate student for the real world.

I would like to thank my entire research team. This work would not have been possible without their support, experience and contribution. Special thanks are in order for Tom Shields, the team lead, for trusting me with this very broad and challenging research topic. His open door policy, laid back nature, and respect for my thoughts and ideas allowed me to think freely and contribute willingly to LAI. I would also like to thank my thesis advisor Prof. Gutowski for trusting my ability to think independently and providing me with appropriate feedback when needed. I would also like to thank Stan Gershwin for his very thought provoking questions and to-the-point feedback during research meetings. These questions helped think twice as deeply about what I was presenting. I would also like to thank my fellow research assistants, Mandy Vaughn and Rhonda Salzman for their contribution to the research, moral support, direct feedback and thoughtful questions.

My experience at MIT has been very fulfilling in many different dimensions besides education. The most important of all is the spiritual dimension. I have grown closer to God and have come to accept that I can not do anything without His will and whatever I have accomplished so far in my life has been through His provision. Thank you Lord Jesus Christ for my success at MIT and always providing for me. Meg, thanks for bringing me dinners and wanting to help me with my thesis. Michelle, thanks for all the thought provoking questions and prayers. Aaron, thanks for my first Bible and putting up with me for two years. Daniel, thanks for the accountability and I hope we find a truly competitive volleyball team when we get to our respective jobs.

"Trust in the LORD with all your heart,

And lean not on your own understanding;

In all your ways acknowledge Him,

And He shall direct your paths." – Proverbs 3:5-6

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1 INTRODUCTION

1.1 OVERVIEW

A framework describing the manufacturing system design process in an aerospace environment is developed. This work was conducted by the manufacturing systems team of Lean Aerospace Initiative (LAI). Manufacturing systems team has been conducting research in manufacturing systems related topics for over nine years. The team focused its efforts on understanding the manufacturing operation in a systems context and developing a good knowledge base for future reference. The work presented here is exploratory in nature and provides a basis for further research to be conducted by the team. The framework presented here is meant to provide a good understanding of the scope of manufacturing system design and the importance of a manufacturing system for the long-term success of a corporation.

1.2 MANUFACTURING SYSTEMS TEAM AND LAI

The work presented here represents only a part of the research conducted by the manufacturing systems team of the Lean Aerospace Initiative (LAI) at MIT. The LAI is in the third, three-year phase and the manufacturing system team has been conducting valuable research in aerospace manufacturing throughout these three phases. In phase I, the team was called the ***factory operations***. The name itself indicates the narrow focus on the factory operations. The research involved industry-wide surveys, case studies to understand what was possible. The results were used to influence management decisions. The second phase involved field research for detailed understanding of specific areas. Subsequently the following topics were explored:

- What enables factory operations to reduce product cycle times?
- Understand the what's and the how's of lean systems
- Production control in complex factory systems

From the results and experience from the past two phases, it became more and more apparent that a manufacturing system is larger than just a factory. This realization set the foundation for transition to approaching manufacturing from a systems perspective. The team name was changed to ***manufacturing systems*** to emphasize this change in team objectives. Phase three research started with the following results from phase two:

- Implementation strategies for different manufacturing systems can be very different
- Aerospace products are complex and require special considerations
- Aerospace manufacturing processes are less predictable than other industries
- Incremental changes erode holistic solutions
- Interrelationships between people, planning and control, customers and external environments need to be considered carefully for effective production operation.

With this much broader perspective of the manufacturing environment, the research team made up of three MIT researchers and three graduate students, focused on answering the following key questions during phase III of the research:

- What are the high level goals of the manufacturing system?
- How do you classify manufacturing systems?
- What is the common lexicon of manufacturing systems?
- How should a manufacturing system be controlled?
- ***What is the best manufacturing system for a given set of conditions?***
- ***At what point does it make sense to redesign the manufacturing system?***

1.3 SCOPE OF THESIS

The information presented in this thesis is aimed at answering the last two key questions mentioned above – what is the best manufacturing system for a given set of conditions, and at what point does it make sense to redesign the manufacturing system***?*** However, to answer these questions, the rest of the questions needed to be explored since satisfactory information was not available in literature. The research team believed that one manufacturing system does not fit all manufacturing conditions. That is, a manufacturing system needs to be designed for a particular business environment. This is not to say that there is only one best solution but that there are better solutions than using the same system for all conditions. This immediately created the need to understanding the factors that characterize a manufacturing system. Research led to identifying the following ten factors: market uncertainty, production volume, product mix, frequency of design changes, complexity, type of organization, worker skill, investment, and time to first part.

The last question above was the most challenging one and many of the companies we spoke to are currently trying to answer this exact question. The answer I found was that manufacturing systems continually evolve into the next “system” through continuous improvement. There is not a time or event where one realizes the need for the switch over. The company should allow the market conditions to drive the manufacturing system changes and should not wait till the system obviously becomes obsolete. This answer comes from observations of manufacturing history and the reasons for the success of the Toyota Product System, whose key strength comes from their constant strive for perfection through continuous improvement [Womack, 1996].

The specific goal of my research was to characterize the manufacturing system design in the form of a manufacturing system design framework. The objective behind this exercise was to understand the manufacturing system design environment such that further research can be defined. Literature search did not yield a complete framework that showed the scope of a manufacturing system or manufacturing system design process. Without a thorough understanding of the manufacturing system, any design attempts will be futile. It was recognized very early that the manufacturing system design task is very complex. The framework presented here is meant to provide a very high level view of manufacturing system design process and a foundation to future detailed research towards manufacturing system design. Therefore, the framework presented here presents team’s current understanding of a manufacturing system and hence the manufacturing system design process presented requires further refinement. The framework also provides a scope of the manufacturing system design problem and provides, at a high level, the necessary steps involved. The framework development task led to exploring the following topics/questions:

- What is a manufacturing system? What are the goals of a manufacturing system?
- What is a manufacturing system design?
- What is the extent of manufacturing system design? (Is it limited to the factory floor only?)
- What are the entities involved and the interactions between them?
- What is the actual manufacturing system design process?
- How were manufacturing systems designed historically?
- How are manufacturing systems designed today?
- How to connect different entities of a manufacturing system?
- How are different manufacturing systems characterized?
- What are the tools available for manufacturing system design?
- Can manufacturing be used as a competitive weapon?
- What is the connection between corporate strategy and manufacturing?

These are only a few of the major questions that were explored. Dealing with these questions itself is a daunting task. Neither industry practitioners nor literature can provide satisfactory answers to many of these topics.

1.3.1 Research method

The work presented here is largely exploratory in nature because of the broad scope of the task at hand. Most of the research is based on existing literature on manufacturing systems and conversations with industry practitioners. This work defines the foundational work for manufacturing system design in the aerospace industry. There is very little, if any, information available on aerospace manufacturing systems. Most of the manufacturing practices in the industry today are craft based and were developed in the 1930s. There is no documentation to show how the existing manufacturing systems were designed. Also, due to the long life cycles of aerospace products, the opportunities to design manufacturing systems occur once in a couple of decades. This makes it very difficult to collect data for analysis. Likewise, there are very few, if any, opportunities to design a brand new manufacturing system in the aerospace industry due to the capital-intensive nature of tooling and machinery involved. The only opportunities for new system design may be when new factories are built, which in itself is a rare occurrence.

The following steps were used in developing the framework over a two-year period:

1. Understand the aerospace industry goals, direction, and scope of manufacturing
2. Develop a way of characterizing manufacturing systems
3. Conduct literature search to gather current research information on manufacturing systems
4. Develop a preliminary manufacturing system design framework
5. Conduct factory visits to see current manufacturing methods and present our work
6. Refine the framework and our thinking
7. Invite various aerospace companies to present their manufacturing system design methods at a workshop
8. Finalize the framework and incorporate all of the relevant feedback

All of the informational data presented here came from interviews, seminars, factory visits, workshops and discussions with industry practitioners. The research started with interviewing nine executives and five middle managers from various major aerospace companies to understand their perspective on the goals, direction and state of the aerospace industry. Their opinion of the role manufacturing was also explored during the interviews. Below is a breakdown of the sectors and number of companies represented during the interviews:

Airframe manufacturers (3 companies)

3 executive managers

1 middle manager

Engine manufacturers (2 companies)

1 executive manager

3 middle managers

Aerospace electronic component manufacturers (3 companies)

5 executive managers

Satellite manufacturer (1 company)

1 middle manager

The companies selected for the interviews represented both commercial and military business adequately as shown in Table 1.1 below:

Company	% Military + NASA Business	% Commercial Business
A	66	33
B	High 90s	< 5
C	70	30
D	N/A	N/A
E	10	90
F	N/A	N/A
G	50	50
H	85	15
I	30	70

Table 1.1 Representation of Commercial and Military Business

The information obtained from the interviews was presented to roughly 30 attendees of manufacturing system team meeting in March 2000. An initial attempt was made at describing the manufacturing system design framework at the same meeting.

Based on the feedback from the 14 managers, 30+ meeting attendees, and knowledge from existing literature, the framework was updated and a list of factors useful in characterizing manufacturing systems was developed. The recent information was presented at nine different aerospace manufacturing locations to seek feedback. The following locations were visited:

Boeing Commercial Group (Seattle, WA)

Boeing Military Aircraft and Missiles (Seattle. WA)

Boeing Delta II Rockets (Huntington Beach, CA)
Boeing Delta IV Rockets (Huntsville, AL)
Northrop Grumman (EL Segundo, CA)
Lockheed Martin (Marietta, GA)
GE Aircraft Engines (Rutland, VT)
Textron Systems (Wilmington, MA)
Wiremold (non aerospace; Hartford, CT)

The information was presented to more than 100 people familiar with the aerospace industry and aerospace manufacturing practices. The team visited the factories at each of the eight locations to understand the current developments in manufacturing and standard manufacturing methods. The information is still being presented to various other companies currently by one of the other research assistants.

With the rich feedback obtained from the above visits, much effort was devoted to developing the framework. A manufacturing system design workshop was held in Mesa, AZ. in February of 2001 to discuss current manufacturing system methods used in the industry. The most recent framework was presented to the 28 representatives from various aerospace corporations. Some attendees also presented the manufacturing system design methods used at their companies. Each of the presentations provided valuable information regarding the current manufacturing developments in the industry. The final version of the framework presented here was developed based on the information obtained at this meeting.

1.3.2 Thesis structure

The framework itself is presented in the last few chapters of the thesis. The first seven chapters give necessary information to understand the framework. The information is presented in two parts. The first part of the thesis (chapters 2 – 4) gives an overview of the aerospace Industry, state of aerospace manufacturing, direction of the industry and the importance of building a strong manufacturing capability. First part establishes the need to consider manufacturing as competitive weapon and the need to design a manufacturing system based on a strategy rather than a product design. The second part (chapters 5 – 9) discusses the manufacturing system, manufacturing system design, strategy tools, design tools, explains the framework step by step and shows the applicability of the framework to the aerospace industry. Chapter 9 presents a manufacturing system design process based on the framework. Chapter 10 reiterates the contributions of this thesis to LAI research, manufacturing world and makes recommendations for further research.

2 OVERVIEW OF THE AEROSPACE INDUSTRY

2.1 THE AEROSPACE INDUSTRY

Compared to industries such as the automobile, electronics, construction, and oil and gas refinement, the aerospace industry is unique in terms of its products, customer profile, market dynamics, required employee skills, capital intensity, and amount of risk assumed by the companies. The following simple model is adopted for the aerospace industry in this thesis. The industry has two distinct branches, commercial and military. The two branches can be further divided into four sectors – airframe, engines, space and electronics. The manufacturing operation within each of these sectors can be divided into fabrication and assembly operation even though this differentiation is not unique to aerospace industry. Furthermore, the ***manufacturing system design*** under each one of the sectors can be in one of two environments – design of a brand new system (a greenfield environment) or a modification of an existing system (brownfield). Due to maturity of the industry, it is safe to say that in most of the situations a brownfield design environment will be encountered. Figure 2.1 shows this breakdown.

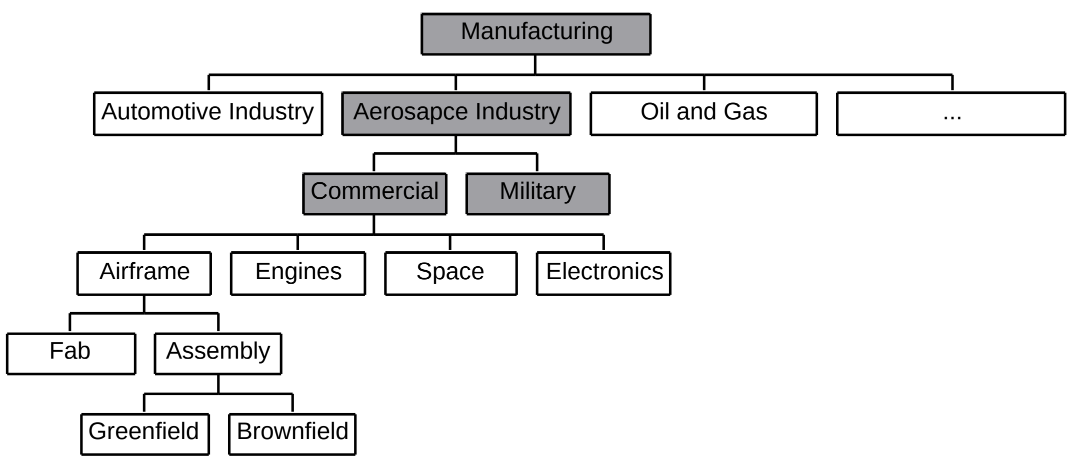

Figure 2.1 Aerospace Industry and its sectors

The two branches of the aerospace industry, military and commercial, are unique in terms their business environments. The differences can be characterized by examining the products offered, product mission, customer profile, market size, market dynamics, competition structure, cost structure, and investment attitudes. The military and commercial branches are discussed in more detail in this chapter.

2.1.1 Goals of Aerospace Industry

In an attempt to understand the current goals of the aerospace companies and to understand the direction of the industry, 14 managers from various prominent aerospace companies were interviewed. Seven out of nine executives and two of the five middle managers mentioned that ***profitable growth*** was the top most goal of their corporation. This is a two-part goal, which calls for both business growth and an increase in profit. Even though many of them did actually use the words 'profitable growth', some of them described it in various other forms such as, increase profit, ROI and increase revenue, higher sales, double revenue, etc. There were also some other items mentioned such as, Return On Invested Capital (ROIC), Cash flow, Return on Net Assets and Economic Profit.

The interviews indicated that the Wall Street has the strongest influence on corporate goals. Corporations respond to the stock market by trying to meet or exceed shareholder expectations, constantly seeking to reduce cost, trying to meet short-term profitability pressures, and lately trying to keep up with dot-coms. While Wall Street is the major external driver, company culture, type of business (military or commercial) and personal interests of the decision-maker were reported to be the strongest internal drivers. Likewise, changes in management typically lead to changes in goals. Appendix A gives a full account of the information gathered through the interviews.

2.1.2 Commercial Business

As shown in Figure 2.1, commercial branch can be further broken down into its four sectors. The airframe sector manufactures commercial aircraft of various passenger capacity and range capabilities. The engine sector provides turbojet, turbofan, and turbo prop engines of various thrust/SLIP capabilities to airframe manufacturers. The commercial space sector manufactures telecommunication, weather, scientific earth observation and research-based satellites as well as launch vehicles. The electronics sector supports all of the other sectors by providing electronics capabilities. A general description of the commercial aerospace business environment is given below. It should be noted that there might be some subtle differences between the sectors but at a high level, the general business model holds.

Commercial aerospace business operates in a substantially larger market (global) compared to the military business. However, in terms of total market volume, the entire aerospace market is relatively small compared to, for instance, the automobile industry. For instance, the volume in the space sector can range from 1 to 100 satellites per year (in US). The airframe sector volume is somewhere in the neighborhood of 3500 aircraft per year [Aerospace Facts & Figures, 2000] and the engine sector manufactures roughly 7000 engines per year. The business is very capital intensive. Moreover, there are several major players in the global market competing heavily for this small market. Being a small, capital intensive market with multiple competitors makes aerospace a very high-risk business.

The space sector, which includes satellites and launch vehicles, operates in a highly unpredictable business environment. Since this is a relatively new business in the aerospace industry, there is not enough knowledge to predict the need for satellites with any degree of certainty. Even though the majority of the launches has been successful and satellites are typically in good health in orbit, there is still much uncertainty in the launch capability and satisfactory operation of the satellite in orbit. This has created a lot of pressure on the manufacturer to test the satellites repeatedly on the ground since once launched the satellites can not be serviced. In addition to the cost of repeated testing there are also enormous insurance costs involved to recover financial losses if the launch fails for whatever reason. Because of the high costs and unpredictable market demand, the space sector is still a risky venture. However, the manufacturers are participating to build the capability for future needs.

In the airframe sector, the market demand is highly cyclical. Figure 2.2 shows this cyclical nature from 1970 – 1997. It can be seen that even though the amplitudes vary, the demand cycles are cyclical. The products have very long operational life cycles, typically over 30 years. Therefore, new products are introduced roughly once in a decade. The product development typically spans 5 – 10 years. Hence, the manufacturers can not satisfy market needs immediately. To avoid this problem, manufacturers have resorted to developing new products based on long-term (typically 20-year) demand forecasts generated by the manufacturers themselves. There are multiple players in the market and the forecasts produced by different competitors can be very different leading to utter confusion in the marketplace. Based on these forecasts, company sales representatives attempt to sell customers (airlines) a new product with the claim that it will benefit the operation in the future. Thus, the demand for new products is actually artificially created (or heavily influenced) based on this highly uncertain long-term forecast. Because the products are sold this way, the customer has gained great bargaining power and plays in integral role in price determination. The customers are diverse and are located worldwide demanding a wide range of requirements and custom products. To ensure customer retention and gain customer loyalty, the manufacturers sometimes sell the product at cost or even below cost.

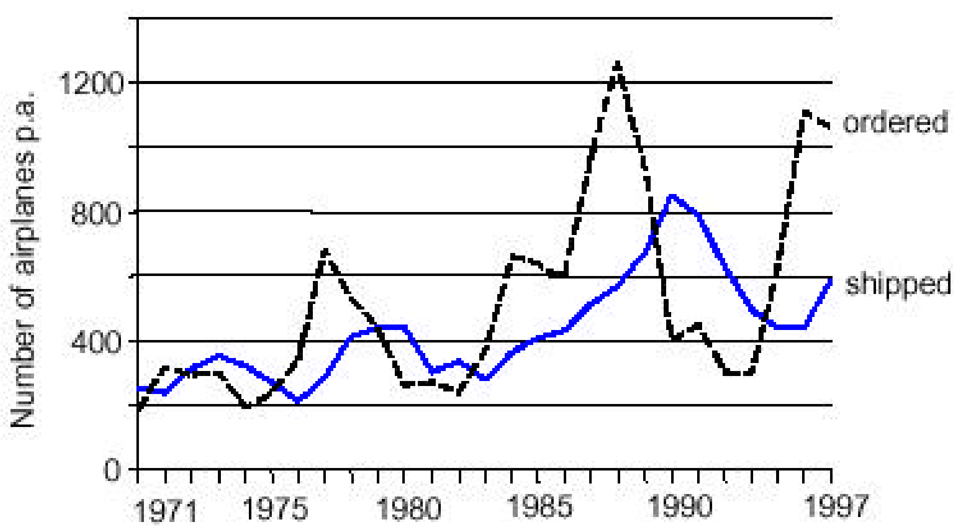

Figure 2.2 Orders and Shipments of Commercial Aircraft from 1970 – 1997 [Source: Lufthansa Analytical Reports]

Due to its dependence on the airframe sector, the engine sector also experiences this demand modulation but with a higher amplitude. The higher amplitude results from propagating the forecast errors to the second tier, which is the engine sector. Some engine manufacturers have a unique business model where the engines are not sold to the airlines but are leased. The airlines buy power by the hour from the engine manufacturers. Thus, the engine manufacturers perform maintenance on the engines and provide power to the aircraft for a certain fee. Most of the revenue is generated through spare parts and overhauling fees.

In the airframe and engine sector, the product development payback period is usually on the order of 20 – 30 years. Any return on investment can only be seen after 20 years, creating serious cash flow challenges. Therefore, each new program has the potential to risk the company's future due to the very high investment (multiple of billions of dollars), uncertainty in sales and long payback periods.

Most of the companies typically compete by product performance, reliability and customer support agreements. There is a strong push to reduce overall cost of the product. On the manufacturing arena this is done by outsourcing fabrication and any other operation that can be done outside the company for lower cost. Most of the companies are also trying to implement principles of lean manufacturing to reduce manufacturing cost. Due to the high-risk nature of the business, management is risk-averse to investing in manufacturing system redesign to lower internal production costs.

2.1.3 Military Business

The military business is unique in its own right. The military aerospace products are special purpose products, which include fighters, bombers, stealth aircraft, spy aircraft, attack helicopters, fuel tankers, surveillance aircraft, satellites, and missiles, etc. Because they are special purpose, each product often can be a one of a kind product. The US government with its four branches (Army, Navy, Marines and Air Force) is the major, if not the only, customer. Even though some defense contractors do have international customers, the sales are done through the US government. Due to the nature of the business (national security), the customer (government) is heavily involved with the product design, manufacturing and accounting details of a contract. The manufacturers typically do not have the freedom to design and sell the products at their will. Therefore, the military business operates in a restricted business environment.

Programs are awarded through design competitions. The manufacturers are given a set of requirements and proposals are requested. Manufacturers, based on their interpretation of the customer's priorities, design products and submit the proposals for review during the concept and technology development/demonstration phase [Defense Acquisition Management Framework, 2001]. The government pays the development and tooling cost during this phase (cost type or cost plus fixed fee type contracts). The customer reviews the proposals and evaluates prototype performance during the Systems acquisition phase and decides on the contractor. The government can use one of many strategies in awarding contracts such as single source, dual source, annual production contracts, and multi-year production contracts. Most of the production contracts are awarded on an annual basis and typically are fixed price or fixed price plus incentive fee. Due to the short business stability of the annual production contracts, there has been a push for multi-year production contracts and the Department of Defense (DoD) has already awarded some multi-year contracts (e.g.: F-18 E/F). The production contracts typically allow a profit margin between 8 – 12%. The defense contractors interviewed felt that this profit was insufficient to attract investors. The manufacturers use learning curve benefits to make additional profits during the contract term. However, because the production contracts are awarded on an annual basis, the customer has the opportunity to review manufacturer's financial performance over the past contract year and adjust the contract for the next term. That is, the government will adjust any savings made through learning curve benefits into the next contract period practically eliminating the part of the profits gained through the learning curve.

The market volume is highly unpredictable over the long-term but is very stable over the contract term. The military market is much smaller in volume compared to the commercial branch. The demand can be thought of as step-wise stable as shown in Figure 2.3. The turning points in the steps can not be predicted since they depend heavily on the defense budget, current administration, and current defense needs. But, the stable business prior to the abrupt changes is an attractive characteristic of defense business from cash flow point of view. One reason for the push for multi year contracts is to lengthen this stability.

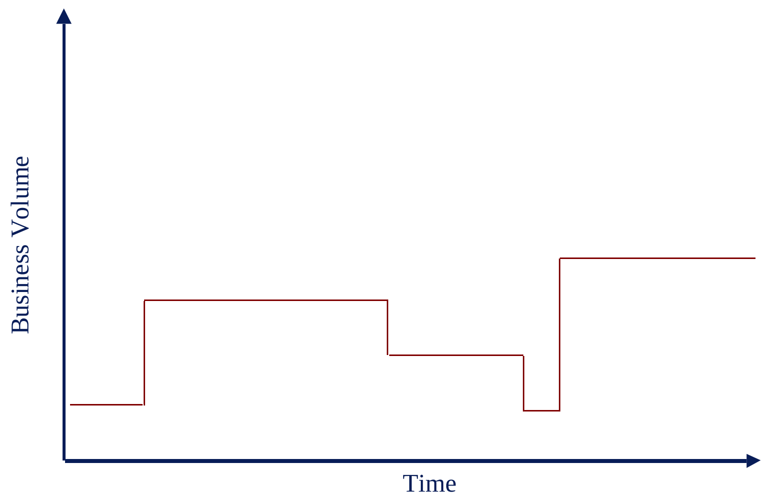

Figure 2.3 A Schematic of Military Demand Profile

The military business is a relatively low risk business compared to the commercial environment. The government pays the development cost of all competitors, therefore the contractors do not have to assume any risk for participating in the competition. If the contract is not awarded, the manufacturer will lose only the relatively small investment made by the company, if any. Some companies might choose to make higher company investment to develop and retain capability. But due to the annual production contract re-negotiations and the very possibility of losing the contract, encourages low and short-term investments. Program cancellations are a constant worry among defense contractors, particularly when a new administration takes charge.

There have been instances where entire programs have been cancelled regardless of the program maturity. Another major risk involved in military environment is the lack of business opportunities upon losing a contract. Since there is only one customer and if the lost contract were a major contract, the government might not have any other immediate business opportunities for the manufacturers with the unsuccessful bids. This can result in the long periods with relatively low activity for a defense contractor as can be seen in Figure 2.3. To avoid this situation, many aerospace companies compete in commercial and military environments. They have developed a “portfolio” of military and commercial products to balance the low activity in one of the two branches. The right balance of military and commercial participation is a tricky challenge.

Post cold war military spending cuts have created a strong need for affordability and initiatives such the “war on cost” throughout the industry. Defense contractors are seeking tools to reduce cost in product development and manufacturing. There is also a strong drive for reducing life cycle cost of aerospace products. Even though affordability has become the industry focus, there is no true incentive for companies to cut cost. During annual production contract negotiations, the companies are expected to share the cost savings with the government. Thus, the government greatly minimizes opportunities a company has to make higher profits by cutting cost. It appears as if only the customer is winning and the contractors are getting the short end of the stick leading to a lukewarm attitude towards cost saving measures.

2.2 CURRENT MANUFACTURING SITUATION

Different sectors in the aerospace industry manufacture products in many different ways. There are differences in assembly and fabrication methods as well. Interestingly enough, most of the major aerospace manufacturers consider themselves system integrators and have outsourced most of the fabrication work. Typically, the product is assembled in many stations of a final assembly line. Parts assembled on subassembly lines feed the final assembly line, the sub assembly lines are in turn are fed by fabrication centers, suppliers and storage rooms. Even though there is one final assembly line, there are multiple sub assembly lines assembling products at different levels. Some of the subassembly lines are geographically separated and therefore require major transportation before coming to final assembly. Figure 2.4 shows a schematic of this process, with different sub assembly lines intersecting the final assembly line.

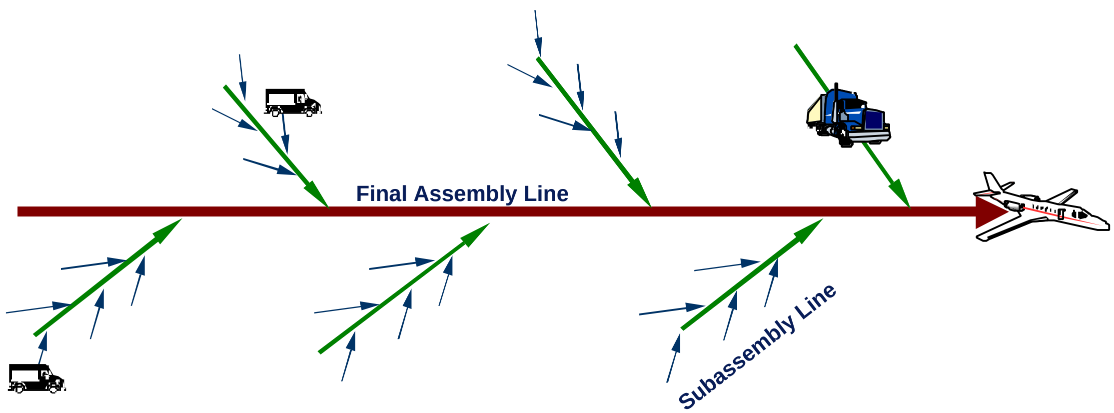

Figure 2.4 Schematic of Current Aerospace Product Assembly Method

The final product stays at given station on the final assembly line until all work associated with that station is completed. The product is then physically moved (usually using cranes) to the next station and the next sets of assembly operations are performed. This type of assembly operation, with some variations, can be seen in airframe, rockets, satellites, missiles, and engine manufacture. For example, the satellites are typically manufactured in one (or few) station(s) to minimize movement, but the process can be abstracted to an assembly line with few stations. The assembly line is not necessarily an actual straight line. Some companies use a fishbone like arrangement and some use a straight-line arrangement. Figure 2.5 shows schematics of these assembly lines and stations.

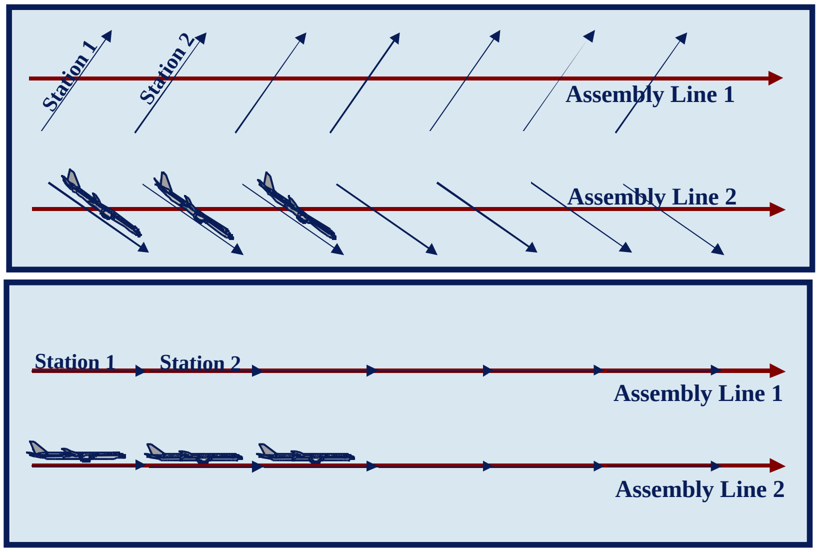

Figure 2.5 Schematic of Final Assembly Line Stations

Some companies are experimenting with continuously moving or pulsed assembly lines. Here, the product moves at a desired pace along the assembly line as the work is being performed on it. The work expected to be finished by the time the product arrives at a predetermined position. A new set of workers become active and performs the next set of assembly operations. The idea of assembly stations still exists, but the assembly time is greatly reduced since the crane moves between the stations are completely eliminated. Some companies are also experimenting with cellular manufacturing, flexible manufacturing, and other types of manufacturing systems. Aerospace manufacturing needs have led to the development of some impressive innovations in high speed machining, direct laser forming, composite manufacture, precision drilling and automatic riveting machines.

The actual manufacturing process, however, resembles craft production in many ways. In the airframe sector, most of the work is not standardized and large parts are typically not interchangeable. Moreover, various types of shims (reminiscent of filing, bending and fitting or craft production) are used throughout the assembly. A high level of worker skill is typically needed. Repeated inspections and rework can not be avoided. In space and electronics sectors, the need for repeated testing of the product indicates that the processes are not stable or trustworthy. It is recognized, however, that the customer considers testing as a value-added activity. The assigned work is typically not always finished at the designated stations on the assembly line. The product is still moved to the next station with trailers, traveled work or rejection tags, attached to the product to indicate unfinished work. The tags can indicate parts that are installed but are defective, which would be replaced at a later point in the assembly. The tags also can indicate unfinished work that must be performed at the subsequent stations.

2.3 BARRIERS TO MANUFACTURING IMPROVEMENTS

Research revealed that there are many barriers to changing the existing manufacturing systems. Biggest one of all is the natural human resistance to change. However, the situation is particularly compounded in aerospace industry due to the high-risk nature of the business. The management is used to meeting short-term goals by either expediting, adding temporary capacity and re-sequencing work. Any change on the factory floor that takes this freedom away from the managers will naturally be resisted. The US aerospace industry hasn't yet experienced the kind of market attack that the automobile industry experienced in the 80s. Therefore, there is no real urgency to introduce changes in the system that has been working since the 1930s. However, many companies are proactively working to prevent this situation. The airframe manufacturers are already seeing increasing competition from international manufacturers, who seem to have found a way to use the market dynamics to the benefit of the company instead of just dealing with it.

There is a strong reluctance to disrupting factory floor operations for any reason. In commercial airframe manufacture, for example, the manufacturer incurs cost for late deliveries (late delivery charge). This is a direct financial consequence on the company bottom line compared to indirect impact of losing future sales due to late deliveries. This direct and visible impact creates a strong barrier to disrupting factory floor operation for process improvements.

Tooling needed for aerospace products is very expensive and often requires multiple years to recover the cost. Any suggestions to remove a particular piece of tooling from the factory floor before the payback period is over will not be supported. The ultimate focus is on individual machines rather than on the entire system. Existing monuments will be kept even if they are constraining the system performance.

The military branch shares all of the concerns mentioned above, along with a few additional challenges. The executive interviews revealed that there was no real incentive to reduce cost in military programs until recently since the government paid the development cost. The government seems to have remedied this situation by focusing on affordability. This has caused the manufacturer's to focus on affordability as well. Yet another challenge in the defense contracting business is the short-term contracts (annual production contracts). Contractors tend to invest small amounts of money in process improvement programs to avoid being left exposed to unrecoverable capital if the contract is not renewed in the following year. History of manufacturing, especially that of TPS, shows that it takes decades to achieve leaps in manufacturing performance improvements. The short-term improvement programs might not even make a dent in system performance. Process improvement initiatives are slowly spreading throughout the company and gaining management support but not many companies are aggressively pursuing these improvements.

2.4 SUMMARY

Aerospace is a unique business in its own right. The two branches, commercial and military, operate in very different business environments. As the Table 2.1 shows, there are unique favorable qualities of both branches. Realizing this many aerospace companies are trying to achieve a comfortable balance between commercial and military branches. None of the companies show any preference between military and commercial businesses. All seem to maintain a healthy balance of both businesses. Companies are using best traits of one business to compensate for the challenges of the other.

