Massachusetts Institute of Technology
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Manufacturing System Design Framework Manual

A product of the Manufacturing Systems Team
of the Lean Aerospace Initiative

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Executive Summary

Previous Lean Aerospace Initiative research in factory operations had indicated that the greatest performance gains are realized when the manufacturing system is designed from the top down and from supplier to the customer. Manufacturing system designs were most effective when the entire product value stream was designed or redesigned (not just a shop, division or segment of the factory). This led to a focus on manufacturing system design. The objective in this study was to develop a method or process that would assist manufacturing system designers as they developed (or modified) the manufacturing system for their needs. This effort was developed to be applicable to a single product manufacturing system design or a multiple product manufacturing system design. A systems approach was used with an enterprise perspective. Several important products were produced as the problem was addressed: a list of the manufacturing system design inputs and a definition of manufacturing system types (each included in the appendices).

The current knowledge of manufacturing systems and the lack of a generally accepted scientific basis for relating the multiple variables needed for a successful manufacturing system design required us to develop a framework to approach the manufacturing system design process rather than a definitive design methodology. The Manufacturing System Design Framework developed is a meta-framework containing other tools, methods and processes applicable to the manufacturing design process. The Manufacturing System Design Framework consists of two distinct design elements: an infrastructure design element and a structure design element. In infrastructure design, the enterprise strategy defines such important attributes of the system as the operating policy, organizational structure, location and overall operating environment that satisfies the enterprise stakeholders. The structure design is the physical manifestation of the manufacturing system design consisting of the factory layout, machines, methods and processes. Linking the two design elements is the product strategy. Product strategy is the congruence between corporate level business strategy and the different functional strategies and involves such functional elements as marketing, product design, suppliers and manufacturing.

This manual provides guidance to manufacturing system designers on the sequence of events that should be considered in the manufacturing system design, tools that are useful at each of the steps during the design process, and the important interrelationships between marketing, product design, manufacturing and suppliers. In the appendices, specific infrastructure and structure tools are summarized. Subsequent studies of manufacturing system designs have shown that manufacturing system designs that followed this process correlated with better performing manufacturing systems.[1]

[1] Vaughn, A., *A Holistic Approach to Manufacturing System Design in the Defense Aerospace Industry*

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1.0 Manufacturing System Design Framework

Overview

The Manufacturing System Design Framework is introduced in this manual. The framework, and each phase within it, is outlined. The use of the framework in either a green or brownfield environment is discussed. Key insights and unique qualities of the framework are highlighted throughout the manual.

1.1 The Need for a Methodology

The variation in available tools prompts the need to develop a meta-framework which can show where all these other tools fit in the overall design process and add the considerations unique to the aerospace industry. In addition to adding in the aerospace considerations, a model is needed to help provide a common language for communication between the various functions and programs involved with the design process. It also must provide a common means for measuring and benchmarking the progress of the design process.[2] Also, proposing a methodology for this process helps make what can become a rather undefined process explicit as well as helping to ensure that important issues are not forgotten.[3]

When creating a methodology, or framework, for the manufacturing system design process, there are a few concerns that must be addressed. This methodology must incorporate a systems perspective to enable the user to view the manufacturing system holistically and it must be a strategic framework showing how this design process fits into the overall enterprise view of the system.[4] The framework must also strike the right balance between difficulty of application and usefulness of results. Namely, the process of following the framework must not be so complex as to be impractical, and not so simple that the results are of no use.[5] Whatever purpose a framework must serve, it must simplify as much as mimic the system or process of interest.[6] Finally, creating a framework to describe this process will help definitize the process helping to further the creation of a theoretic base to assist in the decision making involved with designing a manufacturing system.

1.2 Introduction to the Framework

The Manufacturing System Design Framework is a product of the Manufacturing Systems Team of LAI. It was created based upon the experiences, knowledge and observations of the team members. It is an attempt to describe the manufacturing system design process in a holistic

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[2] McManus, H., et. al., *Generic Product Development Model*
[3] Ulrich, K.T. and S.D. Eppinger, Product Design and Development
[4] Muhamad, M.R., *The deployment of strategic requirements in manufacturing system design*
[5] Miltenburg, J., Manufacturing Strategy
[6] Gleick, J., Chaos: Making a New Science

manner. It is a meta-framework, meaning that the framework itself contains other tools, methods and frameworks within it. The framework organizes the tools in a manner that helps reduce abstraction through the design process.[7] It is an attempt to structure those tools into a single framework that utilizes the principles of systems engineering, addresses the unique constructs present in aerospace products and acknowledges that manufacturing is a strategic addition to a company's competitive skill set. The framework is also meant to be a visual tool that shows how manufacturing system design extends far beyond the layout of machines on a factory floor.

The framework is divided into two main portions, the top half representing the manufacturing system "infrastructure" design and the lower "structure" design. The infrastructure portion contains the decision making or strategy formulation activities that precede a detailed manufacturing system design. The framework does not assume any specific corporate objective and, therefore, does not lead to any particular solution. The structure portion contains the detailed design, piloting and modification of the manufacturing system. These two portions are linked by a new concept, the product strategy, which is discussed in more detail below.

The following page is the Manufacturing System Design Framework.[8]

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[7] Maier, M.W. and E. Rechtin, The Art of Systems Architecting

[8] For a more extensive description on the development of the Manufacturing System Design Framework, please refer to P. Fernandes, *A Framework for a Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor*.