There is a very strong trend to outsource fabrication in order to reduce manufacturing cost. While a few executives highly favored this idea, few others anticipated many problems with the strategy. These problems are mostly related to the risk of loosing control of the business unit outsourced as far as scheduling and quality issues are concerned as well as loosing the knowledge and capability of the outsourced work. This could lead to serious production problems, if the supplier goes out of business.

Military	*Commercial*
Excellent for cash flow	High potential for profits (retain all profits after payback period)
Piece-wise stable	Highly cyclical
Pays development cost and tooling	“Bet the company” on new programs
Investments based on requirements for individual programs	Investment based on market forecast
Indirect incentives to reduce cost	Cost reduction always pays off
Cost savings are shared with the customer	Cost savings directly add to the profit
“No control over your destiny”	Always under management control
Encourage short term investments	Long term investments can be afforded due to amortization over longer periods

Table 2.1 Comparison of Commercial and Military Business Environments

It is apparent that the companies respond to Wall Street pressures promptly. Since the Wall Street heavily influences company goals, the strategies are likely to change often to satisfy Wall Street. By majority consensus, the highest goal of the industry was Profitable Growth. The aerospace industry operates in a highly uncertain market environment. The low return on investment generated by the industry is further compounded by the fact that this industry is also capital intensive. This highly undesirable environment has created a strong risk-averse mentality towards investment in manufacturing.

3 CURRENT AEROSPACE MANUFACTURING SITUATION

3.1 OVERVIEW

Conversations with industry practitioners and literature revealed that the manufacturing system used by most of the aerospace companies was developed during World War II [Ruffa, 2000]. The factory floor operations part of the system, as described in Appendix B, has been modified over the years to meet the current needs but the entire system doesn't seem to have been modified. People in charge of implement changes in the system do not speak of operations beyond factory floor when it comes to improvement activities. Besides, the system was developed for an entirely different market demand and business environment. The infrastructure of the system requires high levels of inventory, uses craft based techniques and pays little attention to cost. The manufacturers have found a way of dealing with volume fluctuations by hiring and laying-off workers, adding additional stations on the line, and adding additional shifts.

3.2 CURRENT METHOD OF MANUFACTURING SYSTEM DESIGN

As mentioned above, companies have adopted a standard manufacturing system. Whenever a new product is designed a copy of the existing factory (or a production line) is implemented to manufacture the prototype models. The business unit management tasks the manufacturing function to implement a manufacturing facility to produce the newly designed product. The plant operates at a low-rate or prototype mode while all the bugs in the system are being worked out. Factory is eventually brought up to full rate production capability. But, a factory operating a full rate is by no means an efficient, waste-free factory but it is only a factory that can meet the market demand. The manufacturing system design and operation is largely experience based and not analysis driven. Most of the decisions are made using manager's intuition and not data. This might have been acceptable when the original system was developed in the 30s. The manufacturing systems and products have become much more complex. None of the companies visited had a manufacturing system design process or manufacturing system design group. Some companies did use some simulation tools.

3.3 PERCEIVED ROLE OF MANUFACTURING

From discussions with many managers (executive and middle management), manufacturing managers, and hourly workers, it was evident that manufacturing most often is considered as a "***necessary evil***" or an expense of doing business. This is also evident from the increasing enthusiasm of companies to outsource as much manufacturing as possible. The idea of using manufacturing as a competitive weapon is not well understood. Manufacturing is expected to meet market demand regardless of the challenges on the factory floor. Some companies do not have a good understanding of their own production capacities.

Until recently, product design was simply "thrown over the wall" to manufacturing. The manufacturing function was expected to develop the necessary tools and processes to fabricate anything the engineering had thrown at them. Likewise, marketing expected manufacturing to meet market demand with existing facilities and resources. There seems to be a clear hierarchy between business functions, where manufacturing is usually considered to rank below engineering and marketing groups. There is an assumption that manufacturing can cut costs indefinitely, increase rate instantaneously and meet demand indefinitely while it is hard for engineers and marketing folks to change. Lately, however, there have many attempts to include manufacturing in the design process. With Integrated Product Teams (IPTs) manufacturing function is getting some say in product design criteria. Some companies have made headway into designing products based on existing manufacturing capabilities. There is a strong push for Design For Manufacturability and Assembly (DFMA), concurrent design and early supplier integration.

Conversations with industry practitioners revealed that the manufacturing system design activity is limited just to the factory floor. More specifically, no one believed that there was a need for manufacturing system design. There is a belief that the current system in place is fully capable of meeting demands but currently it is not being used optimally. Therefore, there is a strong push for cleaning up factory floor waste. Manufacturing system design is usually described in terms of Kaizen, accelerated improvement work shops, continuous improvement events, and/or 3P. All of these tools are very effective in cleaning up waste and improving processes on the factory floor.

3.4 Improvement Activities

Almost all of the aerospace companies have by now realized the need for cost reduction, waste minimization, and process improvements. The stimulation for this awakening on the commercial side most probably comes from the noticeable increase in the competitors' market share. On the military side, the stimulation comes from the reduction in military spending and the implications of Norm Augustine's plot showing that at the current rate of expenditure, the entire defense budge is sufficient to buy only one tactical aircraft in the middle of 21st century [Augustine, 1997]. Companies are trying to implement lean manufacturing principles under the assumption that becoming lean will solve this problem. Some have succeeded wonderfully and others have not been so lucky. Most of the improvements, however, have been local "islands of successes".

Few of the companies mentioned that the lean initiatives in their companies are nothing but waste reduction programs. There is no real strategy for lean implementation or even any commitment from top level management. Most of the companies are deploying "lean consultants" to run periodic weeklong Kaizen events. As someone put it "these Kaizen events are like throwing paint balls against the wall repeatedly and hope that the wall will be painted some day." The lean consultants often do not have a common goal in mind other than reducing waste. The assumption is that reducing waste will result in some good to the company. The assumption is a good one, but were these efforts directed strategically, the system-wide benefits might be realized sooner and in a predictable manner. Many of the companies have decided to implement lean based on the faith that lean will benefit the company some how. Companies do not necessarily know the end-state of the company after accomplishing lean. Since companies just know the direction they are headed but not the exact point, it is difficult to know when the company has achieved the goals. There is also the feeling that heading in the right direction is good enough. This leads to abandoning lean initiatives mid stream if results are not seen immediately, creating frustration on the factory floor. Likewise, some companies have compiled all the best practices in one place and have called it their “new standard manufacturing system.” There has been some research done in this area**,** [Maccoby, 1997; Hayes & Wheelwright, 1984] which says that without the right infrastructure a manufacturing system can not perform as expected. Rechtin claims that many companies are failing at lean implementation due to conflict between existing architectures and the architecture needed for Toyota Production System [Rechtin, 1997]. He is essentially stressing that any given system works well only if the architecture and the system are matched appropriately. The system architecture needs to be implemented before attempting to implement best practices. The new system might work under isolated situations but the robustness of the system is realized only if the entire system (the infrastructure and physical entities) has been properly understood and implemented.

To the credit of all lean implementation efforts, there has been a tremendous impact on the management and workforce from these activities. The factories appear much cleaner and organized. The tools are easily located, minimum required inventory is organized in supermarkets, right sized machines are seen, ergonomic work environments are created and management is recognizing the need for lean. Some major players have included “lean” in their vision statements to show top-level management support and encouragement to this change.

3.5 SUMMARY

Even though lean initiatives are benefiting the industry tremendously, it seems as if all of the improvement focus is directed to the factory floor. Moreover, the factory floor directed initiatives themselves have only one goal – waste minimization. A Manufacturing system is much larger than the factory floor. While modifying the factory floor operations can yield results relatively quickly, it is also necessary to realize that these localized results might have negligible, if any, impact on the company bottom line. This is especially true if the improvement activities are randomly distributed throughout the factory.

4 IMPORTANCE OF A MANUFACTURING SYSTEM

4.1 OVERVIEW

Previous two chapters discussed aerospace industry as a whole and the current state of aerospace manufacturing. It was shown that even though the companies have recognized the need to focus on cost minimization, waste elimination and process improvement, the focus of all these activities are limited to the factory floor. That is, the manufacturing system as a whole is not being improved. Moreover, it was mentioned that manufacturing is considered a cost of doing business by many executives. Here, it will be argued that the aerospace industry is in a phase where manufacturing organization has the highest leverage in helping the corporation achieve its goals. That is, manufacturing capability has a better chance of generating revenues (selling products) compared to design excellence and marketing genius. The chapter also discusses future negative implications of not building manufacturing capability.

4.2 DYNAMICS OF INNOVATION: INTRODUCTION TO UTTERBACK'S MODEL

Current position of the aerospace industry can be described using Utterback's [Utterback, 1994] dynamics of Innovation model. Utterback has abstracted the well-known product life-cycle curve to the industry level. The concept can be used to visualize the status of the industry so that appropriate decisions can be made concerning products and processes. Having adequate information on the current state of the industry, current issues of interest and future directions of the industry can be extremely useful in formulating a long-term strategy. As will be shown shortly, Utterback's concept readily explains the current state aerospace industry and becomes a guide in identifying an industry focus.

According to Utterback's dynamics of innovation model, during the early stages of an industry the companies focus on design flexibility and product performance. In this period, the product design is highly unstable, there will be multiple product designs to meet the same need, and multiple competitors in the market field. The barriers to market entry are low and the number of competitors increases as market grows. Realizing that their design does not meet the market needs, all competitors constantly compete with themselves as well as external competitors to meet those needs. The focus is on product innovation while manufacturing processes are ignored. The product is fabricated using crude inefficient processes. This phase is called the ***Fluid Phase***. This phase is equivalent to the rapid growth stage of the product life cycle. Figure 4.1 shows a schematic of the Utterback's model. [Utterback, 1994]

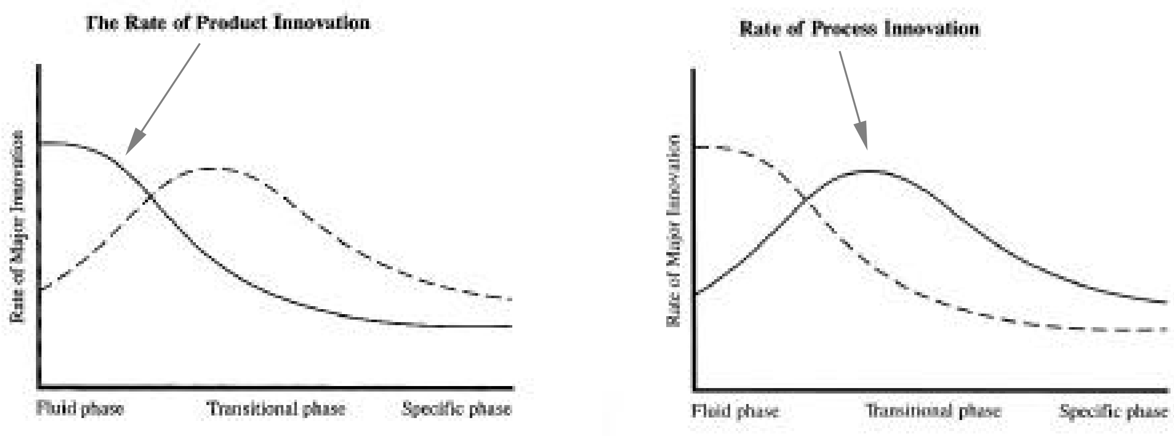

Figure 4.1 Dynamics of Innovation [Utterback, 1994]

The next phase is called the ***Transition Phase***, where a '***dominant design'*** emerges. A dominant design is not necessarily the best or most efficient design but it is a design that incorporates majority of the known customer needs. Any additional design improvements are generally not noticed or desired by the market. For example, graphing calculators have reached a dominant design stage. Most of them come with over 400 functions but students usually do not end up using more that 100 of those functions. Every now and then a calculator manufacturer claims to have incorporated 437 functions, this hardly makes difference in students' desire to buy that calculator. She will pick the one that meets most of her needs at the lowest cost. A dominant design is a stable or standard design, where products become more commodity-like and undifferentiated in terms of performance and features from competitors. This is the phase where barriers to entry start to become evident and companies start exiting markets. Big players start to dominate the market. The industry focus switches from product performance and innovation to process improvement.

The last phase is the ***Specific Phase,*** where the focus is mainly on process improvements. Those making strides in this area dominate the market. The number of competitors steadily drops as smaller companies exit the market or merge with bigger companies. The product is highly defined and the differences between products of competitors are insignificant. Product innovations do occur but these are mostly incremental and evolutionary compared to the revolutionary innovations seen in the fluid phase. For example, increase in payload capacity, reduced noise, and longer range would be some of the product innovations that can be expected in this phase. The competition is no longer based on product performance and number of features but on product cost. Process improvements in product design, product development and manufacturing methods become the area of interest.

4.3 DYNAMICS OF INNOVATION AND AEROSPACE INDUSTRY

Researchers at the Lean Aerospace Initiative of MIT applied Utterback's model to the aerospace industry dynamics and found a very good agreement. Figure 4.2 shows the result of research. The plot shows the number of major aerospace firms as a function of time (1900 – 2000).

The aerospace industry appeared to be in the ***Fluid Phase*** until approximately 1960. The pattern of growth in number of firms and number and various aircraft designs introduced (as shown in Figure 4.3) agrees well with Utterback's description of the fluid phase. The dynamics between 1960 – 1990 are unique to the aerospace industry where heavy defense spending from US government literally halted the natural industry dynamics until the 1990s (end of cold war). As can be seen in Figure 4.2 the natural progression returned during the middle of 90s. According to Utterback, the decline in number of firms between 1960 - 2000 is indicative of the industry reaching the ***transitional phase*** or ***specific phase,*** which also means that a dominant design has already emerged and manufacturing process improvement should be the industry focus.

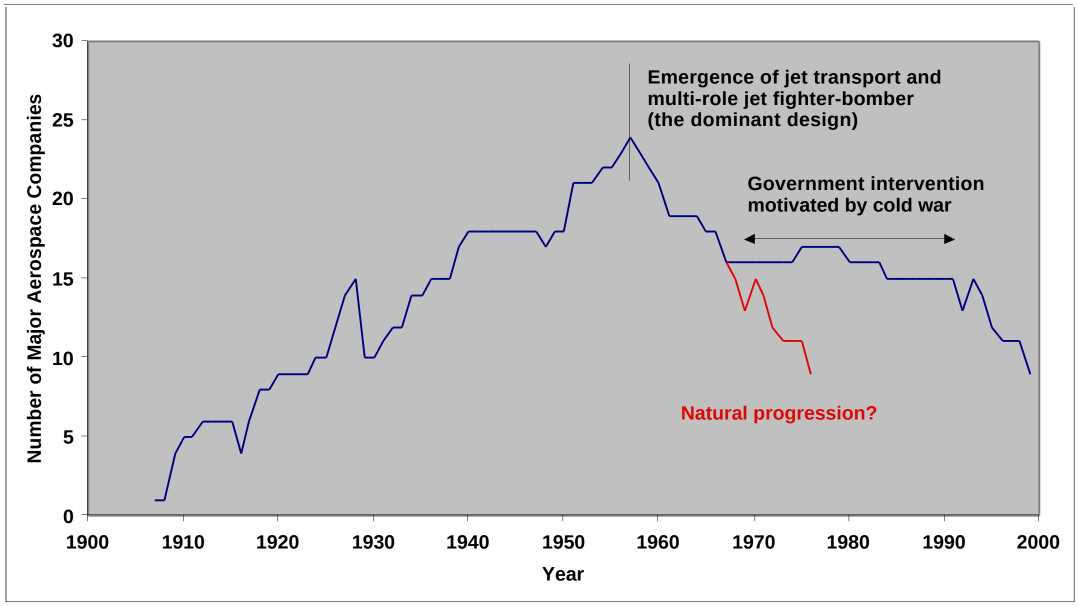

Figure 4.2 Number of Aerospace Companies Vs. Time [Weiss & Amir, 1999; Shields & McManus, 2000]

Many sectors of aerospace industry are showing signs of operating in the transition or the specific phase. As described earlier, most of the companies are focused on product affordability over the product life cycle. Acquisition cost seems to be the determining factor in sales. The differentiation in product features and performance characteristics is diminishing rapidly. Companies are predominantly offering incremental and aesthetic improvements to products rather than drastic performance improvements. As Figure 4.2 shows, the current number of major aerospace firms can be counted on one hand. Mergers, acquisitions and exits from market are in progress. The efforts to implement lean principles and eliminate waste are indicative of industry's focus on process improvements. All of these occurrences are characteristics of the specific phase and hence it can be assumed that the aerospace industry is approaching the specific phase.

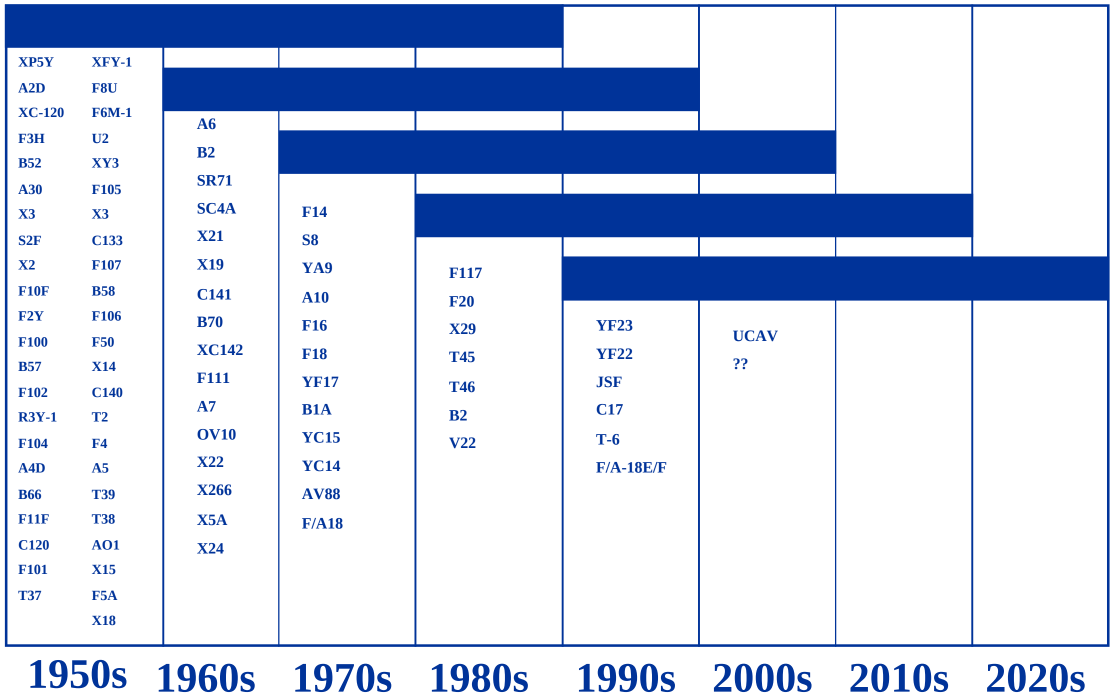

Figure 4.3 Number of Aircraft Designs Vs. Time [Hernandez, 1999]

4.3.1 Dominant Designs in the Aerospace Industry

According to Utterback, once a dominant design emerges, only the big hitters remain in the market with their ability to compete on cost. New products will be introduced at a much slower pace, and the number of firms declines steadily due to mergers and market exists. These characteristics very closely match the aerospace industry as a whole. Table 4.1 shows various products in various aerospace sectors and the level of design maturity. Based on this evaluation, it is safe to assume that majority of aerospace products have reached a dominant design level of maturity.

General Aviation	Yes
Commercial aircraft design	Yes
Commercial aircraft interiors/systems	No
Military fighters flight characteristics	Yes
Military fighters of stealth designs	No

Commercial/military engines	Yes
Commercial/military space launch vehicles	Yes
Commercial/military communication satellites	Yes
Military specialty satellites	No

Table 4.1 Dominant Designs in Aerospace Industry [Adopted from Shields]

To explore this claim a bit further, the physical appearance of commercial aircraft has not changed significantly since the introduction of the B707. The same aluminum fuselage, wing and tail design has been tweaked over the years. The manufacturers now are concentrating on adding additional systems to make the aircraft different from each other. Some have invested in aircraft systems commonality, in-flight entertainment systems, navigation systems, passenger comfort, etc. The aerodynamic performance has not changed much over the years. The airline customers are aware of this fact and are pressuring the manufacturers to reduce acquisition cost. The added comforts and functions are being taken for granted; they are not convincing the customer to make the purchase. One who can sell the aircraft for cheaper will win the orders. This has cost Boeing many orders since Airbus has been able to sell aircraft at much steeper discounts compared to Boeing. Similar descriptions can be given to other products described in Table 4.1.

4.3.2 Manufacturing – the competitive weapon

The discussion above shows that in the specific phase, the manufacturing function can gain the highest leverage. A manufacturing system becomes a formidable competitive weapon if and only if it is capable of meeting market demand better than the competitors' system can. That is, simply having a manufacturing system will not make any company successful. The key is having the right capability in-house at the right time. Cost efficient, time efficient and dependable manufacturing processes are needed the most in the specific phase. A Company that has this level of capability, according to Utterback's model, will no doubt win over the competition since the company will be able to offer the same product at the lowest possible market price.

Importance of a Manufacturing System

It can be argued that less attention is paid to manufacturing process design and process improvement during the growth phases of an industry since rapid product introductions require highly flexible manufacturing systems. A manufacturing system that is not designed to handle rapid product introductions can accumulate waste (of all types) as new processes, machines, workers, floor space are rapidly added to satisfy the market demand. This exactly is what leads to the build up of “bad practices” and waste in the system that becomes visible in the specific phase. Since the product introductions become rare and sales of existing products decline focus naturally turns to the enormous waste in the manufacturing system. This closely resembles the current state of aerospace manufacturing.

4.4 STRATEGY DRIVEN MANUFACTURING SYSTEM DESIGN

The only way a company can have a manufacturing system that becomes a competitive weapon when needed is by ***designing*** a manufacturing system that incorporates industry and product life cycle dynamics. The system should be specifically ***designed*** to meet the business needs of the company as opposed to blindly implementing an existing system. This requires the product designers, manufacturing system designers, marketing personnel and the decision-makers to be aware of the industry and product life cycle dynamics. The second step in achieving the desired capability is the continuous improvement of the system. A Company should develop a discipline of modifying the manufacturing system continuously to meet the market needs. Being aware of the industry dynamics should be reason enough to strive for continuous capability development. This discussion implies that the manufacturing system design should be based on a plan or a strategy.

This plan is called the ***Product Strategy*** in this thesis. The needed capability can be made available at the right time by designing a system based on a strategy that already accounts for dynamics of innovation. The idea of product strategy will be explored in detail in later chapters. Based on this strategy, a system should be designed to accept rapid product introductions initially without adding unwanted waste in the system. By formulating the product strategy, the corporation, manufacturing organization, product designers, and manufacturing system designers can be made aware of the changing needs at different phases of the product life cycle. If the manufacturing system is then designed based on this strategy, it can become a very strong competitive weapon when needed since it was designed to do so. A manufacturer with this level of capability will be the one who sustains business while others are detecting and eliminating waste in the transition or specific phases.

4.4.1 Continuous Manufacturing Capability Improvement

The easiest way of having the needed manufacturing capability available when needed is continuous adaptation of the system to present business environment. The word capability here does not refer to C_{pk}, but it refers to the over all ability of a manufacturing system to meet current business needs. Since the designers can not anticipate all interactions at the design stage, a manufacturing system when first implemented typically does not operate at the best level of performance. The system needs to be tested and fine-tuned over time to reach the level of capability desired. The strategy-driven design discussed above also calls for continuous modification of the system. It might seem difficult to change a system continuously but it is better than having to make unexpected drastic changes to meet business needs. Miltenburg [Miltenburg, 1995] supports this argument in saying, that when the level of manufacturing capability is low (say, at newly implemented stage), anything beyond a few small changes is difficult. As the level of capability is continuously improved, more changes can be made at a faster pace.

The need for continuous capability improvement to achieve the capability readiness can be summarized using Miltenburg's manufacturing capability metric below (Table 4.2). It is emphasized in the part II of the thesis that the target manufacturing system capability should be at the world class level as described in Table 4.2.

The current status of the aerospace manufacturing capability is shown with an oval in Table 4.2. The current capability at best can be considered average. There are only a few companies making headway into the adult level. There is no one remotely close to the world-class level that is needed to use manufacturing as a competitive weapon. This is all the more reason to invest more in eliminating waste from existing manufacturing systems, map the value stream to understand the processes, and improve processes to catch up with the manufacturing capability needed to compete in the specific phase.

Infant Level 1	Average Level 2	Adult Level 3	World Class Level 4
The production system makes little contribution to the organization's success	Manufacturing is satisfied to keep up with its competitors and maintain the status quo	The production system provides market qualifying and order winning outputs at target levels	The production system strives to be the best in the world in all activities in all manufacturing components
Manufacturing is low tech and unskilled	Manufacturing consists of standard, routine activities	All manufacturing decisions are consistent with the manufacturing strategy	The production system is a major source of competitive advantage

Table 4.2 The Overall Level of Manufacturing Capability [Miltenburg, 1995]

4.5 SUMMARY

The aerospace industry is in a phase where manufacturing capability seems to have the highest leverage of contributing to the success of the product. However, the aerospace manufacturing capability may not be at a level where it can be used as a competitive weapon. This should be a reason enough to increase spending on process improvement activities to achieve the needed level of capability as soon as possible. To avoid this situation in the future, it is argued that a manufacturing system design should be based on a product strategy that takes the industry and product life cycle dynamics into account. The importance of continuous improvement to keep up with the industry dynamics is also emphasized. In the next part of the thesis, a manufacturing system design framework is presented that shows the scope of manufacturing system design activity in its entirety with the above ideas incorporated. An outline for a manufacturing system design process is also developed based on the framework. Both, the framework and the design process, emphasize the need for a strategy and continuous improvement.

5 MANUFACTURING SYSTEM AND MANUFACTURING SYSTEM DESIGN

5.1 OVERVIEW

The long-term benefits of a strategy driven manufacturing system design were discussed in the previous chapters. Utterback's dynamics of innovation theory was used to identify the current state of the aerospace industry. It was argued that manufacturing capability currently might have the highest leverage in helping achieve the company objectives. This can be also be understood in Miltenburg's two choices for offering a product -- "order winning" and "marker qualifying" [Miltenburg 1995]. In the aerospace industry, it appears as if a product becomes order winning if it is perceived to be affordable over the product life cycle. Products with other characteristics, including new designs, might be considered simply market qualifying. This calls for understanding the current interests of the customers and designing a manufacturing system to fulfill those needs. The discussion on state of aerospace manufacturing highlighted the need for a structured, methodical manufacturing system design process based on a strategy that directs the factory operations. Currently, there is very little information available on manufacturing system design. To provide the companies with a way to achieve the desired capability when needed, and in an attempt to minimize trial and error and "gut-feel" decisions in manufacturing systems, a manufacturing system design framework and a manufacturing system design process that complements the framework is developed. The framework provides a good understanding of the scope of the design challenge, develops a sequence for design activities, highlights the tools available, and

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Order winning products differentiate manufacturers from one another. They are the reason why customers buy from a particular manufacturer.

Market Qualifying products are the ones the customers expect to receive. A product needs these characteristics to compete in the market place [Miltenburg, 1995] provides a way to think about various design possibilities. Moreover, it helps one to understand the strategic advantage of a manufacturing system.

The framework incorporates a great deal of information, which needs to be introduced in steps. The next few chapters will provide all of the information needed to understand the framework. Work presented in this thesis is influenced by the concepts of systems thinking and principles of systems engineering. In the sections that follow definitions for a system, systems thinking and systems engineering are provided. The systems nature of manufacturing operation is explored. A definition of manufacturing system is provided. The need for systems approach and systems engineering practices in manufacturing system design are also explored. The research team's view of manufacturing system design is presented. Also, the need for a holistic manufacturing system design tool is explored.

5.2 SYSTEM

A system can be defined in many different ways. Majority of the literature however agrees on defining a system as a collection of interrelated elements with functionality greater than the sum of the independent element functions [Boppe, 1997]. This definition is preferred since it highlights the major elements of a system. These are:

Collection of elements - indicating potentially more than one element
Interrelationships – indicating interactions and need for a structure
Functionality – indicating the existence of a specific function to satisfy a goal and existence of a system behavior to achieve the goal.

Simply put, a system exhibits "the whole is more than the sum of its parts" principle. A system exists within its boundaries. Any entity within the boundary becomes a part of the system and any entity outside the system becomes part of the ***system environment***. A system interfaces with its environment by accepting inputs and generating outputs. A system operates by accepting inputs, processing these inputs and producing outputs.

The internal processing of the inputs is governed by the function the system is designed to accomplish. Input is any stimulus that causes the system to operate and produce an output. Figure 5.1 shows a schematic of a system.

It should be noted that the elements of a system can themselves be major systems as is often the case. These component systems are called the subsystems. Thus, the system under consideration can be a subsystem of a larger system. This suggests that it is possible to have a system of systems. The need to define system boundaries to indicate where one system ends and the other begins becomes crucial in this case.

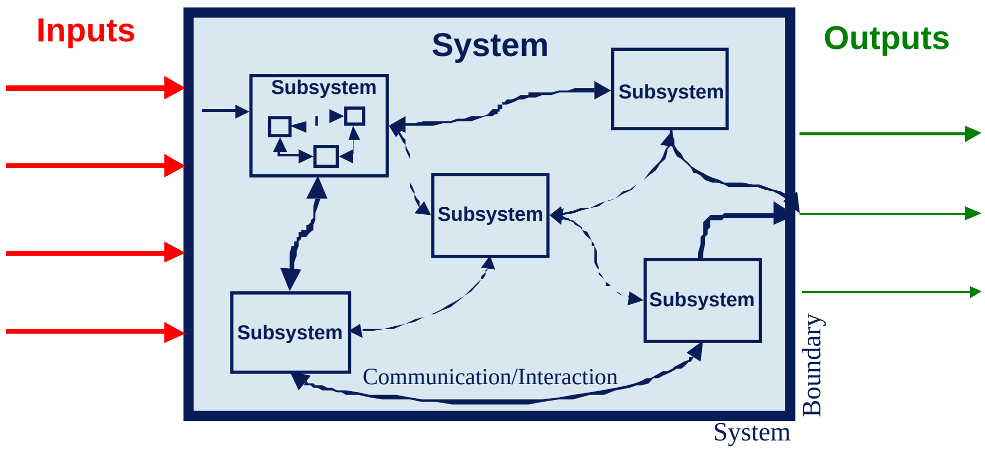


Figure 5.1 Schematic of a System

5.2.1 Systems Thinking (Systems Approach)

Systems thinking is the ability to approach tasks from a holistic view. It is a discipline to consider all components, interactions, system inertia, and the effect of any action on the entire system before implementing a solution or making a decision. It is the ability to realize that everything is connected to everything else and learn to compensate for this fact in every decision. Sterman says,

> "Accelerating economic, technological, social and environmental change challenge managers and citizens to learn at increasing rates. And we must increasingly learn how to design and manage complex systems with multiple feedback effects, long

> time delays, and nonlinear responses to our decisions. Yet learning in such environments is difficult precisely because we never confront many of the consequences of our most important decisions. Effective learning in such environments requires us to become system thinkers…" [Sterman, 2000]

Systems thinking is (1) a way of thinking, (2) a method or technique of analysis and (3) a management style [Wetherbe, 1988] all of which should be used concurrently to understand and process the task at hand thoroughly.

It is extremely difficult for humans to understand the effects of the interactions we have with each other and with the countless objects in the "world system". Humans have found a way of managing this level of complexity by focusing on the immediate locality of his/her presence and dealing just with those local interactions. It has also been shown that humans can process only 7 ± 2 bits of information at a time [Miller, 1967]. This severely limits human ability to process information requiring us to breakdown the tasks into small manageable chunks and to invent machines such as computers to deal with complexity. World system seems to function well with this reductionism approach. Reinforced by this observation, humans have relied too much and too often on breaking tasks down to the point of focusing on too small of a chunk of the problem. This makes the task easier to accomplish and might even yield the best results for that particular task. But, as Peter Singe says the problem with this behavior is that we can no longer see the consequences of our actions on larger tasks and we lose our intrinsic sense of connection to the larger whole. [Singe, 1990]. When the individual tasks are accomplished, we often try to connect all the pieces together hoping to achieve the larger task but this effort is futile, similar to trying to reassemble the fragments of a broken mirror to see a true reflection

5.2.2 Systems Engineering

Systems engineering can be defined as the selective application of scientific, engineering and management effort to transform user needs into a system configuration that best satisfies the operational need within an environment according to appropriate measures of effectiveness. [Boppe, 1997]

Systems engineering is a relatively new field of engineering necessitated by the advent of complex engineering products. As described above, humans reduce complexity by breaking down the problem to manageable levels but this leads to losing the perspective of the whole. The components of a complex system interact heavily with each other and influence the behavior of each other. A reductionist approach can not capture these influences and interactions unless the decomposition retains connections with the larger whole. Therefore, the development of complex systems requires a structured way of breaking the problems down yet retain the systems perspective. This exactly is what Systems Engineering helps accomplish. A systems engineering process achieves the following: [Oliver et al., 1997]

- Ensures that the components will integrate successfully and perform together as required
- Matches the product (design) to market place (need)
- Defines the components to enable the designers to design and build them
- Determines most of the design choices affecting system cost and performance

5.3 MANUFACTURING SYSTEM

A manufacturing system has the characteristics of a system. A manufacturing system takes inputs (product orders), processes inputs (transformation of raw material into products) and generates outputs (products), there are strong interactions between the various components of manufacturing system, and a system boundary can be identified around a company's manufacturing system. A manufacturing system typically is made up of multiple subsystems such as single machines, groups of machines, humans, fabrication units, assembly lines, job shops, cells, computer systems, suppliers, of other factories. For the manufacturing system to operate properly, all of these subsystems have to perform their specific functions at the right time and in right quantities. The system performance can be hampered if one of the subsystems fails to perform its task.

Likewise, the decisions made within one subsystem without considering the systemic effect, can have long lasting consequences on the entire manufacturing system. A manufacturing system therefore is in fact a major system. A manufacturing system is not just limited to the operation within the walls of a single factory. A manufacturing system may be made up of just one factory, multiple factories, suppliers, and/or contractors; all connected to operate as one system. The complexity of the manufacturing system can be appreciated by considering the interactions between these often geographically separated subsystems. It should be pointed out that each one of the subsystems could be major system by itself. Therefore, a manufacturing system is a system of many systems. Figure 5.2 shows a schematic of the manufacturing system to illustrate the general systems nature of manufacturing. The arrows are representative of the interactions between components.

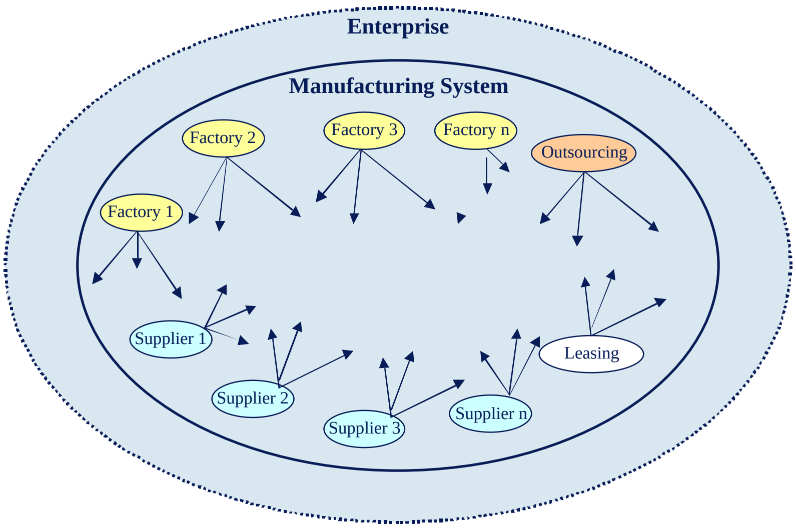


Figure 5.2. Representative Manufacturing System

A manufacturing system can be just one factory. All of the above discussion can be applied to a single factory itself. A factory is a network of various machines, manufacturing processes, software systems and people. Therefore, a factory also has subsystems. These could be one or more of job shops, cells, transfer lines, FMS, assembly lines, etc. All of these elements are tightly interrelated and interact with each other at every moment the factory is in operation. At any given moment, all elements have a specific function to accomplish to achieve a specific goal. It is important to note that these elements will not be able to accomplish the over all function of the manufacturing operation if they were to act independently. Note also that the elements themselves can be entire systems by themselves. Figure 5.3 is a schematic of a factory viewed as a system. A factory is also a system of systems, made up of different systems connected to form a “factory system”.

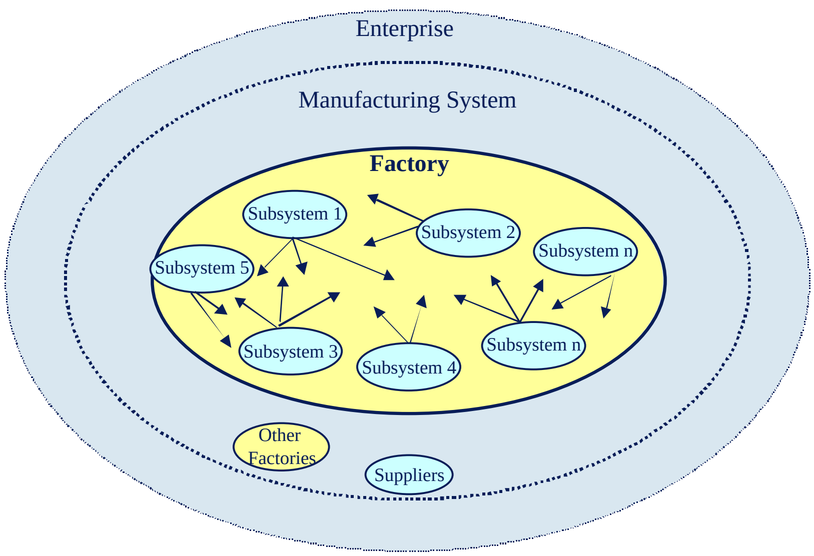


Figure 5.3. Factory Viewed as a System

5.3.1 Definition of Manufacturing System

With the above general description, it is clear that a manufacturing system is not just a production line, an assembly line, a cell, a unit that processes raw materials, a computer system, FMS, ERP or MRP. But, it is all of the these items interacting with each other along with workers, suppliers, processes and management to produce the strategically chosen products. Therefore, the goal of a manufacturing system is to support the business strategy of a corporation by producing products (or services) that have been chosen to help achieve corporate objectives.

A manufacturing system can thus be defined as an objective oriented network of people, entities, and processes that transform inputs into desired products and other outputs; all managed under an operating policy. [enhanced version of Hopp & Spearman, 1996]

The underlined words are key items of interest and they are described below:

Objective: The ultimate objective of the manufacturing system should be to help satisfy corporate goals. This view will be explored more in the chapters that follow.
Entities: Machines, tools, floor space, software, transport equipment, suppliers, etc.
Inputs: Raw materials, energy, and information
Outputs: Desired products, wasted materials, wasted energy, and knowledge
Operating Policy: A set of rules that determine how people, system entities, and the processes are interconnected, added, removed, used and controlled.

The manufacturing system plays major role in helping the corporation achieve its goals. Even though it appears as if selling the product generates revenue and hence the product design should be regarded highly, without adequate manufacturing capability the sales group will not be able sell for long.

Skinner describes the idea of operating policy (or manufacturing policy) very clearly [Skinner, 1969]. Skinner says that a manufacturing policy is a tool or a guideline to operate a factory in compliance with corporate strategy. The policy makes it possible for the manufacturing managers to make day to day decisions that support corporate objectives. A useful analogy to explain the manufacturing policy is the operation of a computer program. The main program has the logical set of rules to call various subroutines as appropriate. It has the authority to stop a subroutine prematurely and it has the authority to accept or reject the outputs of subroutines. Various subroutines are executed and depending on their outputs other functions are carried out. Here, the main program is analogous to decision-makers in a corporation and the set of logical rules that determine what is done when, is analogous to the manufacturing policy. The subroutines themselves are the manufacturing resources. Therefore, manufacturing policy is the underlying guide to add, remove, use and control workers, entities and processes. A manufacturing policy is needed in today's complex manufacturing environment. Due to the strong interaction between many different entities, even an experience manager might not be able to process all considerations and make wise decisions for the system without certain guidelines that assure positive results.

5.4 MANUFACTURING SYSTEM DESIGN

There is very little, if any, information available in literature on manufacturing system design. Because manufacturing system is a complex system, it should be designed as rigorously as one would design an aircraft. This design process typically takes a set of requirements, analyzes them using known scientific principles, makes assumptions, generates solutions, tests and fine tunes the results, and ultimately produces a solution with an acceptable level of performance. However, it is difficult to picture designing a manufacturing system using these traditional design methods. The aircraft, for example, can be designed and verified on paper using various well-known scientific principles before building any physical part. Not only is there a structured method to design and to evaluate the design, but it is also possible to verify the feasibility of design requirements based on mathematics and science prior to attempting the design. In the case of manufacturing, however, a complete 'manufacturing science' is not yet available. There are however pieces of scientific knowledge available such as the Little's Law and mathematical and scheduling techniques described by Gershwin [Gershwin, 1994]. Without a science, a designer can not even validate if the requirements themselves are feasible. In designing an automobile, depending on the vehicle weight and the horsepower generated by the engine, the acceleration and time to reach certain speed can be calculated. If any design requirements are outside the feasible range, it can be immediately shown using the scientific knowledge. There are neither equations nor complete dependable models describing a manufacturing system to make this possible.

It is too difficult to model a manufacturing system due to highly non-deterministic nature of the manufacturing operation. There are too many uncertain variables, the most uncertain of which are the human beings. Yet, factories have been designed and successfully operated over the past centuries. As discussed in Appendix B, most of the systems were put together using trial and error and continuous fine-tuning over the life cycle of the system. These methods are used even today, though they are much more sophisticated. Trial and error requires one to pick a certain system, try it first and then modify it to work in the current environment. Since there are numerous choices available, choosing the wrong system can lead to wasted time, and wasted investment. In manufacturing applications, both of these quantities can be in the millions of dollars. Most managers rely on their experience and intuition to select a system and make it work. Once a system appears to work under normal conditions, this system is used repeatedly for all conditions.

Most companies have found their own ways of designing factories. Some of the methods observed during research visits are discussed in detail in Chapter 6. Here, the thoughts of the research team on manufacturing system design are discussed. As described in Chapter 3, in practice, a manufacturing system design appears to be limited to trial and error and bounded by the four walls of a factory. We take a much broader perspective of manufacturing system design. The manufacturing system design begins and spans outside the factory floor. As described in the definition of manufacturing system, the goal of the system is to help satisfy the corporate goals. To do this effectively, a manufacturing system must be a part of the corporate strategy. Therefore, manufacturing system design begins as the corporate strategy is being formulated. This view gives manufacturing a much higher position in the corporate hierarchy and highlights the role that manufacturing can play in the success of the corporation.

Manufacturing system design can be viewed as the process of selecting manufacturing resources and designing an operating policy to produce the strategically chosen products at the right time and in right quantities. These manufacturing resources can be people, manufacturing processes, machines, tools, floor space, software, transport equipment, suppliers, energy source, and information. Therefore, a manufacturing system design activity is not just factory floor improvements, Kaizen events, value stream mapping, changes within the four walls of a factory, and waste elimination. But, it is all of these in addition to, selecting the appropriate layout, developing an operating policy, selecting right processes, technology, location, capacity and suppliers, determining the degree of supplier involvement, selection of organizational structure, and designing the interactions between all of the above.

5.4.1 <u>Structure</u> and <u>Infrastructure</u> Design of Manufacturing System Design

Careful observation of the above paragraph reveals two levels of manufacturing system design. One set of activities are associated with the factory floor – the ***structure*** of the manufacturing system – and the other set are associated with the overall operating environment of the system – the ***infrastructure*** of the manufacturing system. [Idea borrowed from Hayes & Wheelwright, 1984] Activities such as selecting the capacity, machines, layout, people, processes, etc are very closely associated with the factory floor. Activities such as the operating policy formulation, supplier selection, job design, organizational structure and choosing of the plant location, etc can be associated with infrastructure design. Note here that the manufacturing system design activity is NOT the summation of these two independent activities, instead it is a combination of infrastructure and structure design. The structure design follows the infrastructure design and both follow the product needs. One can not design a structure independent of the infrastructure and vice versa. Likewise, there are no practical reasons to design an infrastructure and not design a structure to go along with it. One can insert a new factory in an existing infrastructure, as is done often in practice, if the existing infrastructure supports the current product needs. Miltenburg [1995] observes the following from research done by Skinner [1974], Hayes & Wheelwright [1985], Buffa [1984], and Fine & Hax [1985]:

- Structural and Infrastructural designs are equally important.
- Both depend on each other
- Manufacturers who ignore either area for long will not be successful [Miltenburg, 1995]

Therefore, manufacturing system design should be a disciplined activity, which looks at the entire problem holistically. Systems approach is the most appropriate way to go about designing a manufacturing system. However, it should be noted that the manufacturing system design is vulnerable to fall prey to all systemic issues pointed out in section 5.2.1. The manufacturing system designers must consider all possible systemic issues to ensure stable and predictable operation of the factory. As described in section 5.2.1, a reductionistic approach can not guarantee a solution that takes into account all of the interactions between components. Literature warns manufacturing system designers against the potential for risk of sub-optimization, which can result from focusing too narrowly on a single system or task. As Wu [1992] says, the reductionist approach needs to be supplemented by a form of thinking based on wholes and their properties. The properties and behaviors of a system cannot be entirely predicted even from the fullest knowledge of each part's performance in isolation since each of these parts on its own does not exhibit the emergent properties of the whole. [Wu, 1992]

5.5 SUMMARY

The concepts of system, systems approach and systems engineering were briefly discussed. The manufacturing system was shown to have the characteristics of a major system of systems. A consequence of this view is that a single factory itself can be a major system. It was discussed that a manufacturing system often is larger than a factory. A formal definition and the purpose of manufacturing system were explored. The concept of operating policy, based on Skinner's work, was introduced. Based on the definition of manufacturing system, the scope of manufacturing system design was discussed. The design was explored briefly in terms of ***structural*** and ***infrastructural*** design categories. The need to treat manufacturing system design as a holistic and systematic activity was emphasized. The next two chapters will explore some tools available for structural and infrastructural designs. As it was mentioned earlier, a manufacturing system design is a combination of both, structural and infrastructural, design activities. A best design tool is the one that makes provision for both. As the next two chapters show, hardly any tools in literature come close to doing this. The framework presented here does a very good job at addressing both factions of manufacturing system design.

6 MANUFACTURING SYSTEM "STRUCTURE" DESIGN TOOLS

6.1 OVERVIEW

In chapter 5, manufacturing system design activity was discussed in terms of manufacturing system structure design and infrastructure design. Subsequently, the need for a holistic manufacturing system design tool was discussed. This chapter presents the tools that can be useful in designing the structure of the manufacturing system. None of the tools are complete by themselves but in appropriate combination, they do guide one in the right direction. Some of the tools discussed below were encountered during literature search and others were observed from factory visits and conversations with industry practitioners. Tools currently being used in factory design and concepts explored in the literature are discussed. Some of the tools or concepts behind the tools are used in the manufacturing system design framework developed in this thesis.

6.2 TYPES OF MANUFACTURING SYSTEM DESIGN AIDS

The research team encountered three different types of factory design aids during literature search and conversations with the industry practitioners. The literature provided two of the three types of tools. One recurring concept in literature was the attempt to fit existing manufacturing systems to current production needs. The second category of tools was various frameworks aimed at describing a manufacturing system pictorially. The third category we encountered was the practical methods used in the industry to implement manufacturing systems. Each of the following design aids is discussed in detail below:

- Mapping of the existing manufacturing systems
- Manufacturing system design methods
- Manufacturing system design frameworks

6.2.1 Mapping of the existing manufacturing systems

These maps are based on characterizing existing manufacturing systems (job shops, cells, JIT, etc.) on a two dimensional plot. The axes typically chosen are product volume and variety. To use this tool, one would simply plot the expected volume and product variety and see which existing system qualifies. Even though the tools have limitations, the concept itself is a useful design guide since it helps in narrowing down the design possibilities to a few manufacturing systems based on expected volume and product mix. The designers can concentrate on these systems and explore them further. However, this tool has many limitations and it should be used only as a rough guide. Appendix D describes these existing systems in more detail.

To be effective, this approach requires the ability to characterize a manufacturing system well. There have been many attempts made in the past to characterize manufacturing systems using only two variables. While this mapping gives a fairly good description of the manufacturing system, the research team believed that two variables could not describe a complex system sufficiently. There are dozens of these charts available in literature. One of the best ones found is shown in Figure 6.1. Other such 2-D plots by [Chryssolouris, 1992; Miltenburg, 1995; Kalpakjian, 1995; Groover, 1980; Wakil, 1989; Boothroyd, 1983] are provided as part of Appendix D.

While all of these charts give valuable information and help eliminate guessing at the system once the two quantities are determined, they do not present the entire picture. First of all, from correspondence with some of the above authors revealed that these charts were generated based on author's experience and not on actual data. It is not to say that these charts are not credible but for sure they are not exact. Moreover, a manufacturing system can not be characterized with only two factors. Due to the complex nature of the manufacturing systems, the two factor depiction of the system leads to ignoring many of the important factors that make each manufacturing system unique. One of the consequences of reducing the multiple dimensions to two is the extensive overlap of systems seen in Figure 6.1. A designer will have to make a gut-feel decision if he finds himself in the overlap zone. Likewise, the system boundaries in these tools seem very concrete and deterministic, it is hard to believe that there are such boundaries between systems in reality since any system can be stretched to perform outside its zone, though with reduced performance levels. Most noteworthy shortcoming of these manufacturing system maps is that these are depictions of the current state. They do not incorporate knowledge gained since the systems were designed. This fact severely reduces the usability of these charts. The systems in place now were developed for a different set of conditions. Most of them probably were based on unit cost minimization. The manufacturing and business environment today could be something entirely different. Using these charts without realizing this fact can lead to selecting a wrong system for the current manufacturing environment, even though the plot suggests one has selected the right system based on the two factors.

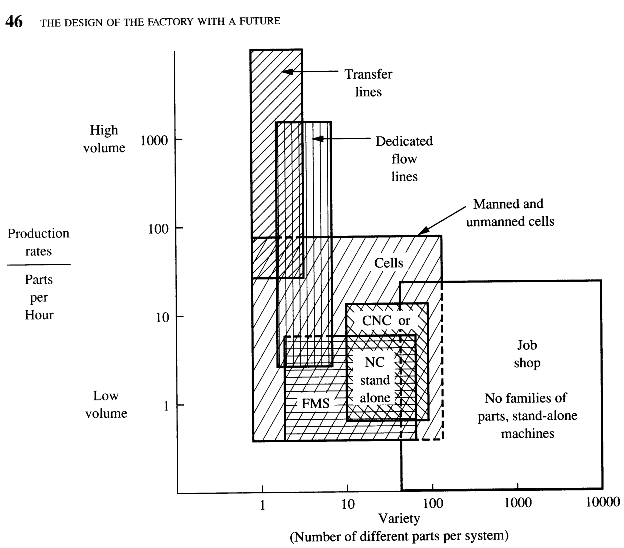


FIGURE 2-15
A comparison of different kinds of manufacturing systems with cells.

Figure 6.1 Characterization of Manufacturing Systems [Black, 1991]

The research team attempted to enhance these existing 2-D plots by adding additional information to them. The task was to find out what other factors are needed to describe a manufacturing system sufficiently. Industry wide plant visits, discussions, seminars and individual interviews lead to adopting 10 factors to describe a manufacturing system. These factors are compiled from a list of inputs from more than 100 people with varying levels of experience in manufacturing systems. A detailed description of each of the following 10 factors is presented in Appendix C.

1. Market Uncertainty
2. Product Volume
3. Product Mix
4. Frequency of Changes
5. Product Complexity
6. Process Capability
7. Worker Skill
8. Type of Organization
9. Time to first part
10. Investment

These factors not only allow one to understand the challenge at hand but they also direct the design efforts in the right direction and eliminate intuition-based decisions. There is much research to be done in this area. The research team attempted to use three variables to add more some more detail to the plots. The data used in these 3-D plots was purely based on the team members' experience. These plots were produced just to verify if any new information can be revealed. Process capability, product complexity and Product volume were chosen to be the three axes. The team believed assumed that these three axes represent the other factors sufficiently well for the purpose of this exercise. Two different versions of the plots were produced on showing various systems and the other showing various products. The plots are shown in Figure 6.2 and Figure 6.3. The results showed that adding just one more dimension added lot more meaning to the charts. For example, the product chart (Figure 6.3) shows a large separation between the location automobiles and aircraft. This can be compared to the process chart (Figure 6.3) to see which processes are most appropriate for aircraft manufacture and for automobile manufacture. The extensive overlap seen in 2-D plots is mostly nonexistent in the 3-D plots.

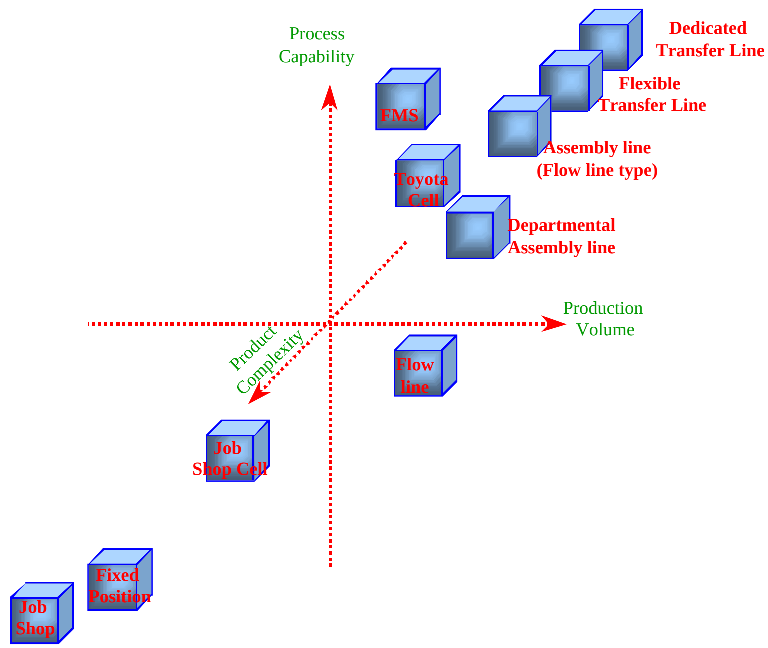


Figure 6.2 3-D Map of the manufacturing world (Process)

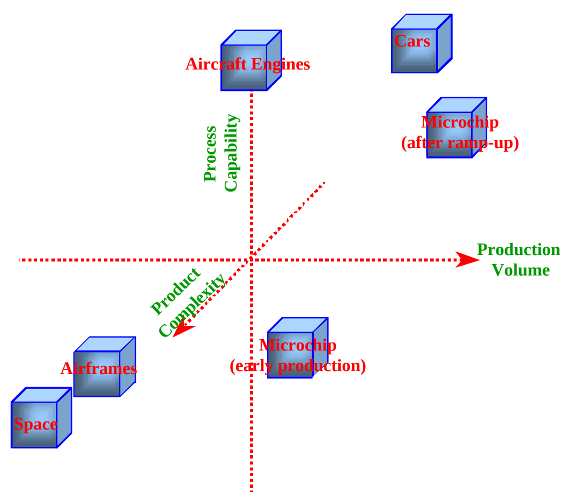


Figure 6.3 3-D Map of Manufacturing World (Product)

These plots show great promise in better understanding manufacturing systems. The research team is trying to come up with a way of quantifying the above inputs and developing a system of plots based on actual data to ease the manufacturing system selection process. Efforts are underway to understand the effect of each of these factors on the manufacturing system performance. There are two research assistants at MIT working on these issues currently.

6.2.2 Observed Manufacturing System Design/Implementation Methods

Even though there is no manufacturing science and formulas to design factories, there are factories all over the world producing parts and meeting customer demand. From observation, literature, exploring the history of manufacturing systems and conversations with practitioners, a combination of the following methods seems to be used in the industry:

- Trial and Error
- Cooperative Decision Making
- Company Standard Manufacturing System
- Structured Design Methodology

6.2.2.1 Trial and Error/Experimentation Technique

As discussed in Appendix B, manufacturing systems have been developed ('designed') in the past using extensive experimentation and trial and error. The developments took decades and an unknown amount of financial resources. All of the major manufacturing system developments such as technique of interchangeable parts, mass production and, even the Toyota Production System were achieved through trial and error and experimentation. This appears to be the solution practitioners have resorted to circumvent the lack of scientific methods.

The way trial and error is used in at least three different ways:

- Scaled mock-ups
- Shop floor trial and error

· Computer simulation

Scaled mock-ups and shop floor trial and error seem to be the methods used in the past. In scaled mock-ups, ideas are tested on scaled down versions of factory equipment to assess the feasibility and performance of the system. These experiments are usually performed outside the factory floor using scarp or other economical materials and simple household tools. Some companies call these areas their "moonshine shops".

In the shop floor trial and error, a pilot area is set up on the factory floor and new ideas are tested on full-scale parts and equipment. This phase usually follows scaled mock-up experiments. Here, parts are produced and the system is continuously fine-tuned. If the system does not perform to the expected level, the whole set can be scraped and a new setup is designed. This method can be significantly more expensive compared to the scaled mock-up method. It is safe to assume that both of these methods were used in the development of all major manufacturing systems mentioned above. Major aerospace manufacturers are still using the method today.

To some extent, trial and error method is still used today in setting up facilities. To reduce time and financial expenditure, companies use computer simulations to verify the designs before disrupting the factory floor. While this can save significant amounts of time and money, the results might not be very accurate since it is very difficult to model a factory mathematically.

6.2.2.2 Cooperative Decision Making

Companies also use group decision-making techniques, where experts from all disciplines (product designers, manufacturing engineers, industrial engineers, sales and marketing personnel, etc.) get together to come up with ways to manufacture a product. This is a structured brainstorming exercise to devise a process to manufacture a part with just the right amount of resources. This method seems most applicable to manufacturing process design. Industry practitioners believe that this method can be used at a system level to design the entire structure of the factory. A commonly used such method is the ***Production Preparation Process*** (3P). The outputs of a 3P exercise can be the manufacturing process, assembly sequence, job design, skill requirement, machinery requirement, and the energy source. These outputs define the structure of the manufacturing system. The 3P has the following steps: [adopted from Wiremold, Inc.]

Determine Evaluation Criteria: As a team the manufacturing criteria, the method of measurement for each criteria and the absolute scale for evaluation are defined

Break the Product Down: The prototype parts, if available, from the design effort are disassembled into components and raw materials. Fishbone diagrams showing the components from raw material to finished product are created.

Find Key Words: Key words such as roll, rotate, form, bend that describe the processes to changed the materials at each branch of the fishbone diagram are brainstormed. Similar words are grouped and for each group two or three words best describing the group are selected.

Find Examples in Nature: Examples of each process keyword selected above are found using nature, books, Internet etc. For example, forming can be found in the nature when a heavy animal such as an elephant walks on mud. Similar examples are grouped and examples that most clearly illustrate the process key word are selected.

Analyze Mechanisms: The selected examples are studied in detail to understand how these examples occur in the nature. Some sketches are made to assess the feasibility of using the selected examples in the process of interest. Assuming that the nature has had millions of years to perfect these mechanisms, heavy emphasis is placed on this step in learning how nature works and why.

Develop 7 Ways: Sub-teams are formed and each sub-team member is required to draw 7 different ways to accomplish the process. All the sketches are collected, similar ones are grouped and posted on the wall.

Evaluate 7 Ways: Each of the 7 ways from each of the team members is evaluated using the criteria defined in step 1 and three best ways are chosen. Any good features from ways not chosen are also considered.

Moonshine 3 Process Ways (simulate process): Without considering the machine or energy source, the three selected ways are prototyped. The three selected processes are thoroughly simulated, evaluated using the measurement criteria defined earlier, and sometimes the process is video taped for later review. A Process-At-a-Glance sheet showing the entire process at high level is generated

Present and Select Processes: The prototype processes are presented by each of the sub-teams. The entire team votes on the processes. The concepts are selected for further refinement.

Hold Design Review: The processes are presented to a larger group including product designers seeking feedback. Any product or component changes proposed by the 3P team to aid manufacturability are also reviewed.

Select Energy Source: For each process the energy requirements are reviewed and quantified. The machinery required to deliver the energy most efficiently is sketched.

Develop Project Implementation plan:

An implementation manager/leader is elected. Work Breakdown Structure (WBS) and resource requirements, responsibility matrix, deliverables and schedule are generated.

6.2.2.3 Company Standard or Baseline Manufacturing System

Some companies have adopted a certain manufacturing system as a company standard or a baseline manufacturing system. As new products are introduced, this system is first duplicated as is and tweaked to fit the current production needs. Historically, this has been the common trend in manufacturing system development, where once a new system is put in place, that system is used over and over again until it can no longer satisfy the production needs. The assembly system currently used for aircraft manufacture in the aerospace industry was originally developed in the 30s for B-24 and B-17 bomber assembly (Appendix B). The system used today is fundamentally the same with some changes in the equipment, people and raw materials. It is often difficult to find out when and why the system was developed and adopted to be the standard. It is should be noted that this type of a mentality assumes that one system satisfy all market/ manufacturing environments. Conversations with practitioners in the aerospace industry revealed that this is the preferred method of designing a new factory or inserting a new production line in an existing factory. Most of the time, the baseline system is implemented and using trial and error, fine-tuned to desired level.

6.2.2.4 Structured Design Methodology

A structured design method is the focus of this thesis. This topic will be explored in much more detail in later chapters. The idea here is to use a disciplined design process such as the one used for a product design. This process doesn't seem to exist in any of the companies visited. But there has been some research in this area. One such approach is to design a manufacturing system using a known design methodology such as the Axiomatic Design [Suh, 1990]. The Manufacturing System Design Decomposition (MSDD), developed by the MIT Production System Design lab [Cochran, 2000], is one of the best examples of this type of a method. The MSDD is an application of axiomatic design. The axiomatic design provides a structured way of breaking the problem down to its lowest levels while maintaining the systems aspect of the design object. Axiomatic design starts with a top level Functional Requirement (FR) and Design Parameters (DPs) to satisfy the FR. Each DP is then broken down subsequently into its own FRs and DPs. The lowest level DP of a given branch is the design parameter that should be considered to achieve the very top level FR. The MSDD will be revisited and discussed in more detail shortly. The MSDD was developed based on research in the automobile industry. Recently, MIT has published an Aerospace version of the MSDD (AMSDD) [Dobbs, 2000]. Almost all of the companies we visited have seen the MSDD. Some of them are trying to use the insights they have gained from the MSDD.

6.2.3 Manufacturing System Design Frameworks

There are several frameworks available in the literature all attempting to describe a manufacturing system. A complete framework can be a very useful tool in understanding the scope of the manufacturing system design and in understanding the manufacturing system itself. Most of the frameworks, which will be discussed shortly, were very instructive and informative but not complete. They are applicable at various stages of manufacturing system design but not the entire system design. Most of them however, focus on the factory floor implementation.

Some of the frameworks that made some contribution have been discussed and critiqued below. The criteria used to study the frameworks are as follows:

- Does it show all relevant entities?
- Does it imply a strategy behind the design?
- Does the framework describe a general manufacturing system or focus on a specific system?
- Does it show/imply all applicable levels of decision entities, influences and interactions?
- Does it link corporate, middle and functional management objectives to factory floor design and operational decisions?
- Where does the framework fit in the manufacturing system design process?

The following frameworks are described in detail in the subsequent sections based on the evaluation criteria given above.:

1. Toyota Production System Framework (Toyota Supplier Support Center) [Duda, 2000]
2. Toyota Production System Framework by Monden [Monden, 1983]
3. Integrated Manufacturing Production Systems [Black, 1991]
4. Manufacturing System Design Decomposition [Cochran, 2000]
5. The Manufacturing Strategy Worksheet [Miltenburg, 1995]

6.2.3.1 Toyota Production System Framework (Toyota Supplier Support Center, TSSC)

As the name indicates this framework specifically describes the Toyota Production System (TPS). As shown Figure 6.4, this framework shows that TPS has three goals at the highest level: high quality, lowest cost, and shortest lead-time. The framework emphasizes that a stable manufacturing process is the foundation on which the entire system is built to achieve the above goals. The framework also shows the tools and practices that are necessary to achieve the goals once a stable manufacturing process has been achieved.

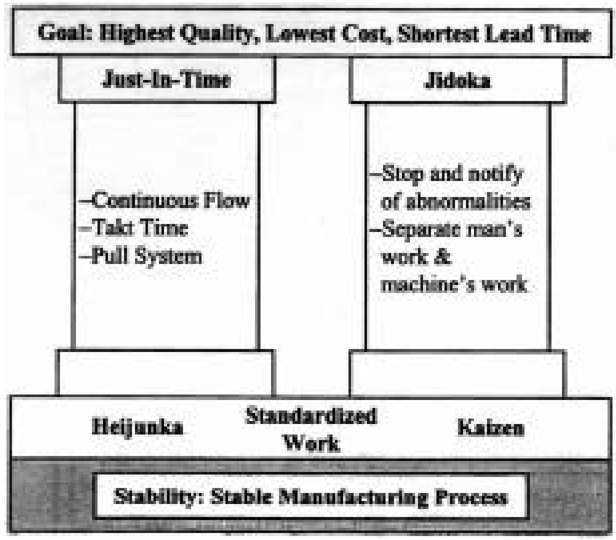


Figure 6.4 Toyota Production System Framework [Duda 2000]

This framework is a great visual description of TPS and a very helpful tool to understand hierarchy of principles of TPS. However, it is very specific to TPS and not useful if a different manufacturing system is chosen for implementation. The framework falls short in connecting the factory floor to other important components of the enterprise. It is not clear how product development, suppliers and customers interact with each other. It is also not clear how the highest goals shown relate to the corporate goals. They appear to be the goals of manufacturing system and not necessarily of the corporation. This is a good framework to understand what needs to be done on the shop floor to achieve lowest cost, shortest lead time and highest quality but it is not clear where these goals came from and how they benefit the entire system.

6.2.3.2 Toyota Production System Framework by Monden

The framework developed by Monden, shown in Figure 6.5, emphasizes the importance of factory floor activities in achieving high level goals. It also shows the implementation sequence of TPS principles/practices to achieve high level goals. The upward direction of flow from the shop floor indicates that the lower level activities are prerequisites to achieving high level goals. This framework is very instructive to factory floor improvement leaders. It shows a sequenced checklist of activities and prerequisites to achieve top level goals.

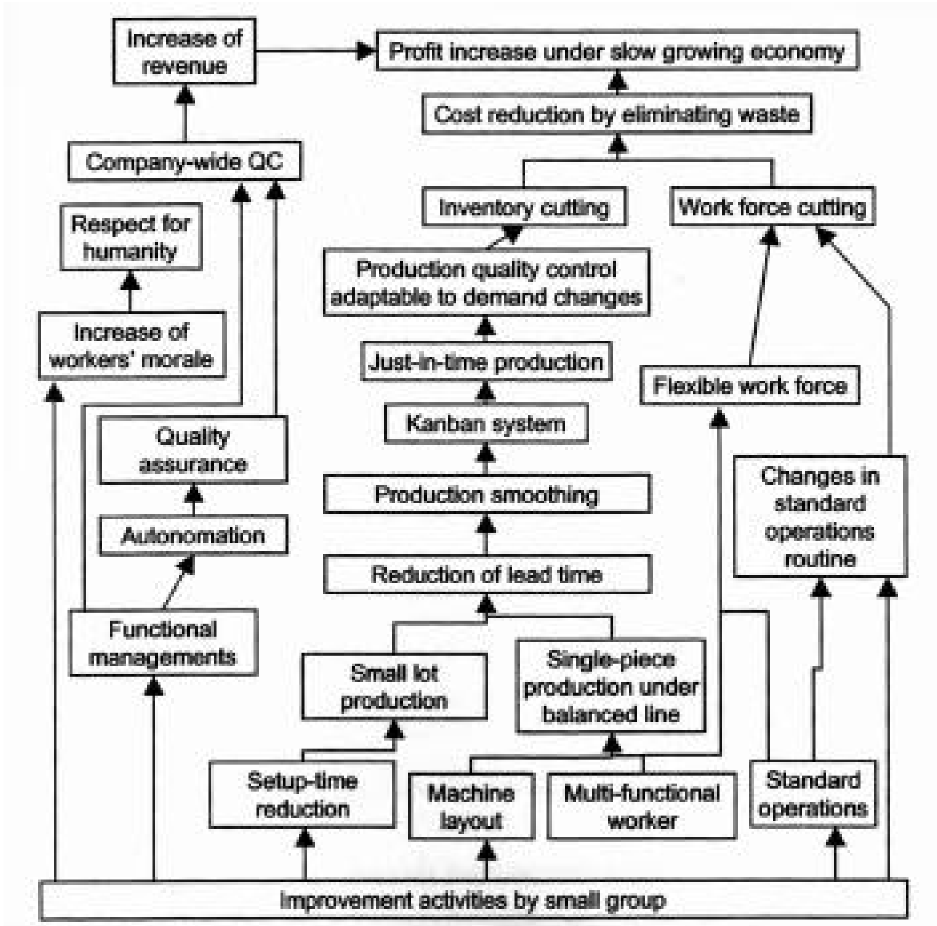


Figure 6.5 Toyota Production System Framework by Monden [Monden, 1983]

This framework is also very specific to implementing Toyota production system. Compared to the TSSC, this framework gives more details and indicates the flow of information. It should be noted that there is a fundamental assumption made here that the factory floor leaders could correctly interpret corporate goals and then design activities to achieve them. If the goals are interpreted wrongly, the solutions generated might not match up with what was expected. Also, the top-level goal is assumed to be increase of revenue, which might not be the case in all situations. But, many of the practices mentioned may benefit the system but might not be the only ways to reach the goal. This framework again comes in handy if Toyota Production System has been selected to the system of choice. This framework can not be used to determine what system to pick. Note also that this framework requires an operational system.

6.2.3.3 Integrated Manufacturing Production Systems Framework

J. T. Black recommends a 10-step process to implementing what he calls an integrated manufacturing production system (IMPS) [Black, 1991]. In his definition, a production system is bigger than a manufacturing system. It includes manufacturing system plus all the other functional areas of the plant that provide information, design, analysis, and control. The ten steps (shown in Figure 6.6) offer a sequential progression towards an automated and computerized production system. The author calls for a system level change, a change that is not limited to the manufacturing floor. In his opinion, implementing the ten steps will require change in top management to shipping.

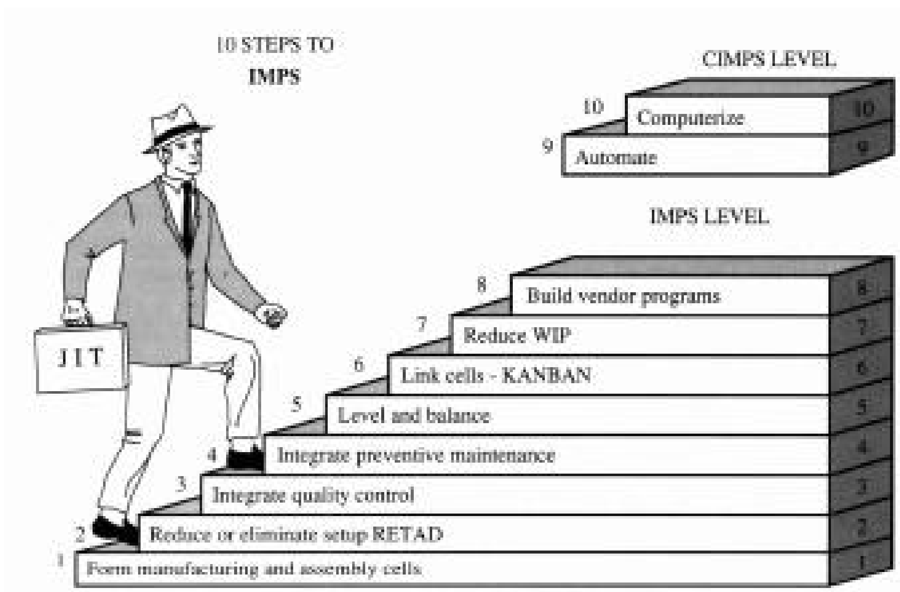


Figure 6.6 Ten Steps to Integrated Manufacturing Production Systems [Black, 1991]

While the idea behind the framework is excellent and agrees with the thoughts presented here, the framework itself leads only to a cellular manufacturing system. The ten steps are mostly applicable at the factory floor level and do not clearly indicate any effect on the activities outside manufacturing floor. A manufacturing strategy or a product strategy is not clear from the framework. Moreover, the end goal seems to be reaching computerized automation but it is not clear how this would benefit the corporation. It appears as if the system is designed assuming that automation and computerization will benefit the corporation some how. The framework also falls short of linking manufacturing and other corporate functions.

6.2.3.4 Manufacturing System Design Decomposition (MSDD)

This is the first tool we came across that clearly, as the author [Cochran, 2000] points out, separated objectives from the means of achievement. The tool is an application of the Axiomatic Design (AD) methodology developed by Nam Suh at MIT [Suh, 1990]. The framework defines one high level goal (Functional Requirement (FR) in AD terminology) and breaks it down systematically into means (Design Parameter (DP)) of achieving that FR. Cochran has used Return on Investment (ROI) as the top-level goal. Here, the AD process in six levels of decomposition translates the top level FR into factory floor level DPs (means of achieving the goal). The various levels of decomposition guide user in reaching the lowest level DP. The framework should be traversed left to right, top to bottom. That is, left branches of all FRs should be achieved before attempting the right branches. The entire decomposition is organized under six categories, they are (from left to right): Quality, Identifying and Resolving Problems, Predictable Output, Delay Reduction, Direct Labor, Indirect Labor. The MSDD offers a structured way of connecting top level goals to factory floor level goals. The DPs at each level embodies a set of industry best practices to achieve the FR. Figure 6.7 below shows a schematic of the entire MSDD.

The MSDD is a very effective tool to communicate goals from management level to the factory floor level. The graphic nature of the tool shows the connections between factory floor processes and top-level management actions. The tool also translates high-level business goals into factory level processes details. The AD technique is very useful since it can lead to a brand new system depending on the high level goals. It can be a structured creativity tool, where new or "hybrid manufacturing systems" can be developed as part of the design process. The design space is not limited to selecting existing manufacturing systems. The MSDD itself is an excellent collection of the industry best practices. It could be an excellent guide to verify if the processes being selected for implementation are the best available in the industry.

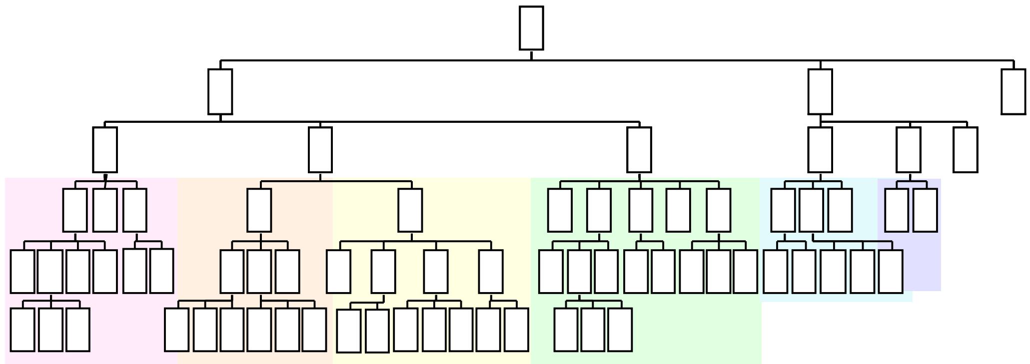


Figure 6.7 Manufacturing System Design Decomposition (MSDD) [Cochran, 2000]

In keeping with the evaluation criteria, the MSDD itself has a few shortcomings. The most striking is the one top-level goal. By its nature, the design obtained at the factory level through axiomatic design methodology depends heavily on the top-level goal. Any changes in the goal can make the manufacturing system incompatible with the enterprise. Not only that, MSDD assumes this top-level goal to be ROI, this appears to be a very good choice but might not be a universal choice. As the executive interviews and repeated conversations with industry practitioners showed that the aerospace industry is concerned more with profitable growth than ROI. It should also be noted that using ROI gives preference to the shareholders more than any other stakeholders.

The MSDD is not based on a business strategy or a manufacturing strategy. This is rather disturbing since the framework makes no mention of selecting a product to strategically meet the business needs of the organization and subsequently designing a manufacturing system to support the market needs. It appears as if the message being conveyed is that no matter what the market or competition conditions are, a manufacturing system based on best practices general and designed to satisfy the over all corporate goal is sufficient for the company to compete effectively. In aerospace industry, however, there is hardly ever been a factory erected prior to a product design or selection. There is too much risk involved with building a generic factory and inserting any product into it. As it will be described later, the middle management interprets corporate strategies and selects products and services to achieve the corporate goals. A manufacturing system should then be designed to support the business strategy since this is the strategy that helps the corporate goals become reality. By ignoring the product, MSDD effectively isolates manufacturing system from product design organization. This in effect isolates the various components of the business unit rather than seeking collaboration between them. There are currently efforts in progress to add the product design component to the existing MSDD.

Even though the axiomatic design method is supposed to yield a unique design based on the top-level goal, MSDD appears to yield a design influenced by principles of JIT or TPS. The assumption might be that JIT or TPS is the best system available. This assumption is also verified by Miltenburg [Miltenburg, 1995]. But, the assumption makes the tool a specific tool than a general manufacturing system design tool.

6.2.3.5 The Manufacturing Strategy Worksheet

This is the best framework of all the different ones encountered during research. The framework is a worksheet to select an appropriate manufacturing system based on a manufacturing strategy. John Miltenburg has compiled recent research and developed this excellent worksheet/tool [Miltenburg, 1995]. The worksheet links six ***manufacturing outputs (***delivery, cost, quality, performance, flexibility, innovativeness) to existing manufacturing systems (Job shops, Batch flow, Operator-paced line flow, Equipment-paced line flow, continuous flow). The author (Miltenburg) evaluates the suitability of each of the manufacturing systems in delivering the six manufacturing outputs. The framework also shows ***manufacturing levers (***Human resources, Organization Structure & controls, Production planning & Control, Sourcing, Process Technology, and Facilities), which need to be added, deleted or modified to achieve the desired system outputs. Figure 6.8 shows Miltenburg's manufacturing strategy worksheet. The recommended use of the worksheet is as follows:

- Determine the Product to be offered to support corporate goals

- Determine if the product is planned to be marketed as a ***Order Winning*** or ***Market Qualifying*** product
- Perform competitive analysis to determine which manufacturing outputs are needed to achieve goals in (2) and to asses the strength of competition
- Select the one or more outputs and see which system provides those outputs
- Perform a company capability analysis to determine if the current manufacturing system can fulfill the new requirements
- Determine which manufacturing levers need to be adjusted
- Develop an implementation plan

This framework is very general, in a sense it gives an option to select different manufacturing systems based on a predetermined strategy. The framework forces the designers to have a product and a strategy in mind before attempting to select a manufacturing system. This eliminates the possibility of selecting a system based on faith, recent fame and on executive recommendation. Instead, it encourages selecting a system that will best meet the market requirements for the strategy chosen. The framework is also not specific as far as the goals are concerned, it allows for up to six manufacturing outputs (or goals). These six outputs can represent a host of corporate objectives.

The framework does fall short of showing a clear connection between corporate goals and manufacturing goals. It is not very clear which of the corporate goals are satisfied by selecting one of the six manufacturing outputs. However, necessitating product knowledge before hand does loosely imply this connection. It can be assumed that whoever selects the manufacturing outputs, has considered corporate objectives prior to making a decision. The framework does lack a clear picture of the activities outside of the manufacturing function. The tool is very useful once an appropriate product strategy has been chosen and manufacturing outputs required to support this strategy can be derived. It should also be pointed out that the linkage between manufacturing outputs and manufacturing systems is purely based on author's experience. The validity of which needs to be verified but the concept behind the whole framework is very useful.

The tool does not provide an implementation plan but does point to the appropriate system and exposes the requirements to get to that system. The framework developed in this thesis uses many of the concepts from this framework.

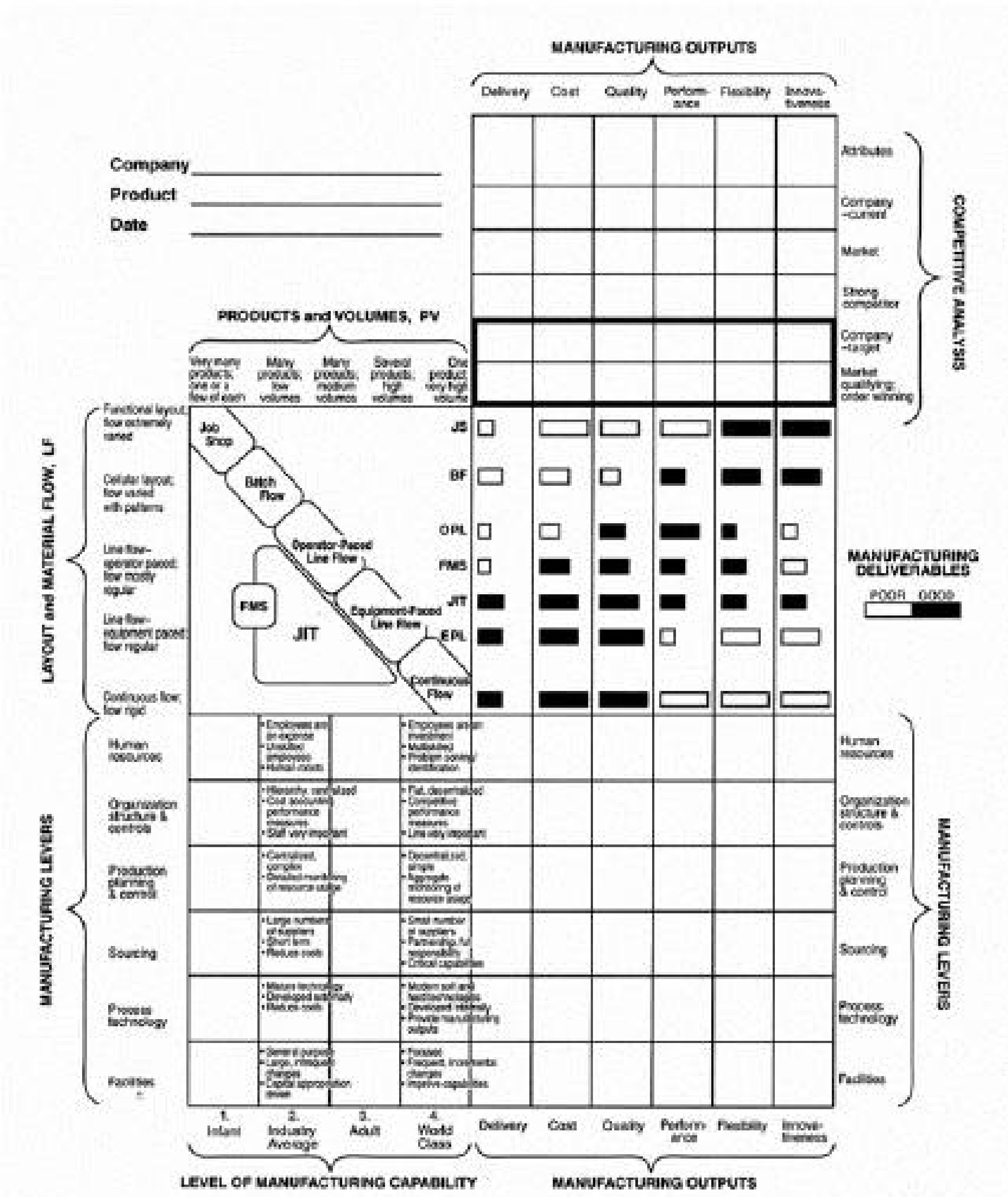


Figure 6.8 The Manufacturing Strategy Worksheet [Miltenburg, 1995]

6.3 SUMMARY OF STRUCTURE TOOLS

In this chapter three different types of tools were discussed, mapping of the existing manufacturing systems, manufacturing system design methods and manufacturing system design frameworks. Even though most of these methods are not complete solutions to manufacturing system design, they do make valuable contributions to various stages of the design. The table below summarizes the applicability of the tools.

Name of the tool	Type of tool	Application
Mapping of the existing manufacturing systems	Classification of systems	· Range of available systems · System selection based on volume and variety · Locating current operating environment
Trial and Error	Implementation	· Computer simulations · Factory floor testing · Fine tuning
Cooperative Decision Making	Process design, system design	· Manufacturing process design · Assembly sequence design · Process Improvement
Company Standard Manufacturing System	N/A	Increasing current manufacturing capacity
Structured Design Methodology	Design, communication, structured decomposition,	· Goal based new system design · Translation of goals into physical activities · Communication between organizational levels
Toyota Production System Framework (Toyota Supplier Support Center, TSSC)	Framework	Understanding TPS
Toyota Production System Framework by Monden	Framework	Understanding TPS
Integrated Manufacturing Production Systems Framework	Framework	
Manufacturing System Design Decomposition (MSDD)	Specific application of Axiomatic Design	Design
The Manufacturing Strategy Worksheet	Framework, Strategy tool, Design tool	· Manufacturing strategy, · System selection · Current manufacturing capability assessment · Determination of changes needed · Decision aid

7 MANUFACTURING SYSTEM "INFRASTRUCTURE" DESIGN

7.1 OVERVIEW

Manufacturing system infrastructure design involves the design of elements supporting the factory floor operation. As discussed in Chapter 5, some of these elements can be the following: developing an operating policy, selecting the right processes, technology, factory location, capacity, suppliers, determining the degree of supplier involvement, selection of organizational structure, and designing the interactions between all of the above. These decisions are crucial and the results of these decisions will no doubt affect the company bottom-line over the long run. This is yet another reason to consider manufacturing as an important component of the corporate strategy. The operating policy, for example, is an extension of the corporate strategy to the factory floor operation. Therefore, the above decisions should be made based on a strategy. As it will be discussed in the next chapter, the view adopted in this thesis is that there are three levels of strategies in a corporation – the corporate strategy, the business unit strategy and the functional strategy. There is one corporate strategy but there can be multiple business unit and functional strategies. The Manufacturing function typically falls under a business unit. Manufacturing function can and should have a manufacturing strategy. The decisions needed for manufacturing system infrastructure design are therefore related to the manufacturing strategy. In this chapter, the need for a manufacturing strategy is discussed, past research on the subject is presented and some strategy formulation tools are explored.

7.2 WHY IS MANUFACTURING STRATEGY NECESSARY?

A strategically managed corporation can have a better chance of growing profitably over the long-term than a corporation managed by just intuition and experience. A manufacturing strategy provides a vision for the manufacturing organization to keep itself aligned with the overall business strategy of the corporation. It consists of long term objectives, programs, and initiatives. These help the business gain and maintain a competitive advantage [adopted from Schroeder, 1990]. The key idea here is to prepare a company to compete in the future. The current state is important and the fact that the company has survived thus far is an indication that something was done correctly in the past. Considering manufacturing operation as a strategic weapon rather than just a “widget producer” has enormous effects on manufacturing system design, manufacturing operation and improvement activities. Moreover, a manufacturing system that is designed strategically, and integrated properly with the rest of the enterprise functions plays an important role in helping the enterprise achieve its goals [Buffa, 1984]. Hayes and Pisano point out that manufacturing strategy is a long-term plan focused on creating operating capabilities a company will need in the future. The key to long-term success is being able to do certain things better than your competitor [Hayes & Pisano, 1994].

This is especially true for the current status of aerospace industry. As discussed earlier, the aerospace industry has reached or is fast approaching a phase where manufacturing capabilities might have the highest leverage. A well-formulated manufacturing strategy can benefit the corporation by enhancing the existing product sales purely through manufacturing abilities. One visible consequence of this phase is the customer demand for low acquisition cost. This is already apparent in the commercial aircraft sector. Airbus is winning more orders since it is offering aircraft at a lower cost. It is not to say that Airbus has a better manufacturing strategy than other manufacturers but, the point being made is that sales are determined by cost and not by product performance. Manufacturing organization plays a major role in acquisition cost of a mature product.

To use manufacturing as a competitive weapon, the corporation needs to be well aware of the market environment and its competitors’ position in the market. The value of the strategy is in selecting those elements that the customer values and are difficult for the competitor to duplicate [Hayes & Pisano, 1994]. This information can be used to design manufacturing systems to give the desired output to differentiate products in the market. This will be covered in more detail in later chapters. Once implemented, having a strategy will help the managers set priorities among daily activities by establishing long-term objectives. As Miltenburg says when a formal strategy exists, decisions follow in a neat, logical pattern and in the absence of a strategy the decisions are erratic and often are based on intuition [Miltenburg, 1995]. Likewise, the process improvement activities can also be based on strategic long-term needs rather than on management shock-responses to the latest 'hot system' of the month. The strategy development process also alerts corporation on competitor's position and any need to further develop existing core competencies. Manufacturing management without a strategy will only lead to the wrong systems and decisions. A strategy is also a strong communication tool between different levels of management to bring all operations in line with corporate objectives.

A well-formulated manufacturing strategy provides the following benefits:

- Aligns manufacturing with business and corporate strategy
- Decisions based on long-term objectives of the enterprise,
- Assures long-term product, capability and process differentiation from competitors.
- Makes manufacturing an integral part of the enterprise strategy,
- Provides for clear communication between management levels,
- Helps select improvement/capability building activities that will contribute to long-term enterprise success

6. Creates an awareness of competition

7.3 MANUFACTURING STRATEGY FORMULATION

Research on manufacturing strategy has been progressing ever since Skinner published his HBR article, "Manufacturing – Missing Link in Corporate Strategy" in 1969. Some of the concepts or high level tools that help one formulate a manufacturing strategy are discussed below.

- Focused Factory [Skinner, 1969, 1984]
- Product-Process Matrix [Hayes & Wheelwright, 1979]
- 3-D Concurrent Engineering [Fine, 1998]
- Nine Components of Manufacturing Strategy [Fine & Hax, 1985]
- The Strategic Manufacturing Planning Process [Beckman, et. al,1990]

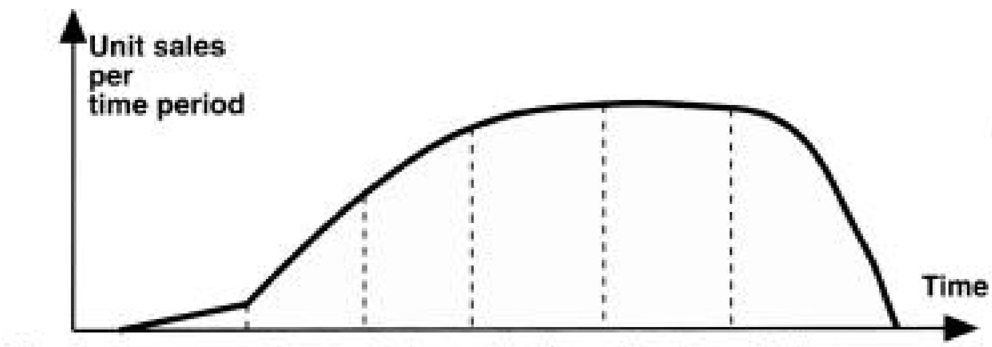
7.3.1 "Focused Manufacturing" Approach [Skinner, 1969]

Skinner recognized the need for a top-down approach to manufacturing system design as early as 1969 [Skinner, 1969]. He emphasized that manufacturing is not a one-size fits all operation. Manufacturing operation should be focused on a given product strategy associated with that particular product. The idea behind this concept is manufacturing excellence through process simplicity (one product, one set of processes to worry about), repetition, experience and consistency. This brings up two key concepts. First, the need for a product strategy, and, second, the need for factories within factories. The "factory within a factory" or a "plant within a plant" idea is actually in practice today throughout the aerospace industry. Commercial airframe assemblers, for example, have dedicated lines for different aircraft within a factory. Skinner also suggested that a ***manufacturing policy*** be derived that translates corporate and business unit goals into manufacturing system goals and requirements. The policy should consider current company capabilities (core competencies, technology, human resources, etc.), market conditions, competitor position, and provide metrics to evaluate performance. All in all, a manufacturing policy is an instruction set for manufacturing management to make daily decisions that support corporate objectives.

An improvement on this thought is the focus on certain competing elements such as cost, quality, flexibility, innovation, and velocity rather than the entire product. [Hayes, et. al. 1984; Miltenburg, 1995] There could be more of these elements. The idea here is to focus on some of these elements depending on the business environment and direct the product design, manufacturing system design, marketing and supplier relationship efforts to achieve the targets. The subtle difference between Skinner's concept and these variants is that Skinner focuses on the product itself whereas the variants advocate that the product should be designed to support the characteristics perceived to be necessary to compete effectively.

7.3.2 Manufacturing System Linked to Product Life Cycle [[Hayes & Wheelwright, 1979]

This approach advocates changing manufacturing processes based on market needs of different product life cycle stages. A product life cycle can be broken into six stages: development stage, growth stage, shakeout stage, maturity stage, saturation stage and decline. Figure 7.1 shows a schematic of a typical product life cycle with some details under each of the stages.



Stage:	Development	Growth	Shakeout	Maturity	Saturation	Decline
Product design	Changes rapidly	Changes slowly	Standard designs appear	Industry-wide standards	Commodity	Commodity
Sales	Low	Increase rapidly	High	Growth at rate of GNP	Growth at population growth rate	Decrease rapidly
Production volume	Low	Medium	Medium to high	High	Very high	Low
Market qualifying outputs	Innovative-ness, performance	Innovative-ness, flexibility, performance	Quality, flexibility, performance	Cost, quality	Cost, quality, delivery	Quality, flexibility
Best production system	Job Shop	Batch flow, FMS, JIT, OP line flow	OP line flow, JIT	EP line flow, JIT	Continuous flow	Job shop, batch flow
Profit per unit of product	Negative	Low to medium	Medium	Low	Very low	Negative

Figure 7.1 Stages in Product Life Cycle [Miltenburg, 1995]

Hayes and Wheelwright introduced the famous product-process matrix [Hayes & Wheelwright, 1979] suggesting a strong link between manufacturing system capability needed and the current stage of product in the product life cycle. Several other authors

[Chase & Aquilano, 1992; Miltenburg, 1995; Utterback, 1994] have since endorsed this concept in various forms. In effect, Hayes & Wheelwright linked the product life cycle to the “process life cycle”. A process life cycle is the change a manufacturing processes goes through as the product goes through its life cycle. A process life cycle starts with a “fluid stage” (highly flexible but not cost efficient) and moves towards higher levels of standardization, mechanization and automation. Hayes and Wheelwright found that manufacturing processes are highly flexible and inefficient during the early stages of product life. As the product matures in the market and a stable design is established the focus is gradually switched towards efficiency and higher levels of mechanization and automation. The product-process matrix developed by Hayes and Wheelwright is given in Figure 7.2. The matrix has two primary regions, the diagonal position and off-diagonal position. A typical strategy can be to stay on the diagonal by changing the manufacturing system based to the product stage. This allows for a good match between manufacturing capability and market demand. On the other hand, a company might choose to stray from the diagonal, at it’s own risk, to fill a niche market. An excellent example would be the automobile manufacturer, Rolls-Royce. The company has chosen to use craft manufacturing even when the market demand is too high for a craft based system.

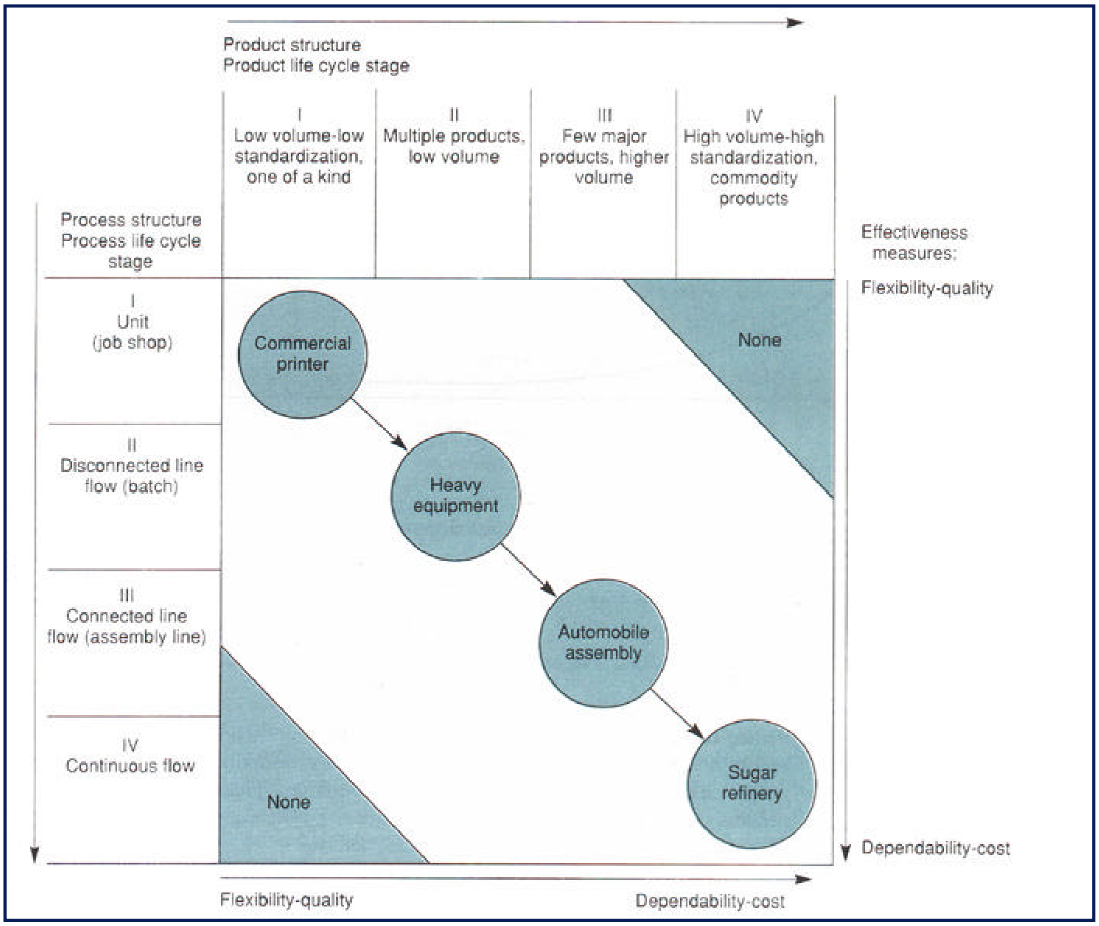


Figure 7.2 Product-Process Matrix [Hayes & Wheelwright, 1979]

This matrix is a useful guide to select an appropriate manufacturing system based on the maturity of the product. For a brand new product entering a new market, the matrix suggests that one should pick a highly flexible manufacturing process. In evaluating current business performance, a company can use the matrix to locate the product stage on the matrix and verify if the manufacturing processes being used are appropriate for that stage. A competitive analysis can also be performed using the matrix to analyze a competitor's performance and manufacturing strategy. Likewise, the tool can also be used to determine whether multiple products can be manufactured in the same facility or separate facilities/production lines are needed. This is especially important if the different products offered are at different stages of product life cycle.

This tool also calls for a unique manufacturing system/process for each stage of the product life cycle. This supports Skinners focused factory approach. Skinner advocates product focus but Hayes & Wheelwright take it one step further and suggest a strategy to select an appropriate manufacturing system for the selected product. It is important to note that manufacturing process is a dynamic process. It changes as the product changes. Therefore, one should avoid selecting a "company standard manufacturing system," instead one should continuously evaluate the current manufacturing system to verify the fit between product demand and manufacturing capabilities.

7.3.3 3-D Concurrent Engineering [Fine, 1998]

Charlie Fine discusses the concept of three-dimensional concurrent engineering (3-DCE) in his book ***Clockspeed.*** He discusses the need to consider product architecture, process architecture and supply chain architecture to compete effectively in today's dynamic business environment. Fine advocates concurrent engineering as a means to eliminate throwing the design over the wall to the manufacturing and suppliers. He also points out the need to reduce the time needed to incorporate changes of any type (product improvements, process improvements, new technology insertions) in the current design solution. While advocating traditional concurrent engineering, he emphasizes the need to include the supply chain as the third dimension. His thoughts can be best explained using Figure 7.3.

The intersection of the three ovals in Figure 7.3 is the strategy under which a company should offer the product. Implied here is the early collaboration between product design, manufacturing and suppliers. That is, the product design will have to accommodate supplier needs, manufacturing capabilities and vice versa. Fine introduces the concept of product, supply chain and manufacturing architectures. The product design will have to adopt either ***integrated*** or ***modular*** design architectures depending on how early the suppliers are integrated. Similarly, supply chain architecture can be integral or modular depending on the ***proximity*** (geographic, cultural, electronic and organizational) of the suppliers. Manufacturing architecture can be characterized in terms of time to manufacture and spatial dispersion of activities. All of these differences in architectures argue the need for early collaboration of these three activities. Fine's concept calls for a total strategy. The same concept is referred to as the ***Product Strategy***, which will be discussed in the next chapter.

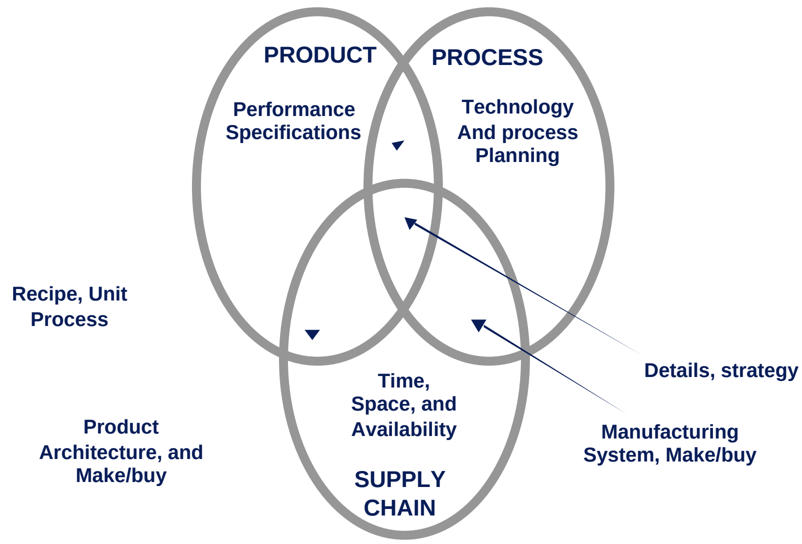


Figure 7.3 Overlapping responsibilities across Product, Process, and Supply Chain development activities [Fine, 1998]

7.3.4 Nine Components of Manufacturing Strategy [Fine & Hax, 1985]

Fine and Hax present nine strategic decision categories to break down the complex task of formulating a manufacturing strategy. Fine and Hax base their work on research by, among others, Skinner, Hayes & Wheelwright, and Buffa [Buffa, 1984]. The nine categories and the author's view on each are as follows:

Facilities: Derived from Skinner's focused manufacturing. Facilities may be focused by location, product group, process type, volume or the stage in product life cycle (Hayes & Wheelwright).

Capacity: Capacity decisions are tightly connected with facility decisions. Capacity decisions include managing cyclical demand (holding excess capacity, seasonal inventories, peak-load pricing, subcontracting), adding capacity in anticipation of future demand (aggressive, flexible approach), responding to existing demand (conservative approach), and using capacity decisions to affect the capacity decisions of competitors.

Vertical Integration: Decisions relating the level of vertical integration versus outsourcing. Some of the important decisions include the cost of the business to be acquired or entered, the degree of supplier reliability, and whether the product or process to be brought in-house is proprietary.

Processes and Technologies: Decisions regarding which processes to choose to fabricate a part, how much automation to use, what type of control mechanism to be used and what level of worker skill to be expected.

Scope and New Products: Decisions must be made regarding rate of new product introductions, product changes and the product variety. Manufacturing organization should have significant input on these decisions. The product designers must understand what demands product design will place on manufacturing.

Human Resources: Decisions regarding selection, training, promotion, retention and placement of personnel must be made as part of the manufacturing strategy. Deciding on worker skill level has huge impacts on the manufacturing system design. Similarly, the compensation method will have impact on the operating cost of the plant.

Quality: This category involves decisions on the level of conformance quality to be achieved. Fine and Hax mention three issues to be considered for decisions: quality measurement, economic justification of quality improvements and allocation of responsibility for quality.

Infrastructure: Decisions need to be made on the operating policies, lines of authority, level of tolerance to failure, control policies, management levels above factory floor, and employee input to decisions.

Vendor Relations: Fine and Hax point out that there are two popular approaches on purchasing: competitive and cooperative. Competitive approach advocates short term, noncommittal relationships where multiple suppliers are sought and allowed to compete against each other. On the other hand, a cooperative approach seeks long-term relationships based on mutual dependence and trust. Companies have to decide on using one of the two or a combination of both approaches.

The above nine categories provide very good guidelines for manufacturing strategy formulation. These nine categories also support some of the ten inputs to manufacturing system design introduced in Chapter 6.

7.4 SUMMARY OF INFRASTRUCTURE TOOLS

The following useful strategy formulation concepts were explored: focused manufacturing, product-process matrix, 3-Dimensional concurrent engineering, and the nine components of manufacturing strategy formulation. Even though these tools were not developed for the aerospace industry, they are applicable since they deal with general manufacturing strategy formulation rather than an industry specific strategy. Each one of the tools provides much insight towards developing and maintaining a competitive manufacturing plan. It is important to mention that Utterback's dynamics of innovation model is also a very crucial and useful concept to consider while using the above tools. Because it analyzes the industry as a whole, the knowledge given by Utterback's model becomes the first step in strategy formulation.

8 MANUFACTURING SYSTEM DESIGN FRAMEWORK

8.1 OVERVIEW

The manufacturing system framework presented here incorporates knowledge from existing literature on manufacturing systems and manufacturing strategy, experience and observations of research team members, information from interviews, factory visits, seminars, and discussion workshops. Past research conducted by Lean Aerospace Initiative's various research arms also contributed in the development of the framework. The framework has been presented in its various early forms to more than 100 people in the industry over a period of two years. The feedback received from the practitioners is incorporated to make the framework represent real situations. The manufacturing system related activities at various companies can be represented readily by the framework. Current positions of some companies will be pointed out on the framework to emphasize the practicality of the framework.

The objective behind developing the framework was to understand the manufacturing system design environment in its entirety. From our early observations, it was apparent that the manufacturing system design in aerospace companies was limited just to the factory floor. Some of the literature also focused heavily on factory floor and layout design. This restricted focus, while intuitive, does not fit well with the definition of the manufacturing system and manufacturing system design given earlier. From a systems point of view, manufacturing system design activity should encompass all entities that manufacturing interacts with. Most of the time in the framework development was spent on formulating the design problem and boundaries of the system. One of the other goals was to represent current manufacturing system design activities on this generalized framework. This is to show the designers where their efforts are concentrated and, if necessary, to make them aware of entire picture.

The framework is shown in Figure 8.1 It is a visual tool that clearly shows that the manufacturing system design extends beyond the factory floor. It shows activities outside the factory floor and design activities related to the factory floor. Most importantly, the framework emphasizes a ***strategy-driven manufacturing system design rather than a product design driven manufacturing system design***. Appropriate tools to be used in each step of the process are also suggested where applicable. Likewise, the framework shows that the manufacturing system design never ends. There is a continuous improvement/modification loop shown in the framework to emphasize this point.

The framework has two regions, the decision-making/strategy formulation region, and the manufacturing system design region. Both of the regions however are part of the manufacturing system design and operation. They are closely coupled and strongly influence each other. The upper left corner of Figure 8.1 is the decision-making/strategy formulation region and the lower right hand corner is the manufacturing system design region. The upper region maps to the ***infrastructure*** design and the lower region maps to the ***structure*** design of a manufacturing system. The link between these two regions is the product strategy. The idea of a product strategy will be discussed shortly. The product strategy is the communication link and the connection between manufacturing and the rest of the enterprise. The product strategy generates the manufacturing system design requirements. The infrastructure and the structure design components are discussed separately below.

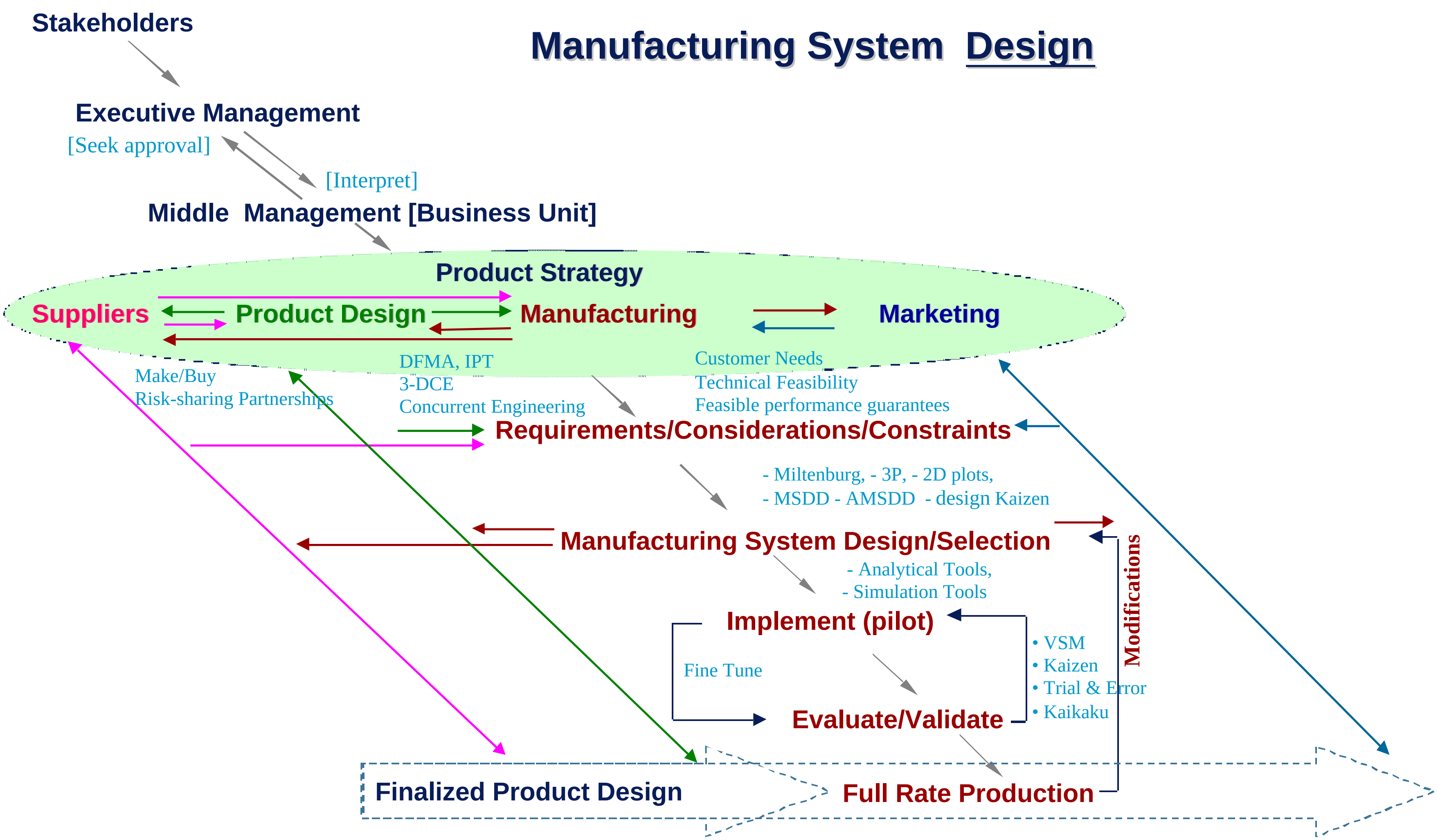


Figure 8.1. Manufacturing System Design Environment

8.2 MANUFACTURING SYSTEM INFRASTRUCTURE DESIGN

One of the major themes throughout this thesis has been the importance of treating manufacturing operation as a system and the need to consider manufacturing as an integral part of the corporate strategy. The infrastructure part of the framework does exactly this. This is the "decision body" of the manufacturing system design process. This is where the needs are processed, goals are generated and strategies are formed. This region of the framework includes the following sections:

- Stakeholders
- Executive Management/Corporate Strategy
- Middle Management/Business Unit Strategy
- Product Strategy (sum of functional strategies)

Before exploring each section in detail, it is necessary to explain the corporate structure as adopted in this thesis. There has been much research done in the area of corporate organizational structures and strategies. [Buffa, 1984; Hayes & Wheelwright, 1988; Fine & Hax, 1985; Duda, 2000] All of this research points to a logical corporate hierarchy similar to the one shown in Figure 8.2. The figure shows three distinct levels of strategies – the corporate strategy, the business strategy and the functional strategy. The corporate strategy is supported by multiple business unit strategies. In turn, each business unit strategy is supported by multiple product strategies. A product strategy is an idea derived from Fine's book ***Clock Speed***. [Fine, 1998] Product strategy is a combination of several functional strategies the most important of which are the product design, manufacturing, marketing and supplier relations. This will be explored in more details shortly. The components of the product strategies are the functional strategies mentioned above.

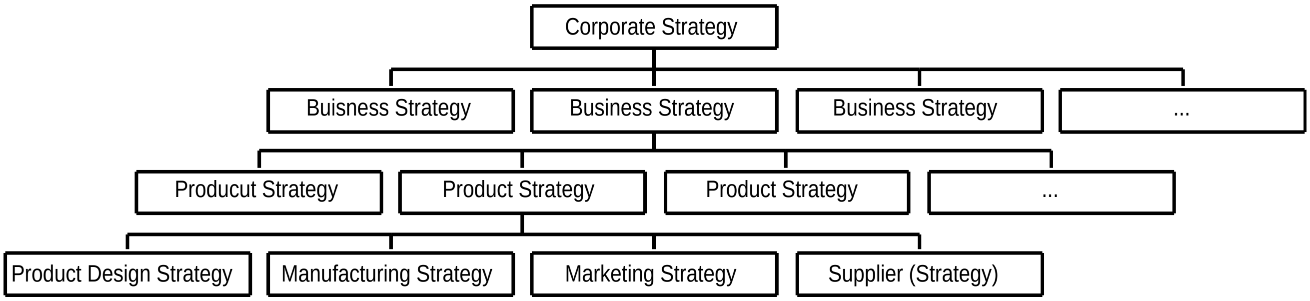


Figure 8.2. Representative Corporate Hierarchy of Strategies

The upper part of the framework can be explained best using Figure 8.3. This representation of an enterprise was created as a result of literature review, interviews and observations from the industry. The figure shows that the corporate strategy is formed in response to stimulus from various stakeholders. A stakeholder is any entity with any personal interest in the corporation. Table 8.1 below shows a list of some major stakeholders in the aerospace industry and their primary needs.

The stakeholders create needs over time at various levels of the corporation. The framework shows that the stakeholders communicate directly with the executive management. While this is not true in practice, the point being made here is that the executive management eventually has to address the needs. Typically, the government and shareholders communicate directly with the executive management, customers communicate through marketing and employees communicate through human resources. Some of the needs might capture executive management's attention immediately, others might take years prior to being addressed. For example, shareholders are typically given the highest preference due to the immediacy of the consequences of ignoring their needs. On the other hand, employee needs are typically not addressed right away. This often leads to union strikes and a decrease in employee morale. The needs of different stakeholders can often conflict with each other, which makes management extremely challenging. No matter where they were initiated, the executive management has to address the needs whether immediately or with a long delay.

Figure 8.3. The Corporate Hierarchy

Stakeholders	Primary Need
Stockholders	Return on Investment
Customers	
General Public	Satisfactory Product Performance, Low Cost
Businesses	Low risk participation, steady business
Employees	Employment, Stability
Hourly	Satisfactory Salary
Management	Promotion opportunities
Suppliers	Stable business
Society/Community/Environment	Responsible behavior
Government	Capability, Tax base

Table 8.1 Stakeholders and Primary Needs

The framework shows a strong interaction between the executive management and the middle management (Business Unit management). As shown Figure 8.3, the executive management interprets and prioritizes the stakeholder inputs and develops enterprise needs. To address these needs, corporate goals are set and a corporate strategy is formulated [Buffa, 1984; Fine & Hax, 1985]. The corporate strategy is in turn ***interpreted*** by each business unit, which develops its own business strategy to support the corporate strategy. It is best if a corporation has multiple and different business unit strategies to achieve the corporate goals [Buffa, 1984]. Here, the business unit has the freedom to offer any product or service that it believes would help achieve the corporate goals. The framework shows that there is an approval seeking feedback from middle management to executive management. This is an important interaction since this verifies the correctness of middle management's interpretation of the corporate strategy. This is a way to keep the successive levels of a corporation aligned with the over all goal [Shiba, 1993].

8.2.1 Product Strategy

Product Strategy simply is a plan under which a product will be offered to the market. It is simply a plan but it is by no means a simple plan. As Figure 8.3 shows, product strategy is made up of inputs from multiple organizations. This is where the expertise, the knowledge, and the core competencies of a corporation come together to form the strongest plan to conceive, design, manufacture and market a product. Traditionally, the product itself has been the flag bearer of a company. Here, it is proposed that product is just a part of the entire solution package; it is just one core competency. A product strategy, however, includes multiple core competencies such as manufacturing, suppliers and marketing working together leading to a much stronger and robust competitive weapon. Suppliers are in fact a "borrowed" core competency. One of the reasons one seeks a supplier is to find some one who has core competency in that operation. Therefore, the prime contractor is in fact borrowing someone else's core competency. Thinking along these lines can help build trust and understanding between suppliers and prime contractors to be able to work together.

It is implied here that a company should offer a total solution, not just a good product. A product then becomes a part of the solution. For example, a F-22 fighter by itself is a useful weapon but it becomes a deadly weapon if used under an attack strategy with the help of other components of the defense system. The F-22 will be much more attractive if the manufacturer makes provisions for this type of use, rather than just concentrating on the product performance itself. If the product strategy is to offer best life cycle cost, one can immediately see that product performance becomes just one part of the equation. Manufacturing and other components become equally important. Defined loosely, life cycle cost = Acquisition Cost + Operating Cost * Number of years – Scrap value. One can see the influence of manufacturing in acquisition cost, operating cost (in terms of external quality of parts and maintenance), and scrap value (materials used, external quality). Thus, offering a solution rather than a product is much more valuable and attractive.

It is important to note that the product strategy is a part of the business strategy. A business unit is thus made up of all the various organizations shown Figure 8.3. Even though, all of the components shown are equally important, product design, manufacturing, marketing and suppliers can be considered the major contributors. Other components such as human resources, customer support, and etc. can be thought of the supporting elements behind the four major groups mentioned above. As discussed earlier, Fine treats product design, process and suppliers as the top three components in his 3-DCE model. Marketing strategy is added here as a major contributor since in aerospace industry, the sales and marketing group plays a major role in influencing the customer demand (discussed in Chapter 2). Figure 8.4 shows a pictorial representation of the idea behind product strategy.

A product strategy is a complete collaboration between the four groups represented. It is important to point out that this collaboration is not just a negotiation process but a complete understanding of each other's strengths and weaknesses and the use of the best qualities of each group to form the strongest strategy. There are strong interactions between the components to work coherently to support the product strategy. Some of the companies we visited already have this idea of product strategy built into their operations.

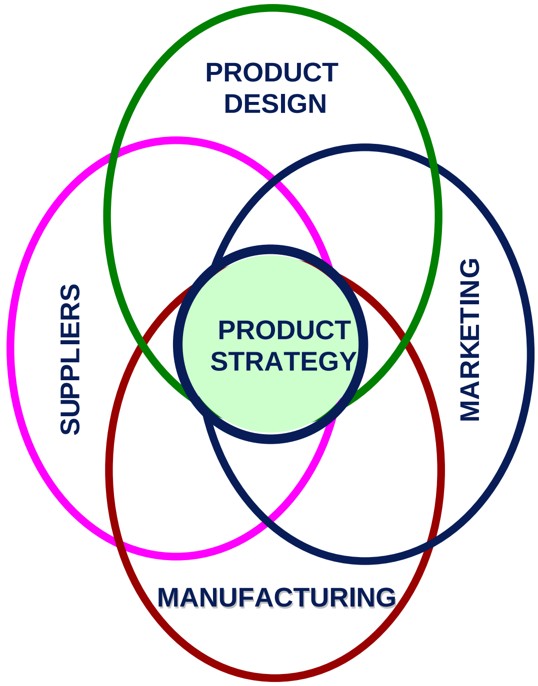


Figure 8.4 Product Strategy

The interaction between product design and manufacturing can occur in the form of concurrent engineering, use of Integrated Product Process Teams (IPPT), design for manufacturability and assembly (DFMA), and concept of Fine's 3-DCE. Most of the aerospace companies are trying concurrent engineering with the use of IPPT teams. The interaction between product design, manufacturing and suppliers leads to make/buy decisions, formation of risk sharing partnerships, decisions whether to allow suppliers to design components or just use them as contractors. The interaction between marketing, manufacturing and design leads to understanding of true customer needs, technical feasibility of the customer needs and ultimately designing, fabricating and selling a product that meets most of the customer needs. Figure 8.5 below is a detailed version of Figure 8.4. Various arrows show the interactions between the components. For clarity, only a few arrows are drawn.

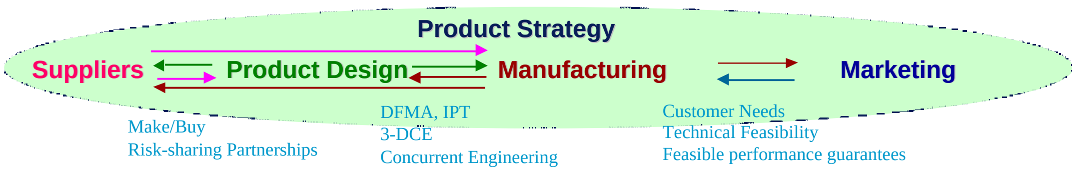


Figure 8.5 Interactions between functional strategies

It was mentioned earlier that the product strategy is the communication link between manufacturing and the rest of the enterprise. This statement is supported by the fact that any product strategy formulated by the business unit is proposed to the executive management for approval. If approved, the strategy can be assumed to be in line with the corporate strategy. Therefore, a product strategy is the instrument to align manufacturing, among other organizations, with the corporate strategy. Even though product strategy might seem foreign, many authors have implied this concept in their work [Duda, 2000; Fine & Hax, 1985; Muhamad, 1997; Hayes & Wheelwright, 1988].

8.2.1.1 Product Strategy Formulation and Tools

Since the success of the product depends on the strength of the product strategy, it should be formulated with care. The strategy tools mentioned in chapter 7 can be very useful here, especially, Utterback's model of dynamics of innovation and the product-process matrix by Hayes & Wheelwright. These two tools, in particular, force the decision-makers to perform product life cycle and competitive analyses. It is important to know which of the four components has the highest leverage at the current time in the industry before attempting to formulate a strategy. The ***nine categories of manufacturing strategy*** and the ***strategic manufacturing planning process*** can provide useful guidelines strategy formulation as well. The formulation of product strategy summarizes and encapsulates the infrastructure design of the manufacturing system design. A Company is ready to embark on manufacturing system design only after it has developed a product strategy.

The discussion up to this point has only been focused on the upper half of the framework. The existence of the product strategy allows the manufacturing system structure design. The product strategy should drive the manufacturing system design and not just any one component of strategy. Traditionally, product design has driven the manufacturing system design initially and marketing has taken over the control after several years. A strategy driven manufacturing system design implies that the strategy itself generates a set of requirements, considerations and constraints for the manufacturing system design. A well-formulated strategy will take into account the initial need for manufacturing flexibility and appropriate transition from product oriented focus to process oriented focus (dynamics of innovation). It will also allow for the change in domination of various groups (first product design, then marketing and eventually manufacturing) over the life cycle of the product. If the design is based on such strategy, the resulting manufacturing system will be a strong competitive weapon for the corporation.

8.3 MANUFACTURING SYSTEM STRUCTURE DESIGN

Once a product strategy is formulated, respective groups can begin their design activities. Figure 8.6 shows the structure design part of the framework. Since the focus of this thesis is manufacturing system design, only the manufacturing component of the product strategy is discussed in detail. However, since product design, suppliers and marketing influence the system design, generous references are made to these groups. The structure design part of the framework includes the following sections:

- Concurrent Product Design, Manufacturing, Supplier and Marketing activities
- Requirements/Considerations/Constraints
- Manufacturing System Design/Selection
- Implementation (pilot plant)
- Evaluate/Validate (Loop)
- Full Rate Production
- Modification Loop

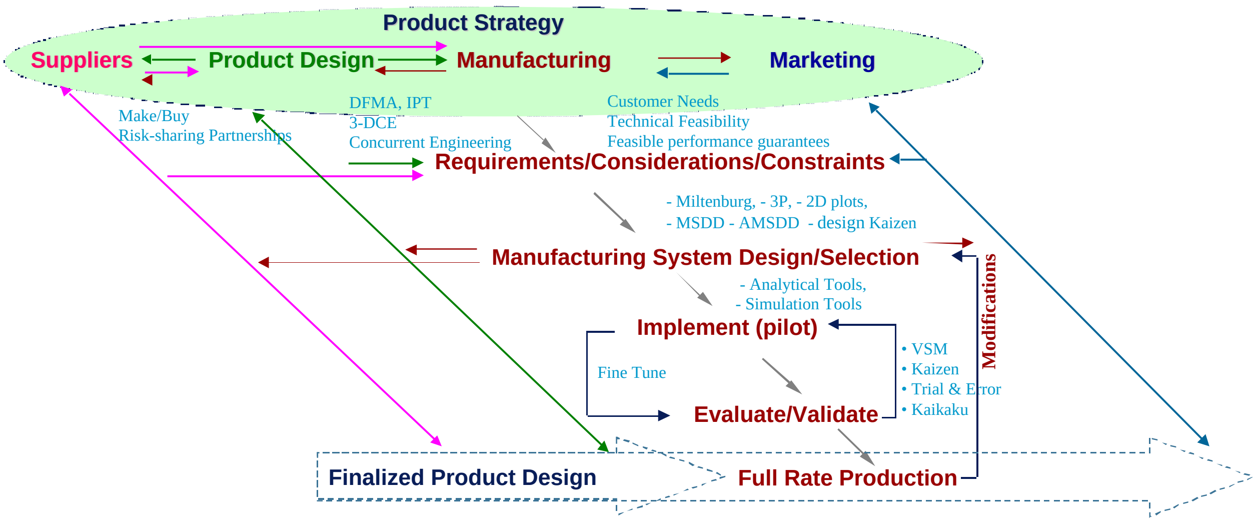


Figure 8.6. Manufacturing "Structure" Design part of the Framework

8.3.1 Concurrent Product Design, Manufacturing, Supplier and Marketing activities

The double arrow headed lines extending from each of the four components of the product strategy bubble down to the full rate production level indicate that design activities are being performed concurrently. For example, the line extending from product design implies that the product design is being carried out as the manufacturing system is being designed to manufacture the product being designed. Similarly, depending on where the suppliers are integrated into the system, the line from supplier component indicates that the suppliers are concurrently designing the product, designing their own manufacturing system, or modifying their existing system to produce the part to print. In an ideal situation, all four activities should converge at the same time. That is, when the manufacturing system becomes ready for full rate production, the design should be finalized and suppliers should be ready to supply the parts to assembly. The arrow with the text ***Finalized Product Design*** that goes through the full rate production is the time when all three activities should be finished. This is where the factory's day-to-day operations occur. Thus, this arrow indicates the operational dimension of the framework. When a company has reached this level in the framework, it can and should begin full rate production activities. In reality, however, one or the other component finishes its activity early and exerts pressure on others. Due to the preference given to product design, this is the group most probably finalizes the design and ends up waiting for other groups to complete their activities. If the other groups such as suppliers and manufacturing are unreasonably late for whatever reason and if the market pressure is high, the companies usually resort to using pilot, low rate plants to supply the market demand. This was the situation in few of the companies we visited.

8.3.2 Requirements/Considerations/Constraints

The framework shows (Figure 8.6) that the first step in manufacturing system structure design is to receive requirements/considerations/constraints from the product strategy as well as from individual components of the product strategy. It should be emphasized here that the requirements flow from the entire strategy and not just from any individual component of the strategy. Traditionally, product design has been the dominant component driving manufacturing system designs. In this model, all components are at the same level in the hierarchy. The product strategy is the owner of requirements. The requirements that flow from product strategy are the feasible, agreed upon requirements. The manufacturing system designers will have to analyze the requirements and design or select a manufacturing system that will deliver these requirements. There might be situations were the designers encounter requirements that conflict with each other or work against the product strategy. This is where the real strength of this framework comes into play. The framework emphasizes that there is ample room for feed back between groups. This reinforces the idea of collaboration between the components of product strategy and the idea of working towards achieving the strategic goals rather than individual component goals.

The requirements/considerations/constraints step receives preliminary product specific requirements from the product design group. These requirements can be related to tolerances, type of material, process capability and key characteristics (unique product characteristics). The manufacturing organization is given a chance to evaluate and provided feedback to design organization regarding current capabilities and alternate solutions. Likewise, the marketing provides, among other things, volume and product mix requirements. The framework allows for requirement inputs from external suppliers as well. This is to help the designers understand supplier capabilities ahead of time. System designers need to understand the strengths and weaknesses of suppliers' manufacturing systems. Supplier location, production control methods, responsiveness, capacity and process capabilities are crucial inputs to prime's manufacturing system design. In the case of a risk-sharing partnership, the manufacturing organization can in fact influence some changes in supplier manufacturing systems. An example of this would be Toyota's relationship with its suppliers.

8.3.3 Manufacturing System Design/Selection

Based on finalized set of requirements, a manufacturing system is either selected from existing proven systems or designed from scratch. Manufacturing system selection is the crucial step in making a product successful. Appendix D explores some of the systems that are widely used in practice (Job shops, cells, FMS, transfer lines, project shops, flow lines, assembly lines, and moving assembly lines). Most of the manufacturing strategy research insists on selecting an appropriate manufacturing system that can readily supply the market demand [Suri, 1998; Miltenburg, 1995; Hayes & Wheelwright, 1988; Buffa, 1985]. A strategy is useless if the associated manufacturing system is chosen arbitrarily. Careful analysis must be performed to design or select a manufacturing system that supports the strategy. As discussed earlier, a manufacturing science does not yet exist. This severely discourages any structured efforts to "design" a manufacturing system since there is no way to design and evaluate a manufacturing system on paper or a computer. However, there are several tools available to guide the designers in the right direction. The following tools/concepts discussed earlier can be useful in this section:

- 2D manufacturing world maps

- Miltenburg's Strategy worksheet
- Production Preparation Process
- MSDD/AMSDD/Axiomatic Design

Research showed that in practice this step is done in one of several ways, all of which are based on intuition and experience of the person in charge. Some companies have a standard or baseline way of fabricating products that was designed several years ago. For new products, this baseline method is replicated and modified to fit the new business environment. Some companies select a system that is working well for others such as TPS or cellular manufacturing and implement it hoping for good performance. The idea behind this strategy is that the 'hot' system is better than the current system, so the results will have to be better. Some other companies considered kaizen events to be manufacturing system design activities. While kaizen activities do play a major role in manufacturing system design, one can not design an entire manufacturing system by performing only kaizen activities. The role of kaizen in manufacturing system design will be discussed shortly. While none of the companies visited had a manufacturing system design group, some companies are realizing the benefits of systems thinking and have already begun changes at a system level rather than at a factory level. Computer simulations are being used widely to simulate machine layouts, workstation setups, material flows and over all system performance. Even though they are not accurate and complete by any means, these simulations do give good guidelines to implementing a specific system compared to faith-based or intuition-based implementations.

8.3.4 Implementation (pilot plant) ←→ Evaluate/Validate Loop

This step calls for implementing the chosen manufacturing system at a scale model level so that it can be fine tuned and eventually brought up to full scale level. This implementation can be done in one of several ways. Companies visited were using computer simulations, scale models, full-scale models operating at low rate, and moonshine shops. This step is where the system is subjected to practical tests in order to pinpoint the obvious problems. The hidden problems will only become apparent upon repeated use. This is similar to the certification and testing phase of a new aircraft program. Even though, problems can be located and fixed using numerical analysis, certain problems are found only during flight tests. In manufacturing, there are several very effective tools available for this step. The manufacturing organizations already have a lot of experience in this area. It was observed that most of the companies start the manufacturing system design at this stage. That is, the first two steps (requirement analysis and manufacturing system selection) are ignored or performed out of sequence. Instead, a baseline manufacturing system is implemented without much analysis. This manufacturing system is then transformed into a system appropriate to the current product needs by continuously fine tuning the baseline system. The following tools are used in this process:

- Macro Value Stream Mapping [Rother, 2001]
- Detailed Value Stream Mapping [Rother, 1999]
- Kaizen [Laraia, 1999]
- Trial and Error
- Production Preparation Process (3P)
- Kaikaku [Laraia, 1999]
- Analytical/simulation tools

It is worth mentioning the role of simulation and analytical tools here. These computer tools can tremendously speed up the fine tuning process at a fraction of a cost. The analytical tools are much faster and as accurate as the simulation tools. Researchers at MIT are developing tools such as the one to estimate inventory levels to achieve a certain production rate. Although a manufacturing system can not yet be simulated as a whole, isolated segments can be simulated to fine tune and get a good idea of improvement targets.

This is a crucial step since the desired capability for the success of the product strategy becomes available if and only if the fine tuning step has been completed. Because of the long life cycles of manufacturing systems, a thorough job done at this stage will benefit the company bottom line for years to come. However, the application of the above tools should be done under a specific plan or strategy. Our research showed that the kaizen leaders were not given much guidance and these activities were limited to eliminating waste from the system. While waste elimination should be an important objective, fine tuning a system can be more than just waste elimination.

8.3.5 Full Rate Production

When the design group has arrived at this stage, manufacturing is ready to support production at full rate. This is when most of the glaring problems have been solved and a good understanding of the strengths and weaknesses of the system have been understood. This implies that there will be many opportunities for improvements over the lifetime of the system. Therefore, the design cycle is not yet complete and never will be. As Womack says, the ultimate goal should be perfection. Since the definition of perfection will change depending on the business environment and external pressures, a manufacturing system design is never complete.

8.3.6 Modification Loop

This loop is similar to the ***Implementation (pilot plant) ←→ Evaluate/Validate Loop*** discussed above but operates on a much longer time frame. The modification loop will be active as long as the manufacturing system is in operation. Any problems detected during full rate production, manufacturing process changes, new technology insertions and factory floor process changes fall under this loop. The idea is borrowed from the Toyota Production System, in which the quest for perfection through continuous improvement never stops. The system is continuously critiqued and fine-tuned. Toyota does not wait for the problems to surface, the continuous system "health checks" eliminate the roots of any problems that might surface later. Interviews with practitioners, their plans for lean implementations and discussions during manufacturing system design workshops indicated that the companies are looking to achieve a certain level of performance in their systems. There was no indication of any future plans to challenge that level of performance once it was achieved. Historically, manufacturing systems have been modified only when unsolved problems led to crisis in the manufacturing world. This mentality is dangerous in today's business environment. A Company such as Toyota, who is proactive in fixing problems, will hardly ever reach crisis of this nature. A Company that waits for a crisis in order to implement change will no doubt lose out.

Almost all of the companies visited were doing an excellent job in this step. Because of the way manufacturing systems are chosen and implemented, that is, selection without analysis, modification loop becomes the crucial step to bring the system up to the required level of performance. It should be pointed out here that the idea of concurrent engineering might not work properly since the manufacturing system will be in pilot/fine-tune stage for a very long time (on the order of decades). The product will have to be manufactured in this partially fine-tuned system with huge amount of unrealized waste. Some of the companies pointed out that there is much unexplored potential in their existing systems that needs to be exposed. This is a true statement but one should remember that these systems were implemented 20 – 30 years ago. This point is made here only to emphasize the need for initial analysis prior to implementing a system.

8.4 BROWNFIELD

In the introductory chapters it was recognized that the majority of the manufacturing systems encountered in the aerospace industry are "brownfields". A brownfield is simply an existing manufacturing facility. That is, in the case of a brownfield environment, the designers will be modifying an existing factory rather than designing it on from scratch. Some typical brownfield modifications can be as follows:

- New product insertions
- Manufacturing process changes (e.g: fixed position assembly to moving line)
- New technology insertions (e.g: laser forming vs. machining)
- Relocation of an existing facility

In all of these situations the entire or part of the framework described above applies. Thus, the brownfield modification becomes a just a small part of the entire manufacturing system design process (a special case). For example, If a new product is being introduced under an existing product strategy, only the bottom half of the framework applies. The key point here is the compatibility between the new subsystem being inserted and the existing systems. The new item being inserted must be compatible with the existing infrastructure. If this is not so, the existing resources of the system such as people, machines, tools, processes, and culture also exist become constraints rather than resources. Therefore, a brownfield design should be treated as a new design with additional constraints. The framework still applies from the Requirements/Considerations/Constraints step onwards.

8.5 FRAMEWORK SUMMARY

The framework developed here paints a very good picture of the manufacturing system design environment. It is a very general framework since it does not assume a specific corporate objective and therefore does not lead to any specific manufacturing system design. It connects the infrastructure design and the structure design with the concept of product strategy. The product strategy is the summary of infrastructure design, which is the starting point for the manufacturing system structure design. By including both infrastructural and structural design elements, this framework does a very good job at representing all relevant entities.

The infrastructure part of the framework truly represents the decision-making activities at middle management level. Our discussions showed that most of the product or service related activities occur at the middle management level. Subsequently, executive management approval is sought on the decisions made at the middle management level. The framework clearly shows this interaction with representing three levels of strategies and feedback arrow between the executive and middle management.

This is a framework based on practical knowledge. The manufacturing system design activities of many of the aerospace companies we visited can be pinpointed on this framework. This is a very unique feature of this framework since it shows clearly where all of the resources are concentrated. This ability to locate the current design activity on the entire manufacturing system design realm immediately shows the areas that might have been ignored or not even considered. As mentioned earlier, almost all of the companies we visited are concentrating on the ***Implementation (pilot plant)*** ←→ ***Evaluate/Validate Loop*** or the ***Modifications*** loop using exactly the same tools recommended by the framework. While this is comforting, it highlights the areas in the design process that need attention.

This framework is a tool of many tools. It combines the academic research and practical methods currently used in the industry to describe the manufacturing environment. Appropriate tools are shown in appropriate places on the framework to assist the designers in understanding where each tool can be used meaningfully.

The framework makes it clear that manufacturing is in fact a competitive element by making manufacturing a part of the product strategy. It gives equal status to product design, manufacturing, marketing and suppliers. This is also another unique feature in this framework, where a true collaboration between the components is emphasized rather than simple interaction or communication.

With the ***Finalized Design arrow***, the framework indicates when the manufacturing will be ready to operate to the design specifications. This is where the time lines of all of the components intersect. As it was mentioned, in reality this might not always be possible and a factory not at full rate might need to be used to produce at full market demand. By showing that a factory is only ready to meet specifications when it reaches full rate production, the framework gives each of the components a way to defend their position when accused of not meeting production needs. While doing this, it also adds the positive pressure on all components to meet the deadlines and reach the full rate production level at the same time.

The following questions were considered prior to developing this framework and other existing frameworks were evaluated based on the same set of questions. I believe that the framework presented here can answer affirmatively to all of the questions below. As far as the last question is concerned, the framework it self defines the entire manufacturing system design process. This 14-step process is presented in the next chapter.

- Does it show all relevant entities?
- Does it imply a strategy behind the design?
- Does the framework describe a general manufacturing system design or focus on a specific system?
- Does it show/imply all applicable levels of decision entities, influences and interactions?
- Does it link corporate, middle and functional management objectives to factory floor design and operational decisions?
- Where does the framework fit in the manufacturing system design process?

8.6 Framework Applicability to Aerospace Industry

The framework is fully applicable to the aerospace industry since it was developed based on observations of the aerospace industry and the information gathered by conversations with practitioners. It is, however, a very high level and general framework describing a manufacturing system design process. Therefore, it is by no means restricted to aerospace manufacturing systems.

The framework represents the decision-making and manufacturing activities in the aerospace industry very well. For example, the interaction between middle management and executive management shown in the infrastructure part of the framework is characteristic of aerospace firms. Products, services, and process improvement initiatives are designed at the middle management level and proposed to executive management for approval. Even though the product strategy is a new idea, some of the elements behind the concept are already being used in the industry. For example, airframe companies have long used risk-sharing partnerships with overseas suppliers such as Japan Aircraft Industries (JAI). All of the major companies are using

IPT teams to attempt concurrent engineering. It should be emphasized that the product strategy idea presented here requires that all of the elements be used strategically and collaboratively. Therefore, aerospace companies have much work to do in developing a true product strategy. The manufacturing system structure design part of the framework points out that the current improvement activities in the industry are just a small part of the entire process. In doing so, the framework does show that these activities are a vital part of the manufacturing system design. Thus, the framework is in every way applicable to the aerospace industry.

8.6.1 State of the industry and applicability of the framework

The discussion in Chapter 4 showed that the aerospace industry is in a phase where process improvements might have the highest leverage instead of product design. The framework supports this idea and extends it a bit further with the concept of product strategy. As discussed, product strategy is collaboration between product design, manufacturing, suppliers and marketing. The product strategy formulation process requires determining the component with the highest leverage in generating revenues at the current time in the industry. Utterback's theory explored dynamics between product and process. Here, two additional components (suppliers and marketing) are provided. It is possible that sometime during the industry or product life cycle one of these two components might have the highest leverage in selling the product. For example, when a brand new, state of the art product is introduced, marketing plays a strong role in selling the products since the market is not aware of the usability or quality of the product. Once the product becomes common place, product characteristics become the selling point and then Utterback's theory follows. It is important for a company to design a product strategy that takes these transitions into account and design a system to handle the switchovers efficiently and quickly.

Chapter 4 argued that the manufacturing function currently seems to have the highest leverage in the aerospace industry. This indicates that the rest of the three components should follow the manufacturing lead. Companies should concentrate on improving processes. Products should be designed using existing capability and tooling. One of the characteristics of the specific phase is that the product differentiation does not win orders. Cost becomes the primary decision factor in buying a product. Therefore, improving the product performance in aerospace industry might not be in the best interest of the company right now. One of the companies we visited is already using its manufacturing capability to compete. The manufacturing organization in this company has heavily influenced the recent product being developed. The company uses affordability as the product strategy and one way they have chosen achieve this is by designing the product around existing manufacturing capabilities. Once again, the framework is fully applicable and is very practical.

The key insights one should take away from the framework are as follows:

- Manufacturing system design extends beyond the factory floor
- Decision-makers at the corporate and middle management level are a part of the manufacturing system design process
- A manufacturing system should be strategy driven not product design driven
- Formulation of the product strategy determines the manufacturing system selection and product characteristics. Therefore, the product strategy should be developed with extreme care.
- Strategy should be designed with consideration to the transition of leverage from component to component during the product life cycle.
- One should be aware of the extent of the manufacturing system design process to avoid concentrating on one particular stage of the activity
- Manufacturing system design never ends

9 MANUFACTURING SYSTEM DESIGN PROCESS

9.1 OVERVIEW

Based on the framework, a manufacturing system design process is presented below. The process not only offers a checklist to ensure all pertinent steps have been followed but it also helps in understanding the design activity. The following 14 steps also provide a quick way of understanding the framework itself. Since the purpose of the process is to provide a way to think about each of the steps involved, most of the steps are in a question form. The process below is most useful in introducing a new product in the market. However, provided that an appropriate infrastructure exists, the structure design part of the process can be very useful in inserting a new product into an existing facility.

9.2 INFRASTRUCTURE DESIGN

1. **What are the corporate goals?**
    - What is the corporate strategy?
2. **What is the business unit strategy?**
    - How do you do business in this unit?
        - Offer Innovative products, market qualifying products, order winning products, post-sale contracts, or new inventions?
    - What are your core competencies?
    - What are the future business growth areas in the industry?
3. **What is the Product Strategy?**
    - How do you plan to sell this product?
    - What is the current maturity of the industry?
        - Dynamics of innovation: Fluid, Transition, Specific? [Utterback, 1994]
        - Determine which of the product strategy components currently has the highest leverage.
            - Product Design, Manufacturing, Suppliers, Marketing?

- What is the product maturity?
  - Product life cycle: growing, mature or declining phase? [Hayes & Wheelwright, 1985]
- Who are the competitors? What is their knowledge of this type of product?
- What are your core competencies?
- What is the total solution package being offered?
  - Affordability, acquisition cost, best life cycle cost, subsystem commonality, “lift by hour”, power by hour, unlimited customer support, guaranteed delivery to space, etc

  - What product design characteristics are you competing by?

Commonality	Passenger comfort
Reliability	Compatibility
Safety	Payload capacity
Weight	Serviceability
Life cycle cost	Performance

  - What manufacturing related characteristics are you competing by?

Delivery	Innovativeness
Quality	Lead-time
Flexibility (volume, mix)	Cost

  - How do you plan on using your suppliers?
    - Risk sharing partners?
    - Build to print contractors?
    - How do you plan on using suppliers’ core competencies?

  - What is the marketing strategy?

Depending on the product strategy, the product can either be offered as “Order winning” or “market qualifying” [Miltenburg, 1995].

With the formulation of the product strategy, the infrastructure design is complete. Based on the strategy, a structure design can be attempted.

9.3 STRUCTURE DESIGN

4. Determine the technical/physical requirements to achieve the strategy needs

- A tool like Quality Function Deployment (QFD) might be useful to convert the strategy requirements into manufacturing system design requirements
- MSDD/Axiomatic Design might come in very handy here to see how the combination of different factors affect the factory floor
- Miltenburg's strategy sheet might come in very handy here

5. Receive requirements from product design, Give feedback to product design

This is not just a one way communication dominated by product design but collaboration between the two. Depending on the status of the industry, the dominant component of product strategy should be given more control.

- Physical product characteristics/requirements
- Tolerance requirements
- New manufacturing technology development requirement

6. Receive requirements from Marketing and Suppliers, Give feedback

- Get rough forecasts on volume, and mix
- Determine supplier location, transportation time, supplier quality, etc.

If manufacturing has the highest leverage, it should provide guidance to product design regarding existing manufacturing capability such that the product can be designed to use current capabilities.

7. Perform a cross check between step 4 strategy requirements and steps 5 & 6 engineering requirements to verify contradicting elements (this could be the correlation matrix of QFD, roof of the house)

- Feedback up the chain to eliminate contradictions
- A check and balance system to keep strategy as the priority and not the design
- Establish final set of technical requirements

8. Manufacturing system design factors

From the result of step 7, compile a data set for the following 10 factors.

- Market Uncertainty
- Product Volume
- Product Mix
- Frequency of Changes
- Product Complexity
- Process Capability
- Worker Skill
- Type of Organization
- Time to first part
- Investment

9. Design/select a manufacturing system that meets the above requirements

Current capability Analysis:

- Determine if the current manufacturing system can fulfill the business needs.
  - Tool: Miltenburg's strategy sheet, 2D Maps of manufacturing systems, Axiomatic Design/MSDD/AMSDD
  - Can the existing system be changed to the required system in the available time? (brownfield)
    - What needs to be changed? (Which of the manufacturing levers need to be changed?) [Miltenburg, 1995]
- Is there an existing manufacturing system (cellular, job shop, etc) that can fulfill the requirements/business needs
  - Tool: Miltenburg's strategy sheet, 2D Maps of manufacturing systems

- Can a hybrid system be developed?
- Can the features of different systems be combined to design a suitable system?
- Tool: Axiomatic Design (MSDD)

Need for a new system:

- Is there a need for an entirely new system?
- Do you have the time, capability and funds needed to develop a new system?
    - Check your strategy, reformulate
    - Prioritize factors
    - Check product design requirements

Useful Tools for step 8:

- Trial and Error
- MSDD
- Miltenburg strategy sheet
- 2D Maps of existing manufacturing systems
- 3P applied at system level (might be too complicated)
- Manufacturing system regions (extended version of tool 4, doesn't exist yet)

- What types of systems do other industries and competitors use for this type of product?

10. Once a system is selected, design an appropriate *operating policy* for that system

Operating policy is a set of rules that translate the strategy into operational guidelines for day to day decisions. It is the operations side of the manufacturing strategy. It is an extension of the strategy to keep manufacturing in line with rest of the company. Manufacturing managers should make their decisions based on this policy, which ensures compliance with the underlying manufacturing, business, corporate strategy.

- Operating policy should determine:
    - Factory control mechanism
    - Inventory levels
    - WIP
    - Required skill level
    - Daily decision guide
    - Metrics
    - Quality checks/quality levels
    - Employee freedom to innovation

11. Implementation plan

Implementation depends on type of system chosen

- Use known implementation methods, if possible
    - Trial and error
    - 3P
    - Consultants
    - Analytical tools/computer simulations

12. Test/fine tune

The prototype system is tested to detect shortcomings, performance levels, and other systemic issues, which can not be detected during the design stage. There are many tools available for this step.

Tools:

- Macro Value Stream Mapping
- Value Stream Mapping
- Kaizen
- Moonshine shops
- Trial and error
- Computer Simulation Models

13. Full rate Production

The system is ready to full rate production when the minimum design performance levels can be achieved at full rate production. This does not mean that the system is operating at its best.

14. Continuous Improvement

The design task is not yet complete. Once full rate production has been reached, the system is just operating at perceived best levels. There is lot to improve, just as a new product design goes through series of revisions. Use Kaizen continuously to find problems before they surface and take care of them before they affect system performance. After repeated Kaizen activities, the rate of change introduced will typically slow down. The next step should be to introduce drastic changes via Kaikaku techniques. The continuous improvement loop operates throughout the life cycle of the manufacturing system to detect and eliminate waste, and inefficiencies. All the tools used in the Test/fine tune stage can be used here. The focus of the continuous improvement should be to build capability for the long term whereas the focus of step 12 was to bring the system up to speed as soon as possible. There should be a plan based on which the improvement activities should be performed.

10 CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS

The main goal of this research was to characterize the manufacturing system design in the form of a framework to understand the manufacturing system design environment. This understanding is the first step in attempting to develop a methodology to design a manufacturing system. It was also hoped that the framework development exercise will also provide explanations to the following two questions:

- What is the best manufacturing system for a given set of conditions?
- At what point does it make sense to redesign the manufacturing system***?***

The development of the manufacturing system design framework provided a great deal of insight into the scope of manufacturing system and its design. The effort exposed the level of difficulty involved, the number of stakeholders needed to be considered, various complex interactions, lack of needed data, the constraints, and lack of adequate tools. The framework development effort opened up many doors to future research to fill the gaps observed in data and tools.

The framework explains the first of the above questions by showing that each manufacturing system needs to be designed to satisfy a given set of conditions (derived from the product strategy). This is not to say that there is one best answer but to emphasize that design is necessary to select from many alternatives available. As far as system redesign question is concerned, it was observed that manufacturing systems are continuously being redesigned and changes are introduced in an evolutionary fashion. There is no such point in time at which a company needs to redesign its entire factory. As a matter of fact, if a company finds itself in such a situation, it might be in serious trouble as far as company's future success is concerned. The framework shows this very efficiently by emphasizing that the manufacturing system design never ends but it is a process of continuous improvements.

The goals and trends in the aerospace industry were explored as part of the framework development process. It was observed that many of the companies are focusing on profitable growth. To achieve this goal, the companies are focused on achieving affordability and providing best life cycle value for the products. It appears as if companies are currently competing by cost rather than product performance/design implying that manufacturing capability has the strongest competitive advantage. However, the required capability use manufacturing as a competitive advantage doesn't seem to exist in the industry. But, there is an overwhelming enthusiasm among the companies to outsource manufacturing as much as possible seeking lower costs. Many of the companies consider themselves engineering and design firms rather than manufacturers of aerospace products; most would prefer to be called system integrators at best.

Manufacturing systems are currently designed using one of the following methods:

- Trial and Error (primarily based on intuition and faith)
- Cooperative Decision Making (3P)
- Company Standard Manufacturing System (based on existing system and history)

It was also realized that an analytical manufacturing system design is not yet possible due to the limited available scientific knowledge on manufacturing systems. Even though there are many mathematical techniques and models available to simulate a manufacturing environment, a complete 'manufacturing science' does not yet exist except for narrowly defined situations. It was also realized that developing such a body of information could take many years due to the amount of data and analysis needed. Gathering data in a manufacturing environment is extremely difficult and time consuming. Many companies do not regularly collect all of the data that would contribute to the development of the scientific knowledge. Because a scientific knowledge base is not available, it is not possible to design a factory on paper and test it before implementation.

The concept of designing a manufacturing system is foreign to aerospace industry practitioners since there haven't been many opportunities to design factories in the recent history of the industry. Most of the factories in operation now were implemented several decades ago. Because the manufacturing systems have only been modified over the years and not designed, the practitioners can understand design only in the context of improvement activities. This is expected since practitioners seldom get asked to think at a system level and are only tasked to develop quick subsystem solutions to emerging problems. The concept of designing an entire manufacturing system is not well supported in the industry due to the apparent academic nature of the exercise. Because of this feeling, many companies are not really interested in design of an entire manufacturing system. Even though this and the research that follows might not have immediate applications to the industry, this work is essential in the development of the manufacturing science. The companies are very interested in eliminating waste from the existing systems as soon as possible. It appears as though gradual changes in the manufacturing system through repeated improvement activities are preferred suggesting that manufacturing system designs will occur in an evolutionary fashion as opposed to revolutionary fashion. This has been the trend throughout the history of manufacturing (Appendix B). Companies are very interested in tools that will help them improve the processes, eliminate waste, and convince management about the need for lean initiatives.

10.1.1 Manufacturing System Design Framework

The major contribution of this thesis is the framework that describes the manufacturing environment with a great deal of detail. It is apparent that the manufacturing system design activity extends beyond the factory floor. This implies a manufacturing system is larger than a factory and its design is influenced by the needs of stakeholders, the corporate strategy, the decision-makers at the corporate and middle management level, the product design, the suppliers and marketing. The effort also exposed the need for a unified strategy, the product strategy, where all of the core competencies of a company work collaboratively to offer the best solution possible. The major components of this strategy are product design, manufacturing, suppliers, and marketing. The strategy also reflects the needs of the corporate strategy and provides a long-term plan for the manufacturing organization. The framework shows that because manufacturing system design is influenced by several entities, it should be based primarily on the product strategy and not just on the product design.

10.2 FUTURE RESEARCH RECOMMENDATIONS

This work is a first of multiple research studies to be conducted by the Manufacturing Systems Team of LAI. The framework provides an understanding of the scope of manufacturing system and manufacturing system design. The framework is a very high level view of the manufacturing system design process, which is meant to show the major contributors, the extent of the activity, the major steps involved, outline currently available tools, expose any major 'holes, and to understand the status of aerospace manufacturing. Each one of the components in the framework requires further research to provide detailed guidelines, tools and methodologies. Due to lack of this knowledge, a design process is currently presented in a question form to stimulate thinking.

It is recommended that both the framework and the design process be used as broad guidelines to manufacturing system design, and as tools to understand the extent of manufacturing system, understand the importance of manufacturing and communicate the same to the management. If the reader is involved in any manufacturing system design activity, it is recommended that the reader try to locate his/her current activities on the framework. This exercise might help recognize the extent of current design activities and might help redirect the efforts if necessary.

Further research needs to be conducted to enhance manufacturing system design steps shown in the framework. As mentioned, the framework paints very high level picture of the design process. Each of the steps (Requirements, system selection, implement/evaluate, full rate, and modifications) can be further enhanced with tools and guidelines. To improve the usability of the framework, some recommendations are made below for further research.

The framework adequately represents both a brand new factory design and modifications to an existing facility. The research can be directed along both of these branches.

Development of a "Manufacturing Science" – The need for a science of manufacturing and the difficulty of developing such a body of knowledge was pointed out earlier. It is recommended that any future research will be performed to contribute to the development of manufacturing science in some way. It is recognized that this effort will take several years to complete. The only recommendation made here is to conduct research in such a way that it will contribute to the knowledge base.

Verification of the framework – The framework was developed based on practical knowledge gathered from conversations with industry practitioners. Moreover similar work by [Moody, et. al, 1990] has already been verified in the industry. It is strongly recommended here that the steps described in the framework be verified with case studies in the aerospace industry so that future research can be based on the framework.

Strategy Tools – While there are many strategy formulation concepts already available (Chapter 7), there are very few, if any, practical tools that assist in formulating and practicing these strategies. The product strategy, for example, is a new concept, requires collaboration between multiple components. Tools need to be developed or existing tools need to be enhanced to facilitate this level of communication and interaction.

Manufacturing System Design Factors – Section 6.2.1 mentioned the 10 factors that affect the manufacturing system design and Appendix C describes these factors in detail. In appendix C the possible effects these factors on the manufacturing system are hypothesized, research needs to conducted to verify these claims. The main topics of interest are as follows: Can these factors be used to compare two or more manufacturing systems? Can ignoring one or more of these factors lead to a 'bad' system design? Can existing system performance (success or failure) be explained using these factors? Are there any analytical relationships between these factors? Is there a subset of major factors within the 10 factors? Are these factors currently being considered in various forms in the industry?

Manufacturing " Regions" -- This idea was briefly mentioned in section 6.2.1 with the introduction of the 10 factors that describe a manufacturing system and representative 3-D maps of the existing manufacturing systems. If all these factors can be plotted in space, various intersections can be conceptualized representing possibilities for various (possibly innovative) manufacturing systems. There are many two-dimensional plots that attempt at this already but as discussed in section 6.2.1, these oversimplify a manufacturing system by reducing it to two variables. A system of plots that consider all 10 or at least a majority of the factors would be very useful in characterizing manufacturing systems better. Extensive data needs to be collected on various types of systems in order to develop these plots. If developed, this tool could be very useful in selecting systems based on the values for the 10 factors instead of the traditional two factors. This selection based on a higher number of variables can lead to a much better system.

Factory Modifications based on a strategy – It was mentioned that most of the manufacturers currently have focused their efforts on manufacturing process improvements. However, these activities are not based on any strategy or plan. The main focus of the investment seems to be simply the elimination of waste. Section 7.3.2 emphasized that the improvement activities should be focused on building manufacturing capability for the future. Research needs to be conducted in using the existing tools such as the value stream mapping, kaizen, and 3P in a strategic way to have maximum impact on the company bottom-line. While a structured approach to using the tools is necessary, enhancements to the existing tools are also needed. For example, one of the limitations of value stream mapping is the difficulty of representing shared resources (resources that are shared between multiple jobs). Similarly, the value stream mapping is a great tool to understand the current processes but it does not provide a disciplined way to improve the current state. Currently, a future state map is developed based on intuition and "guessing power" of the participants. There are no guidelines or tools that help in selecting the inventory between two processes. A simulation tool that takes in available information and suggests an upper and lower bound for the inventory (or any other parameter of interest) between two processes can be extremely useful. Companies are also seeking guidelines in deciding if Kaizen improvements have saturated and whether Kaikaku activities should be attempted. Macro value stream mapping (mapping between multiple facilities rather mapping a single facility) is recently being developed. Any guidelines to help the industry in deciding whether to apply macro value mapping first or to apply single facility value stream mapping would be very useful.

Insertion of new subsystems in to existing facilities **–** It was mentioned in Chapter 2 and Section 8.4 that most of the manufacturing system design environments encountered in the aerospace industry will be brownfields. The manufacturing system design process presented largely deals with adding an entire new facility or a new production line, it does not specifically address insertion of a new subsystem in to a factory. That is, if a company decides to add a new chemical-processing unit to the existing facility, for example, the process does not provided any guidelines. Several of the steps presented in the structure design part of the process (Section 9.3) are applicable assuming the subsystem being inserted is compatible with the rest of the systems in the facility. A subsystem can be treated as a new system, with added constraints (existing resources) and the framework from the requirements/considerations/constraints step onward cab be used. Since new subsystem insertions might be frequent in a brownfield environment, it is recommended that research efforts be directed to develop specific guidelines in this area. Note that the procedures needed to insert different subsystems might be very different from each other.

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11 APPENDIX A: GOALS OF AEROSPACE CORPORATIONS AND INFLUENCE ON MANUFACTURING SYSTEMS

There are many books and conferences on Lean Manufacturing, Quick Response Manufacturing, Agile Manufacturing, Flexible Manufacturing, Computer Integrated Manufacturing, and some 'New' manufacturing system. Are these applicable to the aerospace industry? Are there any parts of the above systems applicable? Should we develop a whole new system by taking the best characteristics of all the systems above? Should we try all and see which one works best? Should we try all at once or one system at a time? These are some important questions faced by manufacturing management on a regular basis. If the answers to all or even some of these questions were known, aerospace manufactures could compete head-to-head with other manufacturers from other industries and the industry as a whole might be able to attract and retain more investors.

11.1 BACKGROUND

The Manufacturing Systems group of Lean Aerospace Initiative (LAI) at MIT is taking on the bold initiative of tackling some of these challenges. Our goal is to develop a ***Manufacturing System Design Framework*** to assist manufacturing system designers in selecting a manufacturing system suitable for their company. Even though the questions above may apply to any other industry, they apply to the aerospace industry in a much stronger and unique way. The aerospace industry differs from, for example, the automobile industry in that there is no comparison between volume and variability of products produced in these two industries. Aerospace products can be one-of-a-kind products or products with extremely low volumes. Likewise, the aerospace market is highly uncertain compared to the automobile industry. The combined effect of low volume, high variability and uncertain market puts aerospace manufacturing in a high risk and a complex environment. Being in the high-risk category forces some very conservative investment decisions, which in turn inhibit efforts to seek any drastic performance improvements in manufacturing. There is a "do it right the first time" mentality wide spread among decision-makers. Therefore, any tool assisting in these decisions can be extremely useful. The ultimate goal of our research is to produce a tool, which will aid the decision-makers in selecting an appropriate manufacturing system. Proper use of this tool can greatly reduce the time needed to select a system and, more importantly, reduce possibility of implementing the wrong system eliminating the cost associated with it.

To develop a system under the banner of "best manufacturing system for aerospace industry," it is crucial that the industry, the business environment and dynamics are understood thoroughly. The first step we took was to understand the goals, the investment drivers and the influences on aerospace companies. This paper reports the results of this effort. In the next few pages, the following items will be discussed:

- Top level goals: Executive level managers and Middle management/plant managers
- Effect of Corporate Goals on Manufacturing
- Barriers to Investments in Manufacturing
- Our Perspective of the Aerospace Industry

We chose to interview individuals whose decisions affected the industry as a whole over the long-term, if not immediately. The interview was a two-tier process where the executive level managers of prominent aerospace corporations were interviewed first and the middle level managers were interviewed subsequently. A strong effort was made to represent military and commercial sides of the industry as well as all sectors such as, airframe, engines, space, and electronics. All in all 14 individuals were interviewed, with 9 at executive level and the rest in middle management.

11.2 The Highest Goal of Aerospace Companies-- Profitable Growth

Seven out of nine executives and two of the five middle managers mentioned profitable growth as the top most goal of their corporation. This is a two-part goal where business growth without an increase in profit does not satisfy the objective. To achieve this goal, both revenue and profit will have to increase. Even though many of them did actually use the words 'profitable growth', some of them described it in various other forms such as, increase profit, ROI <u>and</u> increase revenue, higher sales, double revenue, etc. There were also some other items mentioned as top-level goals such as, Return On Invested Capital (ROIC), Cash flow, Return on Net Assets and Economic Profit.

It was observed that the Wall Street has a very strong influence on corporate goals. Corporations respond to the stock market by trying to meet or exceed shareholder expectations, constantly seeking to reduce cost, trying to meet short-term profitability pressures, and trying to keep up with dot-coms (recent trend). While Wall Street is the major external driver, company culture, type of business (military or commercial) and personal interests and goals of the decision-makers were reported to be the other strong internal drivers. Changes in management also typically lead to changes in goals.

11.3 Effect of Corporate Goals on Manufacturing

Manufacturing operation can be considered one of the many enterprise strategies used to achieve enterprise goals. Therefore, manufacturing management has the responsibility of assisting in fulfilling the corporate goals. Changes in corporate goals will necessitate changes in manufacturing. There is a circular dependency between corporate goals and the stock market. The goals are generated in response to stock market pressures but stock market itself responds to company performance (with some time delay.) It would be beneficial to understand the effect of this circular dependency on manufacturing since manufacturing itself responds to corporate goals. Assuming that the level of investment in manufacturing reflects the perceived return potential of manufacturing operations, we (LAI) asked for all the reasons one would consider investing in manufacturing systems. Some of the reasons mentioned are described below.

11.3.1 Reduce Manufacturing Cost

Reducing cost is always welcome in this capital-intensive industry, but there are also other strategic reasons to do so. By reducing manufacturing cost the companies can convince their customers (especially, military) to acquire additional units. This not only increases revenues but also stabilizes the business over the long run. By convincing the customer to increase the allocated budget by a relatively small amount in return to aggressive cost cutting measures at the manufacturer's site, the companies are trying to deliver more units for less. This can be considered a win-win situation. This also proves to the customer that the cost can be reduced with strong incentives to do so.

11.3.2 "Creating Profit"

What I call "Creating profit" is a concept applicable only to annually renewed production contracts. In a fixed price or fixed price incentive fee contract, a standard learning curve and a profit margin for that contract period are negotiated when the contract is signed. Since this allowed profit margin is typically only around 8 – 10% while Wall Street expects a return of around 12 –15%, the companies have to find other ways to make up for the difference. One way is by executing a steeper than negotiated learning curve. Significant investments in manufacturing system are needed to "learn faster". This is an on going process where more investments would be needed in the next contract year to execute even a steeper learning curve since the new contract will be based on the learning curve developed in the previous contract year.

A second strategy, possible only with dual/multi source contracts, is a rather risky one. A dual/multi source contract is one where the contract is split amongst several competitors. The strategy here is to bid high (cost + higher profit) and win only a small part of the contract but take in a higher percentage of profits. While this seems to be the way to go, there is a high risk of not winning any part of the contract due to the high bid. Also, this strategy can only be used if the government chooses to use a dual source strategy, which might not be obvious at the design and development stage.

Military contractors are trying to expand their markets to foreign military customers. This creates a much bigger opportunity for business growth while increasing the profit potential significantly. Needless to say, this effort supports the highest goal – profitable growth – of these corporations. By entering the global market, the number of customers is increased from one (the US government) to as many US friendly nations as there are in the world. This trend also brings defense contracting business one step closer to commercial sector in terms of the business model.

11.3.3 Increase the Competitive Advantage (Strategic Need)

Investment in manufacturing systems is necessary just to remain competitive over the long run. Using modern tools, methods and processes can lead to significant savings in cost and lead time performance creating efficient responses to customer needs. Also, investing capital to develop core competencies is a strategic necessity to ensure business stability over the long run. Since by definition, a core competency is something that you have that your competitor does not, what else could be more important than to invest and develop this edge?

11.3.4 Development and Transfer of Technology Between Military and Commercial Programs

This applies mostly to companies having an approximately equal share of military and commercial business. It is beneficial financially, if technology developed in one area can be used in the other. Not only does it reduce capital investment, but it also increases company's responsiveness market demand. This typically occurs in the engine and airframe sectors.

11.4 BARRIERS TO INVESTMENTS IN MANUFACTURING

While there are compelling reasons to invest in manufacturing systems, there also are enough barriers to inhibit investment. We found that this is particularly true in the defense aerospace sector due to the way defense contract manufacturing operates. Some of the major roadblocks mentioned during the interview are described below.

11.4.1 Market Uncertainty and Budget Instability

While defense contracts provide up front capital and hence are an excellent source of much needed cash flow, they can be highly uncertain over long periods of time. The uncertainty stems from typical annual production contract negotiations, reduction of units purchased and changes in customer requirements. For an industry with probably the highest capital expenditure per product, this type of uncertainty encourages a strong risk-averse mentality towards investment. Since there is a very good chance that the investment might be lost, the companies hesitate to invest unless absolutely required to.

11.4.2 Low profits

Defense contract business can be described as “piece-wise” stable (Figure 2.3). Once a contract is signed, for the term of the contract, there is a steady flow of capital, revenue and profits. While this is excellent from a stability point of view, the profits generated are much lower (8 – 10%) than required to attract investors (the long-term stock market returns are 12 – 15%). Even though companies find other means (such as “creating profit” described above) to satisfy the difference, it is still a relatively unattractive business for an industry with “Profitable Growth” as the highest goal. Although tinkering with the learning curve might be a good strategy to achieve higher profits, it is not a sustainable method. Since the savings are adjusted during contract renegotiations, there definitely is a limit as to how much more can be saved. Once the system approaches practical efficiency, there will not be any more “visible learning.” Moreover, by having to give away the savings during contract renegotiations, the “award” that the companies deserve is taken away. It was mentioned that any savings even at the supplier level is required to be shared, making it not worth the time invested in achieving the savings.

11.4.3 Government pays cost

The government pays all development and tooling cost during the concept and technology development/demonstration phases. There is no real incentive to reduce expenditure during these phases, which affects the manufacturing system design, especially in the selection of tools and manufacturing processes. The decisions made in these phases however strongly affect the future investment decisions made during the production phase. The production contracts typically are fixed price or fixed price incentive fee, which might require the manufacturer to absorb the investment in manufacturing. If expensive tools and processes were chosen during the development stage, any improvements during the production period might become quite expensive for the manufacturer to justify the investment. Being risk-averse the companies typically choose not to invest in manufacturing system improvements. The only stimulation to invest in manufacturing system improvements would be if a competitor either generates higher profits or offers the product at a lower cost to the government by choosing to design a system during the development stage such that improvement initiatives during the production phase can be afforded. Realizing the potential for higher cost efficiency the government might require the same from other participants in the future contracts forcing careful decisions in manufacturing system design. This is a highly indirect incentive to reduce cost.

11.4.4 Short Payback Periods

As mentioned above, most production contracts are negotiated annually. It is quite impossible to realize significant system improvements of any sort (efficiency, cost, or lead-time) within such a short time period. Companies will have to launch multi-year, megabuck contracts to see drastic improvements in system performance. Due to the short time period, large investments can not be justified. It is quite impossible to recover the cost much less any return on the investment in one year. Unlike the commercial sector, the investments can not be amortized over multiple years and multiple programs to spread the risk. To tackle this very issue, almost all of the companies interviewed showed a very strong preference for multiyear contracts over annual contracts.

11.5 EXECUTIVE VIEW ON THE ROLE OF MANUFACTURING

The most of the executives we spoke to considered themselves engineering and product design companies rather than aerospace product manufacturers. They felt they were product integrators at best. Some mentioned that selling engineering and product design solution generated higher revenues than manufacturing did. We were left with an impression that companies treated manufacturing capability an expense of doing business rather than a competitive advantage. There is a social hierarchy where manufacturing engineers rank below product designers. Manufacturing organization seemed to take “orders” from the product development group. Some of the interviewees mentioned that their engineering employee head count was almost three times that of the manufacturing organization indicating the focus of the company. The trend to outsource as much manufacturing as possible also indicates that many companies are trying to reduce the size of their manufacturing operation.

11.6 SUMMARY

The information gathered through the interviews can be summarized as below:

Military	***Commercial***
Excellent for cash flow	High potential for profits
Piece-wise stable	Highly cyclical
Pays development cost	“Bet the company” on new programs
Investments based on requirements for individual programs	Investment based on market forecast
Indirect incentives to reduce cost	Cost reduction always pays off
Cost savings are shared with the customer	Cost savings directly add to the profit
“No control over your destiny”	Always under management control
Encourage short term investments	Long term investments can be afforded due to amortization over longer periods

As the table shows, there are unique qualities of both businesses. Many aerospace companies have realized this characteristic and are trying to achieve a comfortable balance between both, military and commercial, businesses. Companies are using best traits of one business to compensate for the challenges of the other.

There is a very strong trend to outsource fabrication in order to reduce manufacturing cost. While a few executives highly favored this idea, few others anticipated many problems with the strategy. These problems are mostly related to the risk of loosing control of the business unit outsourced as far as scheduling and quality issues are concerned as well as loosing the knowledge and capability of the outsourced work. This could lead to serious production problems, if the supplier goes out of business.

The companies respond to Wall Street pressures promptly. Since the Wall Street heavily influences company goals, the goals are likely to change often to satisfy Wall Street. By majority consensus, the highest goal of the industry was Profitable Growth. This is a two-part goal where profits and business growth are expected concurrently, that is, just a growth in revenue is not sufficient if profits are not growing. We also noted that many of the companies are assuming a “Portfolio Mode” by carefully balancing military and commercial businesses to achieve company goals. None of the companies showed any preference between military and commercial businesses. All wanted a healthy balance of both businesses. A strong interest is growing among military contractors to obtain foreign military contracts to expand the market and profitability. It is apparent that the aerospace industry operates in a highly uncertain and unstable environment. The low return on investment generated by the industry is further compounded by the fact that this industry is also capital intensive. This highly undesirable environment creates strong risk-averse mentality towards investment. There is a clear social hierarchy between the product design and the manufacturing organizations with manufacturing ranking lower.

12 APPENDIX B: HISTORY OF MANUFACTURING SYSTEM DESIGN

12.1 OVERVIEW

This chapter gives a brief history of developments in manufacturing techniques over the last two centuries. Besides introducing the various manufacturing techniques such as Craft production, mass production and lean production, emphasis is given to the reasons (the need) behind the development, the methods used, and the way the technique was diffused. It will be pointed out that each development was in response to a perceived need in the society at the time. An attempt will be made to identify the stakeholders involved and stakeholders preferred, if any. It is clear that the methods used to develop the technique were predominantly trial and error and extensive experimentation. Note that each of the solutions was developed in an evolutionary fashion at the expense enormous amounts of funds.

The chapter then transitions to focus on Aircraft manufacturing, the attempt to mass produce aircraft and the adoption of a preferred method of aircraft manufacturing during World War II. This method, with some variations, is still being used at all major aircraft manufacturers.

12.2 CRAFT PRODUCTION

“Craft production system” or the “workshop system” is the term attributed to describe the type of manufacturing techniques used widely during the very early ages of manufacturing. It appears that this was the only type of manufacturing known to manufacturers until the late 1700s. I assume that the demand and the customer expectations at the time were very low and craft production was arrived at as a solution to meet the need of the society of that time. This need could be merely the widgets needed for day to day life. The system must have been adequate to satisfy the customer expectations until the late 1700s. Under this type of manufacture, every product was a unique piece of art. The worker in this system was highly skilled in design, machine operation, tool usage, and fitting. The worker often progressed through an apprenticeship to a full set of craft skills. The system was highly decentralized, where each worker worked independently to manufacture his part. In many cases, one worker built the entire product. There were no standard designs and even similar parts were unique. Every part needed to be fitted and the quality of the product depended on the skill level of the worker. As can be expected, this system could support only extremely low demands (for example, less than 1000 automobiles per year). [Adopted from Womack, 1990 and Ruffa, 2000] The main stakeholders in this environment were the customer and craftsperson himself.

12.3 Interchangeable Parts and The American System of Manufactures

The armed forces began to realize the inadequacy of the craft production, especially regarding the limitations on volume production and lead time implications. The battlefield environment had created a new requirement of higher volume, faster manufacture, and faster repair of arms. The solution was the American System of Manufactures based on the technique of interchangeable parts. The U. S. Army had perceived the interchangeability of rifle parts as a real need. Its determined quest for the interchangeability supported by military demand, finance, and ideology ultimately led to achieving the goal. [Zeitlin, 1995]

The technique to produce interchangeable parts was developed over many years of trial and error experiments. There were critics who believed that interchangeability could not be achieved. Some believed, rightfully so, that interchangeable parts were not cost effective. Once the techniques became successful however, it diffused widely into other industries and countries. Visitors from other countries studied the techniques and were impressed. Even though the technique was designed for arms manufacture, it was adopted and modified to fit the specific needs of other manufacturing functions such as clocks, sewing machines, typewriters, agricultural implements, bicycles, and ultimately automobiles both domestically and internationally. [Hounshell, 1985]. It should be noted that some entrepreneurs such as Samuel Colt decided not to adopt the technique of interchangeable parts entirely. They came up with their own way meeting the business needs. The list of stakeholders in this environment grew compared to the craft production. US government was the primary stakeholder. The individual inventors/entrepreneurs, armory officials, and employees were the other stakeholders.

12.4 MASS PRODUCTION

The explosive diffusion of the techniques to produce interchangeable parts along with developments in factory organization, specialized machines, precision manufacture, coordinated work sequence and material flows led to great improvements in manufacturing industry. [Hounshell, 1985]. By the early twentieth century, a new level of living standard had been assumed due to the above developments, and higher incomes. The developments in manufacturing techniques, which facilitated introduction of new and improved products, had created previously unrealized needs and expectations in the society for luxury. The automotive industry, in particular, grew steadily with the development of the motorized car. As Womack says, by 1905, hundreds of companies in Western Europe and North America were turning out autos in small volumes using craft techniques. [Womack, et. al., 1990] As can be expected, the explosive growth (~1000% between 1908 and 1916 [Hounshell, 1985]) of customer demand could not be satisfied by the auto industry using craft techniques and interchangeability alone. Manufacturing industry now faced a major challenge of meeting the unprecedented worldwide demand. The scale of manufacturing became the opportunity, need and the challenge in the early 1900s**.** [Suri, 1998]

The solution was Henry Ford's Mass Production, which satisfied the demand growth above with ease. Mass production came as a result of the important prior developments in part interchangeability, the idea of continuous flow, the rise of an efficiency movement and the insights from the Chicago slaughterhouse "disassembly" lines. [Hounshell, 1985]. The mass production also came as a result of several decades of developments in manufacturing, experimentation, trial and error and very high investment.

As Womack says, mass production drove the auto industry for more than half a century. Similar to the diffusion of techniques of part interchangeability, mass production was eventually adopted in almost every industrial activity in North America and Europe. Ford attempted to mass produce everything, from food to air transportation. [Womack, 1990] It was so popular that American managers and consultants roamed the world, training foreign managers and assisting them in rebuilding their industries. Once again, European and Japanese managers and engineers flocked to the United States to visit and find out the what made them so effective. [Hayes, et. al. 1988]

12.5 Toyota Production System (Lean Production, Just In Time Production)

The concept of mass production and it's variants (flexible mass production by GM) were assumed and appeared to be the solutions for all manufacturing needs until Toyota shocked the world by introducing revolutionary improvements in performance over mass production techniques through the Toyota Production System (TPS). The development of TPS also fits well with my observation that developments in manufacturing techniques resulted in response to important needs or challenges in the society and that each development was an evolution or enhancement of the existing techniques.

To point out that TPS was a response to needs of the society, below are some of the challenges faced by Toyota in the 40s and 50s:

- There was a need to rebuild the nation's economy after World War II. To protect the Japan's Motor Industry, the government issued a prohibition against any direct foreign investment into Japan Motor companies. This was clearly a insulated environment for Japanese auto industry to freely experiment and grow
- Mass production was not an appropriate technique for Japanese auto industry, which only had a small fraction of volume relative to the American auto industry.
- Japan was severely limited in land, financial and raw material resources.
- Toyota concluded that product variety and volume are both important and not just volume

- Mass production lacked the much-needed flexibility to handle a high product variety demanded by the society in Japan.
- Workforce in Japan gained a strong bargaining power and management's right to layoff workers was thus severely restricted. [adapted from Black, 1991 and Womack, 1990]

The above set of unique challenges and requirements led to the development of TPS over many decades of experimentation. It is important to note that TPS was developed using trial and error as well. Moreover, Toyota production system was an enhancement of the mass production system. Eiji Toyoda extensively studied Ford's River Rouge plant in Detroit for three months. In fact this was the second trip for the Toyoda family to Ford's plants. As a result, TPS reflects many of the concepts used in mass production such as single piece flow, point of use tools, and assembly line. Toyota modified and enhanced the existing leading manufacturing techniques to fit its needs and challenges to develop Toyota Production system. History repeated again as far as the diffusion of the system was concerned. Once Toyota proved its way of manufacturing was far superior to any contemporary techniques, every industry wanted to learn and adopt TPS. The process is still ongoing. Companies are spending millions to send employees to Japan, hire Japanese consultants to learn the secrets of TPS. As it was true throughout the history some companies have successfully adopted TPS, others have failed, and many are still trying to implement TPS techniques. The success of TPS can be attributed in part to its wide consideration of stakeholders such as the shareholders, management, hourly employees, customers, government, suppliers and the environment. Figure 12.1 shows a schematic of various stakeholders considered and satisfied in different manufacturing systems.

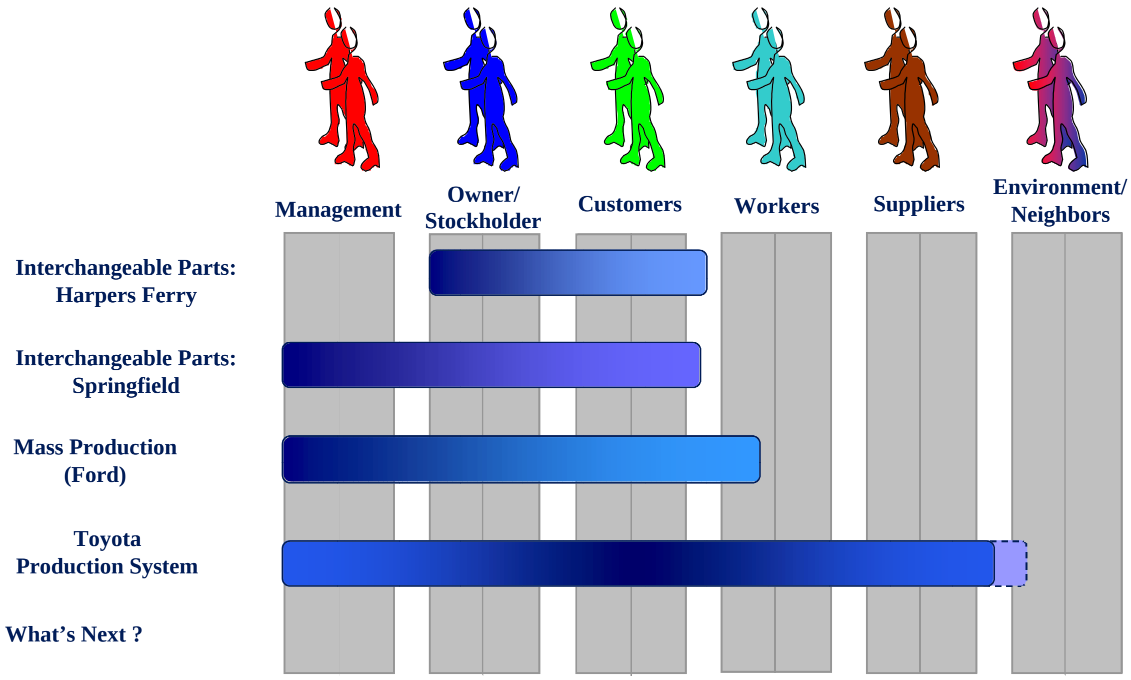


Figure 12.1 Stakeholder Inclusion in Major Manufacturing Systems [adopted from Gutowski]

12.6 Analysis

It is important to note that the craft production, technique of part interchangeability, mass production, and TPS were solutions to perceived major manufacturing challenges of the time. The history shows that there was significant time delay between the realizing the challenge and devising a solution. The invention of the solution came as a result of much financial expenditure, trial and error, and collective effort of many inventors. Also, the solutions were not radical deviations from the existing methods, but were enhancements of the existing techniques/ideas. It should also be noted that these new techniques did offer step function improvements over the performance of existing methods but were developed in an evolutionary fashion. That is, mass production might not have been possible without the mastery of interchangeability among other things. Another theme that should be cited is the rapid diffusion of the techniques into other industries and countries once the techniques were perfected. Figure 12.2 shows this cyclical process.

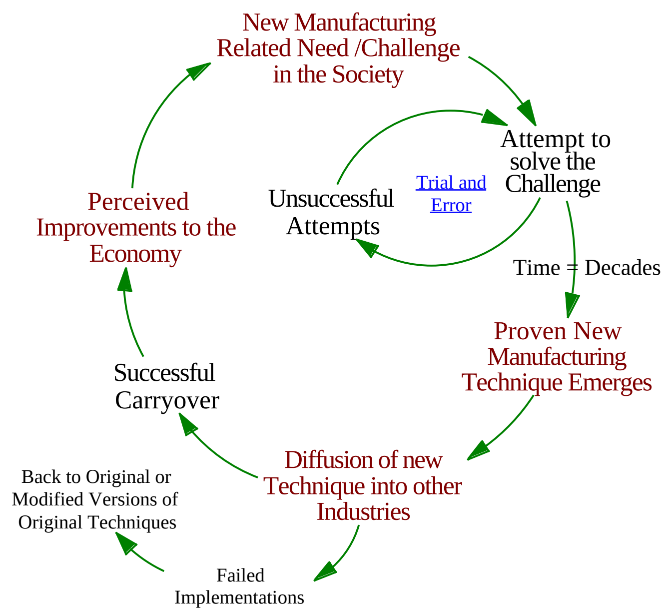


Figure 12.2 Schematic of Manufacturing System Development and Diffusion Cycle

12.7 AIRCRAFT MANUFACTURING

The aircraft manufacturing began in the early 1900s with Wrights' first flight. While other industries were creating or discovering hidden challenges and solving them with innovative manufacturing techniques and processes, the aircraft technology was just taking birth. The utility of the newly invented aircraft was not known to anyone. It was just a rich and adventurous person's "hobby". The demand for such a high risk contraption was very low, in fact only 400 aircraft were built prior to World War I [Ruffa, 2000]. The manufacturing techniques demanded highly skilled individuals, who understood the physical design, who were comfortable with rudimentary wood working tools and were innovative enough to make the various parts fit. [Adopted from Ruffa, 2000]

The above set of skills was almost an exact match to the characteristics of Crafts Production described in section 12.2. Moreover, being a young technology, the aircraft manufacturing required a very high degree of flexibility in manufacturing techniques.

Craft Production, again, was the best candidate for such a need. This is exactly what the early manufacturers of aircraft selected to be their choice manufacturing technique. The system matched the needs of the society and the manufacturer.

12.7.1 Aircraft Mass Production

As established earlier, when a challenge surfaces manufacturers try to invent techniques to solve it immediately. The one who succeeds becomes the industry leader, and the others copy or adopt that solution to their operations. The aircraft manufacturing was not immune to this pattern of behavior.

Many entrepreneurs saw a market for aircraft forming as World War I began. They tried to meet the increasing demand by ramping up their production but were highly unsuccessful due to the systemic limitations of the Craft Production. This was an indication of a new challenge forming in the world of aircraft manufacture. Soon after World War I, the United States Postal service reinforced the demand for aircraft by using airmail service. [Ruffa, 2000] But, the advent of World War II created an explosion in demand for aircraft that is reminiscent of the demand growth of automobile industry between 1908 and 1916. With Roosevelt's call for 50,000 aircraft in two years, the aircraft industry had risen to be the largest industry in the United States from its original 44th position in size. [Ruffa, 2000]. Besides discovering the demand challenge, the industry faced another much more critical challenge. The skilled craftsmen employed in the aircraft manufactures were now off to war and the workforce was now composed of new workers who might not have held a wrench before. [Ruffa, 2000]

The solution to these challenges, again, was thought to be mass production. The requirements for the solution were high volume production and low skill level. Mass production fit the bill very well. Without much a do, automobile giants such as Ford built or converted factories to mass-produce aircraft. With his plant at Willow Run, Ford had proclaimed their ability to produce one thousand B-24 bomber planes a day within eight months. [Zeitlin, 1995] A new manufacturing process based on the principles of mass production was outlined. The work was broken down to relatively short, simple and repetitive tasks. The aircraft were manufactured on an assembly line similar to the automobile assembly line. All in all, the aircraft manufacturing was converted to mass production. The United States was not the only one to use aircraft mass production, British Air Ministry, in fact, forced the use of high-volume techniques on British aircraft manufacturers. [Zeitlin, 1995]

12.7.1.1 Failure of mass production in aircraft manufacturing

Both British and United States aircraft manufacturers soon realized the shortcomings of the aircraft mass production. The technique could not support the most important characteristic of the young aircraft industry and the most important need of Air Force – the responsiveness to design/manufacturing changes. Due to the lessons learned on the battlefield as well as engineering research and development, the aircraft designs were changing constantly. The changes were so prominent and continuous that the last B-24 rolled out of Willow Run plant was an entirely different aircraft compared to the first one [Zeitlin, 1995] The implementation of these changes was crucial to the success of the Air Force strategy and the lives of the pilots. But, as Zeitlin says, changes during manufacture were "tabooed" in Ford's factories. The constancy of design was crucial for the smooth operation of mass production. Unfortunately, this created a serious conflict between the customer need and the requirements for the solution. Listed below are some reasons why mass production was not a suitable solution to the aircraft demand growth:

- The aircraft were not completely engineered and were not ready for mass production
- Mass production required a design freeze once the drawings were released (no flexibility)
- Workers in the mass production system could not readily understand the original aircraft drawings
- Frequent part shortages
- Ford could not recruit more than 40,000 of the needed 72,000 workers

12.7.2 The BDV Multi-line Assembly Concept

Not every aircraft manufacturer in the United States adopted mass production. Companies such as Boeing, Douglas and Vega selectively modified their operations by borrowing from mass production techniques to develop a manufacturing technique called the BDV (Boeing, Douglas, Vega) system. [Ruffa, 2000]

The BDV system sought to minimize the movement of large aircraft structures through the factory. The concept calls for multiple subassembly lines instead of a single straight assembly line. The assembly operation was arranged in series of consecutive semicircles, with each arranged largely based on the size of the components being assembled. Figure 12.3 shows a schematic of this concept. The final assembly operation was located nearest the factory door, which were consequently fed by the larger subassembly lines. These were in turn fed by component fabrication areas and storerooms. This system must have worked very well in the aerospace environment since it is still being used at almost all airframe manufacturers. Even though the consecutive semicircle assembly lines are not seen today, the basic concept remains the same.

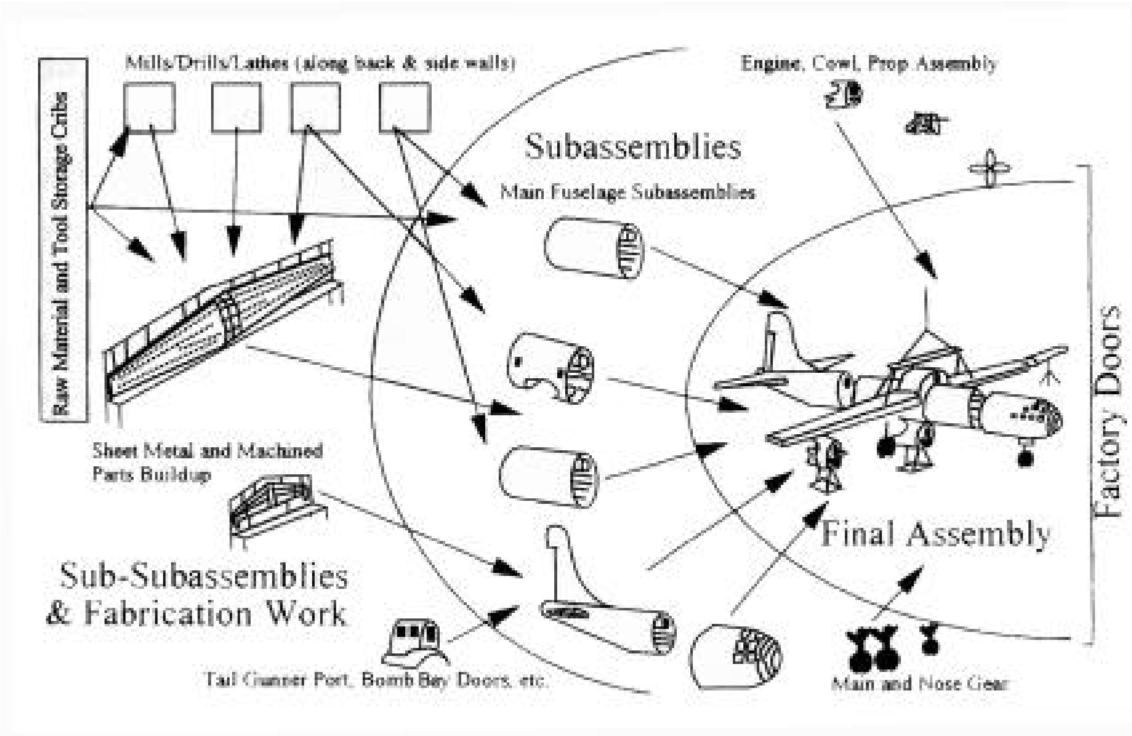


Figure 12.3 The BDV Aircraft Assembly Line Concept [Ruffa, 2000]

13 APPENDIX C: MANUFACTURING SYSTEM INPUTS

13.1 MANUFACTURING SYSTEM DESIGN

It is too difficult to model a manufacturing system due to the highly non-deterministic nature of the manufacturing operation. There are too many uncertain variables, the most uncertain of which are the human beings. Yet, factories have been designed and operated over the past centuries. As discussed in Chapter 6, most of the methods used are based on trial and error. These methods are used even today, though they are much more sophisticated.

Trial and error requires one to pick a certain system, try it first and then modify it to work for current requirements. Since there are numerous choices available, choosing the wrong system can lead to wasted time and wasted investment. Most managers rely on their experience and intuition to select a system and make it work. Once a system appears to work under normal conditions, this system is used repeatedly for all conditions. As discussed earlier, this is type of factory “design” is not based on any strategy or a plan. Without proper analysis and a structured approach, a good solution can not be guaranteed. As a first step, the research team attempted to determine the major factors that must be considered while designing a manufacturing facility. Listed below are the several reasons for this effort:

- These factors will be able to describe a manufacturing system more completely compared to the existing 2-D manufacturing system maps.
- They will provide a common basis to compare two or more manufacturing systems
- One can analyze the effect of ignoring one of these factors on the performance of the manufacturing system
- A better set of plots offering better insight in to manufacturing system selection than the existing 2-D manufacturing maps can be generated
- Any influences of one factor on the others can be understood so that the system can be designed to compensate for these effects

- Any analytical relationships between the factors can be used in developing simulation or analytic tools.

Extensive literature search was conducted to explore any previous work done in this area. Experience of the team members and result of past LAI research was also used to develop a list of factors that were thought to have influence on manufacturing systems. To solidify this list of factors, 9 different factories from different sectors of aerospace industry were visited and Individuals who had any exposure to manufacturing system design (from decision authority to detailed component level design) were interviewed. The audience included plant managers, manufacturing engineers, industrial engineers, Lean champions, Lean consultants, shop floor managers and shop floor employees. All in all more than 100 people were spoken to during these visits. The list of all factors obtained from all of the sources above is given in Table 13.1. The factors listed will be defined and explored further after some initial categorization and elimination. It should be noted that all of the considerations mentioned are listed here to show the number and variety of factors that were discovered. It will be shown later that there are hierarchies and cause and effect relationships in these factors. For example, the "stakeholder satisfaction" effectively represents "corporate strategy" since corporate strategy most often is built to satisfy stakeholders. Similar relationships exist between many of these factors, which will be used to reduce the list down to a manageable level.

Stakeholder Satisfaction	Product Complexity
Corporate Strategy	Process Capability
Make-buy/Outsourcing Strategy	Type of Organization
New Product Introduction Strategy	Worker Knowledge/skill
Market Uncertainty	Investment
Geopolitical Considerations	Time to first part
Offset Requirements	Affordability/Cost
Environmental/Government	Customer Price (Target Price)
Regulations	Product Quality
Product/Program Nature	Resources Available

Product Volume	Existing Resources
Product Mix	Performance Goals
Product Design	Management Culture
Frequency of changes	Product Life Expectancy
Payback Period	Level of Product Maturity
	Response to change

Table 13.1 Considerations in Manufacturing System Design

The list in Table 13.1 is by no means complete, yet it seems overwhelming indicating the difficult nature of the manufacturing system design task. For ease of analysis, understanding, and elimination of duplicates, the items in Table 13.1 were sorted into the following broad categories: enterprise Needs/Objectives/Strategies, external factors, controllable factors, and constraints /targets.

13.1.1 Enterprise Needs/Objectives/Strategies

This category includes any considerations that originate at the enterprise management level. Since the manufacturing system is a subsystem of the whole enterprise system, these factors must be considered highly to ensure proper system-subsystem alignment in objectives. These factors are the goals of manufacturing system itself. Stakeholder satisfaction, for example, is a corporate goal, which in turn becomes the goal of a manufacturing system. The enterprise needs or strategies can have very strong influence on how the manufacturing system is designed. The manufacturing system design team must take these factors under consideration to help the enterprise satisfy its goals. Table 13.2 lists the items in Table 13.1 belonging to this category.

13.1.2 External Factors

The enterprise does not have complete control over these factors yet they must be accounted for to achieve the enterprise and manufacturing system goals. It is difficult to determine exactly how much control an enterprise has on these items. Market uncertainty and government regulations are two examples of external factors. It can be argued that over time the enterprise can have enough influence over market dynamics due to systemic effects and on regulations through lobbying. It is assumed here that the time between a request for change (in the case of regulation) and the subsequent approval is longer than the time available to design and implement the manufacturing system. Although, changes can be built in if sufficient information is available at early stages of a system design regarding an impending change in regulation. These external factors often determine location of the plant, worker composition, and size of the manufacturing operation. For example, due to stricter environmental regulations, many of the manufacturing operations are being moved out of state of California. Some considerations such as offset requirements might require a company to open up a manufacturing plant in a given state to gain congressional support or open a plant in a different country to be able to sell products in that country. Therefore, the "external" factors appear truly external to the manufacturing system designers but a decision must be made to comply or not comply with these expecting a potential effect of this decision on other enterprise strategies. Table 13.2 shows the factors that are considered external to the enterprise.

13.1.3 Controllable Factors

The enterprise or the decision body has enough control over these factors to make strategic decisions based on them. Product mix, for example, is such a factor where a company can decide the number of products it will offer. If there is a demand for 5 different versions of the product, the company can decide to offer all 5 versions or offer only 3 based on some strategy. From Table 13.1, Investment, product quality, and worker skill level are some other examples of these factors. It should be emphasized that the enterprise might have more control over some of the controllable factors than on the others. Nevertheless, the decision-makers have more decision authority over controllable factors than over external factors. The effect of making a hasty choice on these factors might have a relatively insignificant effect on the manufacturing system compared to the global and relatively significant effect that can be expected by not complying with some of the external factors such as government regulations.

13.1.4 Constraints/Targets

Constraints and goals are set by the management or the decision body to ensure that the remains within the established boundaries of corporate standards for financial and manufacturing system performance. The constraints typically limit the design possibilities but allow the manufacturing system to comply and contribute to enterprise system objectives. This category also covers both financial and physical performance goals. Table 13.2 shows the factors considered to be constraints to the design activity.

As mentioned above, the corporation has varying levels of control over the factors within the "controllable factors" category. The level of control assumed can be very subjective depending on the corporation. Similarly, the distribution between "external factors" and "controllable factors" also required human judgement. The enterprises will have to set their own boundaries on all of these categories and sort items accordingly. Some of the items considered here as controllable might qualify as external depending on the context. Thus, it is important to consider these categories in context of your business. The categorization here is based on commercial environment. On the commercial side, while the company has no direct control over present customer demand for aircraft, it does have full control over how much of the demand it will satisfy. That is, a company can make an executive decision to produce only 100 aircraft even if there is a definite demand for 150 aircraft. Depending on the strategy, the corporation can control the level of importance (quantitatively or qualitatively) given to the "controllable factors."

Enterprise Needs/Objectives/Strategies	***Controllable Factors***
Stakeholder Satisfaction Corporate Strategy Make-buy/Outsourcing Strategy New Product Introduction Strategy	Product Volume Product Mix Product Design Frequency of changes Product Complexity Process Capability Type of Organization Worker Knowledge/skill Affordability/Cost Management Culture Response to change (Flexibility)
External Factors	***Constraints***
Market Uncertainty Geopolitical Considerations Offset Requirements Environmental/Government Regulations Product/Program Nature	Investment Time to first part Payback Period Customer Price (Target Price) Performance Goals Existing Resources

Table 13.2 Manufacturing System Design Considerations by Categories

13.1.5 Major Factors in Manufacturing System Design

Even though all of the factors that are mentioned in Table 13.2 are valid, not all of them affect the manufacturing system design directly. This list of factors can be reduced to a manageable level by retaining only the factors that directly affect manufacturing system design. For example, the offset requirements might change the location of a plant but does not necessarily change the design of the plant itself. Similarly, careful investments and efficient manufacturing processes achieve affordability. The core input is the investment and not affordability. Based on this thinking the above list was reduced to the following factors:

- Market Uncertainty
- Product Volume
- Product Mix
- Frequency of Changes
- Complexity
- Process Capability

- Worker Skill
- Type of organization
- ***Time to first part (a constraint)***
- ***Investment (a constraint)***

- ***Available/Existing Resources (a constraint)***

13.1.6 Market Uncertainty

Market uncertainty is defined here as the demand fluctuations for product including both short-term random variability and long-term step/cyclical variability.

Measure: Demand +/- X per time unit

Market uncertainty is a major concern in aerospace business environment. As discussed in the introductory chapters, both commercial and military branches experience unique patterns of demand fluctuations. Commercial aircraft manufacturers, for example, experience a cyclical demand profile, where the ups and downs can be predicted fairly well. In the military branch, the demand profile can be best described as step-wise stable. The demand is stable for a certain period then drops unexpectedly and remains there for an unexpected period of time. Other sectors within aerospace industry might experience the similar or some variations of these to demand profiles. These demand fluctuations are by no means limited to the final product integrators. The suppliers at all levels also experience these fluctuations; sometimes with even larger amplitudes. A manufacturing system should be designed to take these variations into account.

The demand uncertainty affects manufacturing operation by creating over capacity or under capacity in the system. In the case of over capacity, the demand has fallen significantly and the manufacturer is paying for the unused and idle resources. In the case of an under capacity, the manufacturer is unable to supply the market demand causing customer dissatisfaction. In both cases, the corporation's bottom line is being affected adversely. It is always difficult to have the exact capacity needed at all times since the demand itself is uncertain. In aircraft manufacturing, since the manufacturer incurs a charge for late deliveries, the manufacturers might prefer over capacity than under capacity. In military environment, there is a higher chance of budget cuts than budget increases. Hence there is a higher chance of order quantity reductions leading to leaving manufacturers with over capacity.

To cope with uncertain demand, the manufacturers tend to build buffers (inventory) in the system. In the commercial side this can be purchasing material during troughs to lock in low costs. In the military branch where the government pays cost in most of the programs, due to the possibility of budget cuts in the future, the manufacturers buy all materials needed to produce the entire order at once. They hold inventory and start producing products as needed. [Wang, 1999] Therefore, the uncertainty in demand creates the need for buffers in the system

Market uncertainty also affects factory design as far as the worker skill is concerned. Aerospace industry is known for frequent layoffs, which are closely correlated with demand cycles. Frequent layoffs can cause a manufacturer to lose skilled workers. Subsequent hiring to build capacity will require training to build up the lost skill set. The time needed to build the skill might be longer than the available time. The solution to this would be to design a factory that requires the lowest set of skills.

Moreover, the knowledge of market uncertainty affects investment in factory improvement initiatives. The executive interviews also showed that the very possibility of a down turn in demand or budget cuts (military) can create a risk-averse behavior among manufacturers.

13.1.7 Production Volume

-- The number of products to be manufactured over a time period.

Measure: Total production volume per time unit

Production volume is one of the most important considerations in manufacturing system design. The maximum volume that can be produced determines the plant capacity. In fact, market uncertainty and production volume are tightly coupled. The market demand determines the actual current production volume of the facility, which might not be the maximum volume the facility can output. Since the demand fluctuates over time, having a predetermined maximum volume leads to the facility operating with over capacity or under capacity. The maximum production volume can not be changed quickly without financial expenditure. As mentioned above, operating with both over and under capacity will lead to financial consequences. Therefore, careful analysis should be done prior to selecting a maximum plant capacity. It is also crucial that management is aware of the actual plant capacity so that they may not over sell leading to missed or late deliveries.

Selecting a maximum production volume determines most of the factory physical design. It affects the floor space needed, machine selection, machine layout, factory control system, number of shifts, number of workers, ability to meet or not meet market demand, unit cost and operating cost of the plant. Because of this wide effect of volume on factory design, many researchers in the past have used volume as one of the two factors to describe the entire manufacturing system.

13.1.8 Product Mix

-- The number of different products to be manufactured.

Measure: Number of different products manufactured

As the definition shows, this factor allows the designer to build in product flexibility or product variety in the manufacturing system. From a market need satisfaction and resource use point of view, it is important that a manufacturing system be able to produce various versions of a product or entirely different products in the same factory. In the aerospace business, especially, there is a possibility that each product could be one of a kind. In this case, it is crucial that the factory be designed to accommodate this level of flexibility.

Product Mix and Production Volume are closely related since having a large product mix would reduce the volume produced per part. These two variables alone can determine the factory design and hence most of the 2-D manufacturing system maps use Volume and variety as the two factors to specify a manufacturing system. For example, if a corporation desires very high product mix and high product volume, the charts show that currently there is no system available that meets this need. On the other hand, a Flexible manufacturing system can provide a high product mix and low volume. Historically, this has been done using departmental layouts where similar processes such as milling, turning, grinding, etc. were organized in one area and all the products that needed these services went through these departments. Lean manufacturing principles advocate product–oriented layouts as compared process-oriented layouts.

It is important that the designers build in product mix flexibility during the design if the corporate strategy includes rapid product introductions. Also, factory life cycles are typically longer than product life cycles and even if new product introductions are not part of the strategy, the factory most likely will see entirely new products introduced in its lifetime.

13.1.9 Frequency of Changes

-- ***The anticipated possible set and types of changes that will affect the production facility***.

Appendix C

Measure: Number of engineering changes per time period

The changes here refer only to engineering design changes that affect the factory operations. The manufacturing process changes that might occur without engineering changes will be dealt with later. It should also be noted that there is possibility that an engineering change might not affect the factory floor. A software change in avionics suite would be an example of this type of change.

It is impossible to foresee all the changes that might be introduced to the product in the future. To make that happen the system will have to be infinitely flexible and the designers will have to make tradeoffs in other areas. One can, however, anticipate certain types and sets of changes based on past experience and the product maturity. Changes can be grouped by types such as software related, structure related, assembly sequence related, etc. Likewise, within these types, a decision can be made towards the extent of change that should be anticipated and designed in. It should be stressed that these changes are only anticipated and they might not materialize. Thus, having this flexibility might not necessarily enhance the system performance (in terms of response time) but it surely will not worsen it. Since there is some monetary costs involved in designing flexibility in the system, care should be taken deciding on the level of flexibility to accommodate. Note that the frequency of changes is also important. The effect on system performance will be minimal if there were only a couple of changes over a period of a year compared to couple of changes introduced every week.

Frequent design changes are a common characteristic of both commercial and defense sectors of the aerospace industry. In the commercial arena, this can happen in two different ways. First, the design changes can occur due to, the more common, lack of design/product maturity. Second, the changes might be an effect of the corporate strategy. Some aircraft manufacturers have a strategy to offer fully customized aircraft to their customers to increase customer satisfaction. This is an example of the direct effect of corporate strategy on manufacturing. While these customizations mostly affect the interior of the aircraft and might not require major design changes, they do introduce constant variations in the manufacturing process and require the system to be able handle this disturbance smoothly. In the military sector, the changes can be introduced by the manufacturer for various reasons or required by the customer. These changes can be major design changes. As the customer realizes the needs for better performance, maintenance or uses for the aircraft, the manufacturer will be required to make the necessary changes to the aircraft. The changes can be structural or upgrades to existing systems and can occur as the aircraft is being manufactured. Traditionally, aircraft manufacturers have dealt with this variability by introducing the changes in blocks. That is, all the changes will be catalogued and introduced at the next block (a certain number of aircraft) of aircraft deliveries. The system nature of manufacturing operation is evident here where both corporate strategy and engineering divisions have strong influences on manufacturing performance and operation.

13.1.10 Complexity

Measures: Number of parts, number of process steps, size of the CAD file needed to describe the part, size of the part, time needed to finish the task efficiently, number of subsystems involved, etc.

The word complexity mainly is used to describe the level of difficulty associated with fabricating or assembling a part. Complexity is a difficult subject to describe in a manufacturing context since it can represent the product complexity, fabrication process complexity, assembly complexity, the complexity of the entire manufacturing system itself, and a combination of the above. Therefore, a definition is not provided here for this factor. Here, the effect of a complex product or part on the manufacturing system design is described. After much discussion, it was agreed that the level of complexity is affected by the available process capability (here capability is used in the sense of being able fabricate a part of given specifications). That is, if the part or product to be fabricated or assembled is perceived to be complex by human standards and if a machine is available to perform the task, then as far as the human effort is concerned, the complexity of the operation is reduced significantly. Therefore, the complexity of the manufacturing system as a whole depends on the available process capability.

The complexity of the manufacturing system design task can be understood at two levels. One can think of complexity in terms of the operations performed on a part between any two points (or processes) in a factory. This can be called the ***delta complexity***. When a part comes to a work area (it might be worked on before or it could be a raw material), what matters the most as far as the system design is concerned are the operations that will be performed between these two points. The designers will have to design machines, process steps and verification methods for the operation needed in this area. If certain process technology, say a five axis milling machine, is not available, then the process design exercise itself becomes a complex effort. This is because the designers will have to invent methods to manufacture the complex product some how (if product design change is not an option). The second way is to abstract delta complexity idea to the entire factory level. That is, to consider number and types of operations needed to manufacture the whole part or product from its entry in to and the exit from the factory. Designers have to design the entire system to perform all the needed operations on the part or product. If the product is complex and appropriate process technology is not available, the product most probably will be decomposed to a manageable level of complexity where the existing process can be used. A very high level of decomposition requires more subsystems, process steps, workers, machines, inspections, assembly steps and a robust control system, which leads to a complex manufacturing system and a complicated manufacturing system design effort.

It can be concluded that the complexity of the product itself increases the complexity of the manufacturing system design effort if appropriate process capability (or process technology) is not available, which in turn increases the complexity of the system itself.

13.1.11 Process Capability

-- Generalized technological ability to repeatedly make something with minimal intervention.

Measure: First time yield rate and/or Rework rate

This factor describes the quality of the manufacturing processes seen by the company itself. A low process capability would mean high rate of scrap or rework depending on the manufacturing stage. This variable does not explicitly describe the external product quality – the quality seen by the customer. Since rework is allowed, it is assumed that the desired external quality is delivered at the expense of scrap and rework. Therefore, high process capability would achieve a desired external quality at a much lower cost to the company. The process capability is affected by machine process capability, worker skill level, and the capability of the fabrication process (casting, forming, etc.).

Tight tolerances and complex geometry are typical characteristics of aerospace products. The factory floor processes have to be designed to produce these products repeatedly. At the component fabrication level, the process capability refers to machine's capability to repeatedly produce a part to the exact specifications. If the part has a complex geometry, process capability refers to the ability of the machine or group of machines to fabricate the required geometry. Any non-conformance at this stage would most probably result in scrap. At the assembly stage, a low process capability would indicate gaps, mismatched holes, part deformities, etc. Almost all of the cases will result in rework. Due to the size of aerospace products, the process capability at the assembly stage tends to be low. Especially in airframe manufacture, the aluminum components tend to expand and contract depending on the factory temperature, making it difficult to align predrilled holes and body frame edges. These situations are typically remedied using shims or various types.

Process capability and system complexity are closely related. As discussed above, the complexity of the system increases if the process technology to fabricate a complex product/part does not exist since the system has to be designed to fabricate this part in multiple steps. Having the process technology such as the five axis milling machine, for example, will reduce scrap, and the number of machines, operations, workers and time needed to perform the operation. In electronic fabrication, for example, the complexity can often be measured by the size of the part. The smaller the chip, the more difficult it is to fabricate it perfectly every time. However, if a machine is available which can fabricate this part to the required quality then that particular chip does not add to the complexity of the system. The machine itself might be complex but that does not make the system complex. Therefore, availability of capable process technology can greatly reduce the complexity of a manufacturing system.

The existence of the above challenges requires considerations at the manufacturing system design stage to compensate for them. Process capability is the factor that needs to be well understood so that appropriate processes and remedies for non-conformance can be developed.

13.1.12 Type of Organization

-- ***This factor describes the level of innovativeness supported on the factory floor***

The lean manufacturing initiatives have shown the benefits and needs of using employee's knowledge to continuously improve machines, processes, and the overall work procedures in general. Since most of the companies are investing lean initiatives and encouraging employee participation in process improvements, it can be assumed that the future workforce will be more empowered to making improvement suggestions than the current workforce. The manufacturing system should be designed to take this into account. Just as the ***frequency of changes*** factor discussed earlier dealt with engineering changes that affected the factory floor, this factor deals with the process changes that affect the factory floor. A highly innovative workforce, one that strives to improve the work environment continuously will introduce changes on the factory floor frequently. Machines, layouts and level of automation should be chosen carefully since many changes can be expected in a highly innovative work environment. The designers will have to considering the level of employee innovativeness and failure tolerance of management during job design. A risk-averse management would prefer freezing the design and not allowing the employees to tinker with the process and a risk-positive management would prefer a very flexible system that accepts changes continuously.

13.1.13 Worker Skill Level

-- ***Overall skill level of both factory management and hourly workforce available to the factory***

Measure: Skill level available in the geographic area

The available employee skill level determines the level of detail necessary in work statements, type of system, quality of the work performed (scrap rate) and the level of automation. Certain manufacturing systems such as a job shop or a craft production system requires a very high skill level compared to a transfer line, which hardly requires any human skills. It can be seen that if the system requires a high level of skill level, the system itself is relatively simple (craft production system). On the other hand, if the required skill is low, the system itself becomes a complex system (transfer line, FMS) The best example of utilizing a very low skill level to produce a complex product is Henry Ford's assembly line. Ford and his engineers designed the factory to make use of the low skill level (hence, cheap labor) by inventing the assembly line, which in itself was a complex system in those days. Therefore, the available skill level also determines the level of automation. The transfer line was a successor of the assembly line. The main point being made here is that the skill level is a very important determinant of the characteristics of a system. These characteristics can be the required real estate, process capability of the machines, number of supervisors, number of inspections and the inclusion of robotics and computers.

13.1.14 Investment

-- ***Amount of financial resources required for the manufacturing system design activity, floor space, personnel training and all equipment required for the operation of the factory.***

Measure: Dollar amount spent

Investment is treated as a constraint in the manufacturing system design process. It is assumed that this factor limits the choices available to the designer based on cost of implementation, payback period and time needed for the system development. It should be noted that this is the investment for the manufacturing system design and not the product design. Figure 13.1 shows the effect of this constraint combined with the time needed to implement the system. The green blocks are various designs requiring different investment and time. The investment constraint filters out any designs outside the feasible region. There might be some negotiation to adjust the constraint boundaries.

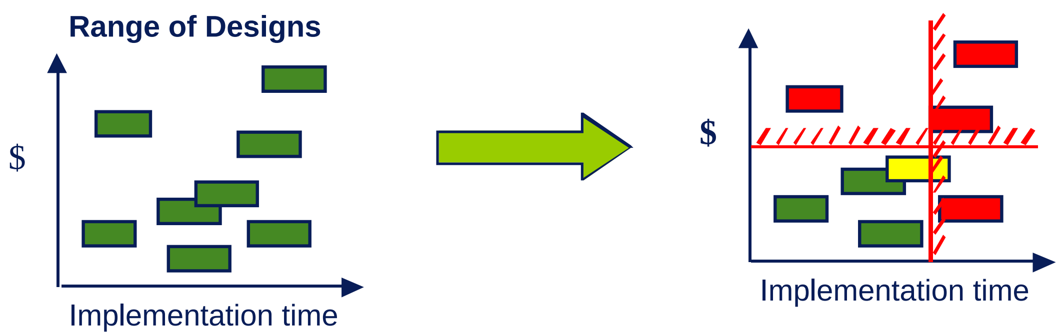


Figure 13.1 Schematic of Investment Vs. Time and Feasible Design Region

This is the factor that indirectly represents affordability and lifetime cost of the product. Since manufacturing cost includes the capital investment that went into building the capability, the product price will reflect a part of this investment. Moreover, the way the factory is designed to operate directly affects the actual cost of the product. Thus, the initial investment and operating procedures have a strong effect of product affordability and the life time cost of the product.

13.1.15 Time to first part

-- Length of time allotted from start of manufacturing system design to the full rate production of the first part.

Measure: Time required from initial system design efforts reaching full rate production

This is the second major constraint on the system design process. As can be seen in Figure 13.1, this filter eliminates any designs that take longer to implement than some acceptable time period. It is often difficult to determine the implementation time and time to reach full rate production at design stage for manufacturing systems. The decision typically is based on experience. The design that is chosen is not guaranteed to be fully operational when the market demand is high. Traditionally, the plant at the current state is used to meet market demand and simultaneously brought up to full rate. Nevertheless, time needed to have the desired full rate capability is an important factor in the design process.

13.1.16 Available/Existing Resources

The available resources are a very broad category, which simply describes what resources (financial, technological, human skill level, time etc.) are available to the designers. The existing resources are the resources already purchased prior to the design, the designers did not have a say in the purchase of these factors. This typically affects the most in a brownfield environment where the existing system resources such as the machines, factory control system, fabrication processes, people and culture are the remnants of the past system. While these are resources from a financial point of view, they typically are constraints to the design effort since the system will have to be designed to accommodate these items. These can significantly restrict a designer's freedom and hence the performance of the new system.

14 APPENDIX D : DEFINITIONS OF MANUFACTURING SYSTEMS

Descriptions of some very commonly used manufacturing systems are provided below. The descriptions are borrowed from many authors and an attempt is made to characterize each of the systems based on the ten manufacturing system design factors discusses in Appendix C. A set of system attributes is also defined at the end of the appendix and each of the system is characterized based on these attributes. This appendix does not cover the major systems discussed in Appendix B (craft production system, mass production system and lean production system or JIT)

Continuous Flow System

Continuous flow system is the least flexible of the types of manufacturing systems. In this system, the product physically flows through the system. This system is typically used to produce liquids, gases and powders. Oil refineries, chemical processing plants and food processing operations are good candidates for this type of system. A continuous flow system is highly automated and is capital intensive. Even though continuous flow system is very inflexible, it is the most efficient system. It has the least amount of work-in-process, if any. [Black, 1991]. A continuous flow system requires a very stable product design. It competes on the basis of cost and quality. Due to the inherent efficiency of the system and little operator assistance required, it can produce a part at the lowest cost possible. [Guerindon, 1995; Miltenburg, 1995]

Cellular Manufacturing System

The term Cellular is used in many different types of manufacturing systems. The most common ones are described below.

Group Technology

Group technology is a philosophy in which similar parts are grouped into families. Parts of similar size and shape can often be processed by a similar set of processes and tools. A part family based on manufacturing would have the same set or sequences of manufacturing processes. [Black, 1991; Guerindon, 1995]

Simple Cell (Job Shop Cell)

A simple cell is a group of all the machines, tools, and related operations necessary to process a family of parts. The cell is not typically computer controlled, but there might be a terminal in the cell, which links it to a rough material sequencer, an assembly sequencer, and computer controlled material handling. The material flow within the cell may differ for different parts of a part family. [Chryssolouris, 1992]

Automated Storage Cell

This cell is similar to a simple cell but it uses an automated storage and retrieval system (ASRS). All machine tools are laid out around two L-shaped conveyors. These conveyors receive rough parts in tote boxes and interface with the ASRS. All machine and ASRS are monitored by a cell computer. [Williams, 1988]

Forced Flow Cell (Toyota Cell)

These cell do not use computers and are labor intensive. Machines are laid out alongside one another on both sides of a walking platform. Machine setup is permanent. Flow moves in one direction. Most parts require more than one operation. Operator keeps the part ready to be loaded when the machine becomes available, then loads the appropriate machine, unloads the machine and loads the next part, waiting to be loaded, and carries the finished part to the next operation. Productivity can be extremely high in a forced cell. Total cycle time is the sum of total spindle time and operator's walking time. Machine utilization is low since machines are activated by operators when needed. [Williams, 1988]

Linked – Cell Manufacturing System (L-CMS)

A L-CMS is composed of manufacturing and assembly cells linked by a pull system for material control. In the cells, operations and processes are grouped according tot he manufacturing sequence that is needed to make a group of products. The cell is often configured in a U-shape, enabling the workers to move from machine to machine, loading and unloading parts. The machines in the cell are usually all single cycle automatics so they can complete the machining cycle untended. [Black, 1991]

Job Shop

The distinguishing feature of job shops is the production of a wide variety of products in small lot sizes, often one of a kind. The volume handled by a job shop is typically very low. But, job shop can process a wide variety of parts and hence require highly skilled machinist who is very familiar with the equipment around him. It is a functional organization whose departments or work centers are organized around particular types of equipment or operations, such as drilling, forging, spinning, or assembly. The equipment tends to be of general purpose and very flexible. Parts flow through departments in small batches corresponding to individual orders – either stock orders or individual customer orders. Work in process inventory is typically high and delivery times can be long. [Black, 1991; Chase, 1992; Miltenburg, 1995]

Transfer lines

Transfer lines are well suited for high volume/low variety manufacturing environments, which use dedicated processing and material handling equipment. This manufacturing technique is also referred to as fixed automation.

Dedicated Transfer Lines

A dedicated transfer line processes a single part number, accepting very little variation of the part design. Parts move from one station to the next automatically and are fully processed when they reach the end of the line. The technology is “dedicated” to a single part because each machine head is laid out in a fixed position relative to the design of the part. Since transfer lines use highly specialized equipment, they are expensive, very inflexible. To switch from processing one part to a different part requires major hardware modification and heavy investments. On the other hand, a dedicated transfer line is an economical and highly productive choice when the part design will be stable over a long time. [Williams, 1988]

Convertible Transfer Lines

Convertible transfer lines can be changed as part design changes. Modular transfer lines are used to speed up conversions. [Williams, 1988]

Flexible Transfer Lines

A flexible transfer line uses standard machine centers with multi-spindle heads that can be changed by head changers in ten seconds or less. There is no set up time between part changes. This type of flexibility allows flexible transfer lines to process similar families of parts. Flexible Transfer lines are closer in concept to Flexible Manufacturing System, but still dedicated to a small family of similar pieces. Parts are run in batch mode to reduce toll change time. Flexible transfer lines need more controls and computers compared to dedicated and convertible transfer lines. [Williams, 1988]

Flexible Manufacturing System

Flexible manufacturing systems cover a wide spectrum of manufacturing activities that include machining, welding, fabricating, assembly and a number of other applications. These systems can attain differing degrees of flexibility. All flexible manufacturing systems have the following characteristics in common (Graham and Rosenthal, 1986)

Integration – Interdependency of system components, so that they work together and in harmony, is based on a set of rules identified by system integration.
Intelligence – This is the ability to interpret given input and to produce output based on the user's expectation.
Immediacy – Immediacy is the speed in which the system can react to changes. [Reza, 1991]

Hybrid System

This is a coined phrase describing a largely automated system that has a number of processes within it that are still carried out by an operator.

Project Shop or Fixed Position Layout

Project shop is characterized by the immobility of the item being built. By virtue of its bulk or weight, the product remains at one location (hence the term fixed position layout). The manufacturing equipment, workers, materials is moved to the product rather than vice versa. In construction industry, bridges and roads are good examples of project shop. In manufacturing, aircraft, satellites and locomotives are excellent examples. The number of end items (final products) is not very large but the component parts going to the end item can be very large. This type of system is typically used in an assembly area. Other types of systems typically feed parts to the project shop or the fixed position layout. [Black, 1991; Chase 1992]

Flow Line Based Manufacturing Systems (Flow Shops)

Henry Ford pioneered flow line based factory layouts in the early part of this century by his development of the assembly line. In a flow line (flow shop), the product travels serially from process to process or machine to machine. This method originally applied to assembly, led in turn to the development of the purpose built transfer line. Flow shops are characterized by large lots, less variety, and more mechanization. Flow shops layouts can either be a continuous or interrupted. In a continuous flow line, one complex item is produced in great quantity and nothing else. In an interrupted flow line, large quantities of different but very similar components (line is interrupted to change over). The change over can take from hours to days. Flow shops are not flexible by design. [Black, 1991; Williams, 1988]

The flow line (shop) has a product-oriented layout. Specialized or dedicated machines are required to manufacture a particular part. A flow shop can have very high production rates and It can produce parts of varying complexities. Also, the worker skill required for this type of system is relatively low compared to a job shop since special purpose machines perform most of work (machining and transferring work piece from machine to machine). The lines are setup to operate at highest rates possible regardless of the system needs. Investment required for the flow shop is very high since machines have to be custom-made to manufacture a given product at very high rates.

Assembly line (Flow line):

(See Flow Line Based Manufacturing Systems above)

Moving Assembly line:

This type of assembly line, a variation of flow line, was first used by Ford's engineers. Here the product moves from worker to worker or workstation to workstation based on a constant pace. The work content is usually broken down to fine details depending on the line speed and number of workers involved. The skill level required for this type of assembly line can be very low. Ford was able to make used of the lowest level skill available to build a complex car using the moving assembly line. The speed of the line typically reflects the actual product demand.

Pulsed Line:

This is also a variation of a flow line mostly used by aerospace manufacturers. In a pulsed line, the product arrives at a workstation and stays there until all the work assigned to that station is completed. The product then moves to the next station to be worked on. The movement of the product involves series of moves and stops, hence the name pulsed line. This type of assembly is also similar to the project shop or fixed position type assembly described above, the main difference here is that the product actually moves without the use of overhead cranes.

System Attributes:

As an additional characteristic to describe a system some attributes such as material flow path, time or pace of movement, batch size, level of automation and level of flexibility were defined as follows:

Material Flow Path:

Contiguous Unidirectional:

Products move in one direction and proceed to an adjacent station for the next process step.

Non-contiguous Unidirectional:

Products move in one direction but may skip adjacent stations to move to the station where the next process must be performed.

Non-unidirectional:

Products move in any direction to whatever process step is needed next.

Time or pace of movement

Synchronous:

Parts move from process to process governed by a set time interval.

Asynchronous:

Parts move from process to process not governed by time but most likely by physical completion of the process.

Batch Size

Single piece flow: one item at a time moves between process steps.

Batch (various types): multiple items move in unison form one process to another.

Level of Automation

Automated System:

Movement and processing of products is controlled by some automatic action or control mechanism.

Manual Operation: movement and processing is done manually.

Flexibility: Movement and processing is done by a combination of automated and manual operations.

Controllability: Level of control on quality of the work performed

Modularity: Speed at which the system set up can be changed.

Table 14.1 and Table 14.2 below indicate which of the above attributes are typical (XX) of a given manufacturing system and which are applicable (X) at some level. The fabrication systems and assembly systems are presented separately. Blank areas represent non-applicability or low applicability.

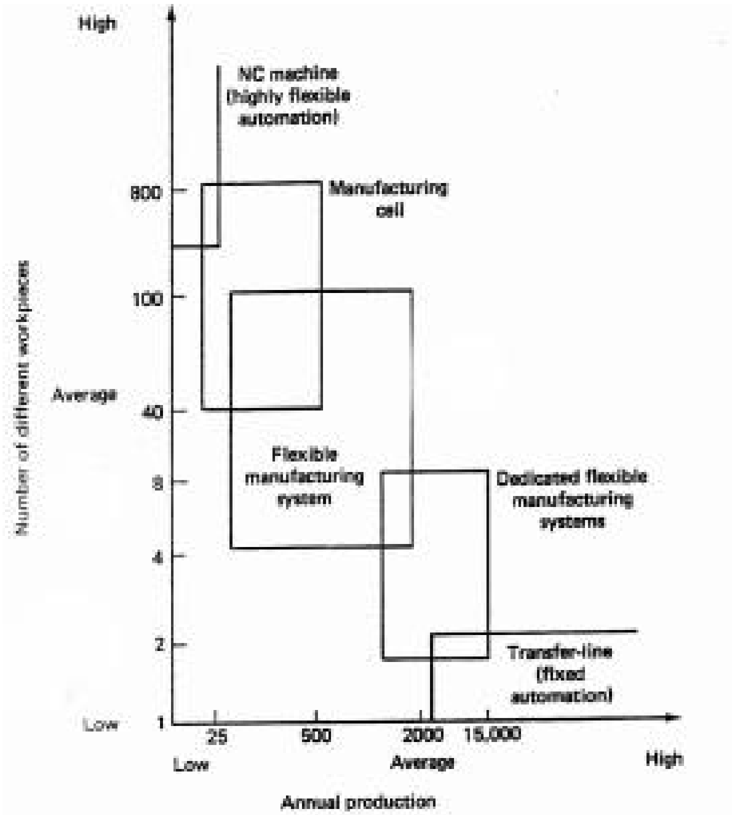
System / **Attribute**	***Continuous Flow***	***Simple Cell***	***Toyota Cell/ L-CMS***	***Dedicated Transfer Lines***	***Convertible Transfer Line***	***Flexible Transfer Line***	***Flow Line***	***Job Shop***	***FMS***
Path: Contiguous Unidirectional	XX	X	XX	XX	XX	XX	XX	X	X
Non-contiguous Unidirectional		X	X				X	X	X
Non-Unidirectional		XX						XX	XX
Time: Asynchronous		X	X					XX	XX
Synchronous	XX	XX	XX	XX	XX	XX	X		X
Batch size: Single Piece	XX	X	XX	XX	XX	X	XX	X	X
Batch		X		XX	X	XX		XX	X
Automated system	XX	X		XX	XX	XX	X	X	XX
Manual		XX	XX				XX	X	
Flexibility		X	X		X	XX	X	X	XX
Controllability (quality)	XX	X	XX	X	X	X			
Modularity		XX	XX		XX	X	X		X

Table 14.1 Attributes of Fabrication Systems

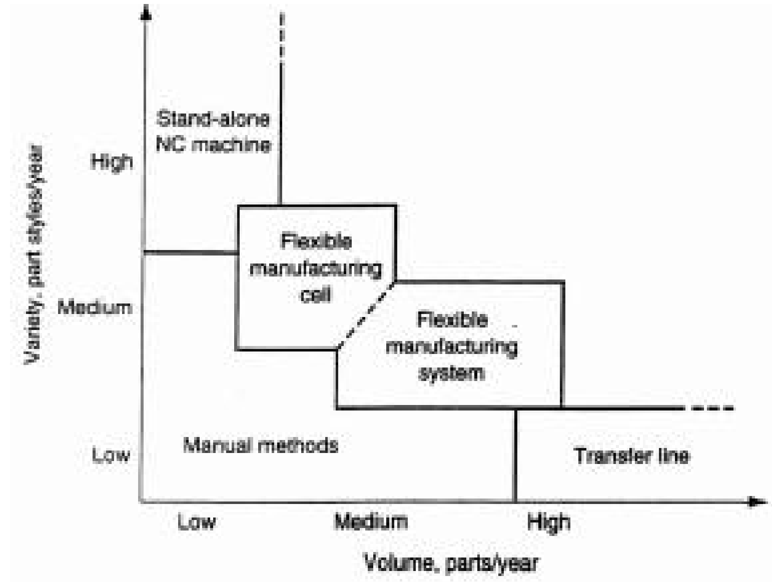
Systems / **Attributes**	***Fixed Position***	***Assembly line***	Moving Assembly Line	***Pulsed Line***
Path: Contiguous Unidirectional	X	XX	XX	XX
Non-contiguous Unidirectional	X	X		
Non-Unidirectional				
Time: Asynchronous	X			
Synchronous	X	X	XX	XX
Batch size: Single Piece	X	XX	XX	XX
Batch				
Automated system		X	XX	X
Manual	XX	X	X	X
Flexibility	X	X		X
Controllability (quality)	X	X	X	X
Modularity				X

Table 14.2 Attributes of Assembly Systems

14.1 EXISTING 2-D MAPS OF MANUFACTURING WORLD

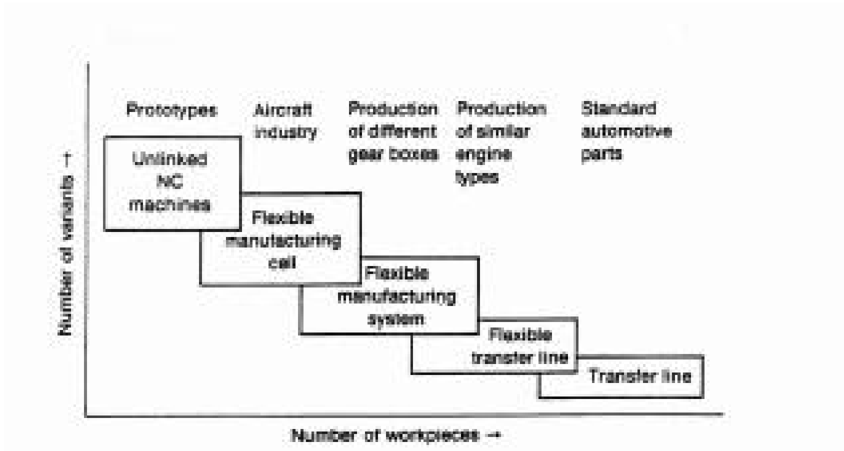


Applications of different automated manufacturing systems [Wakil, 1989]

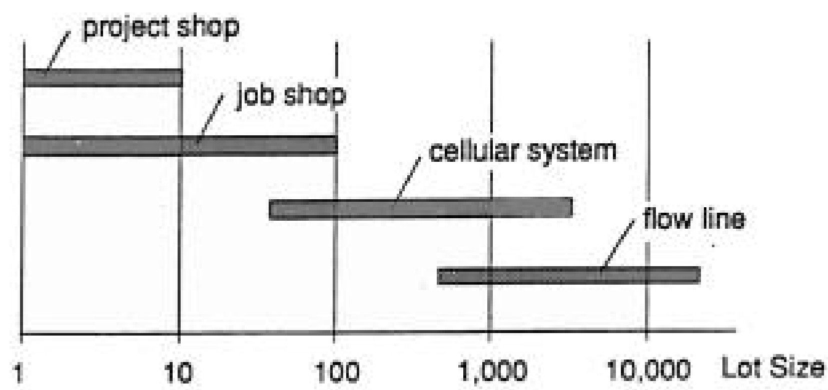


Application characteristics of flexible manufacturing systems and cells relative to other types of productions systems [Groover, 1993]

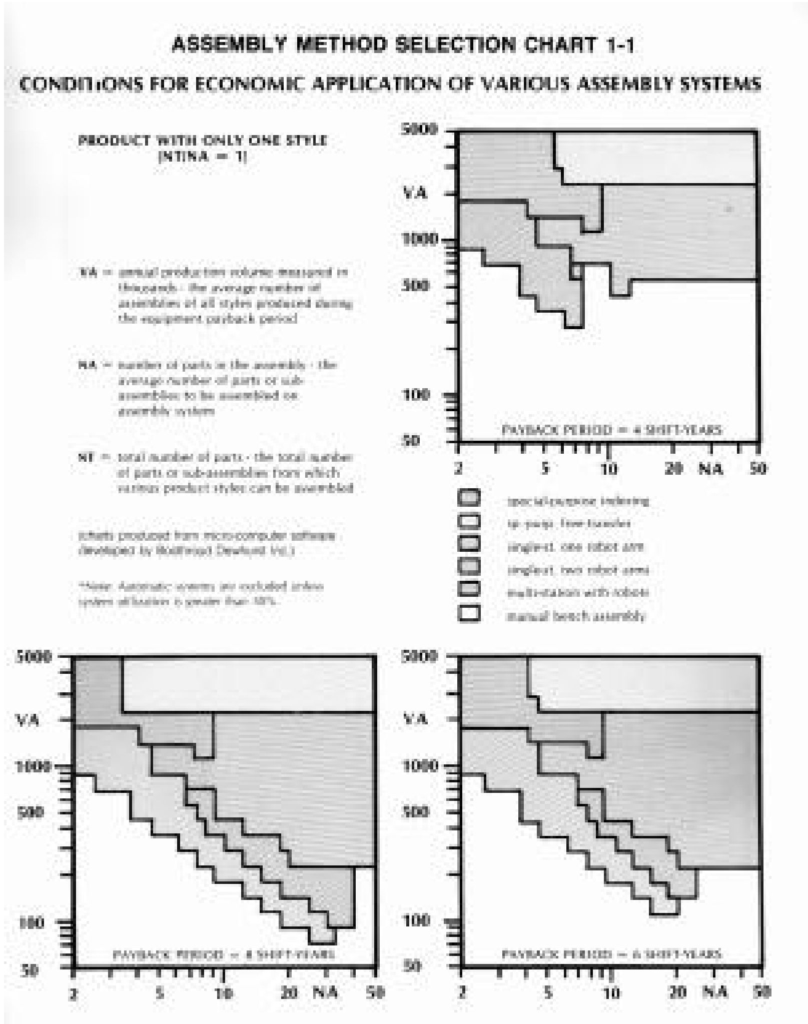
Appendix D



The suitability of various manufacturing systems for specific production tasks depends on the variety of product and the number of work pieces [Schey, 1987]



Suitable manufacturing system types as a function of lot size [Chryssolouris, 1992]



Conditions for economic application of various assembly systems [Boothroyd, 1989]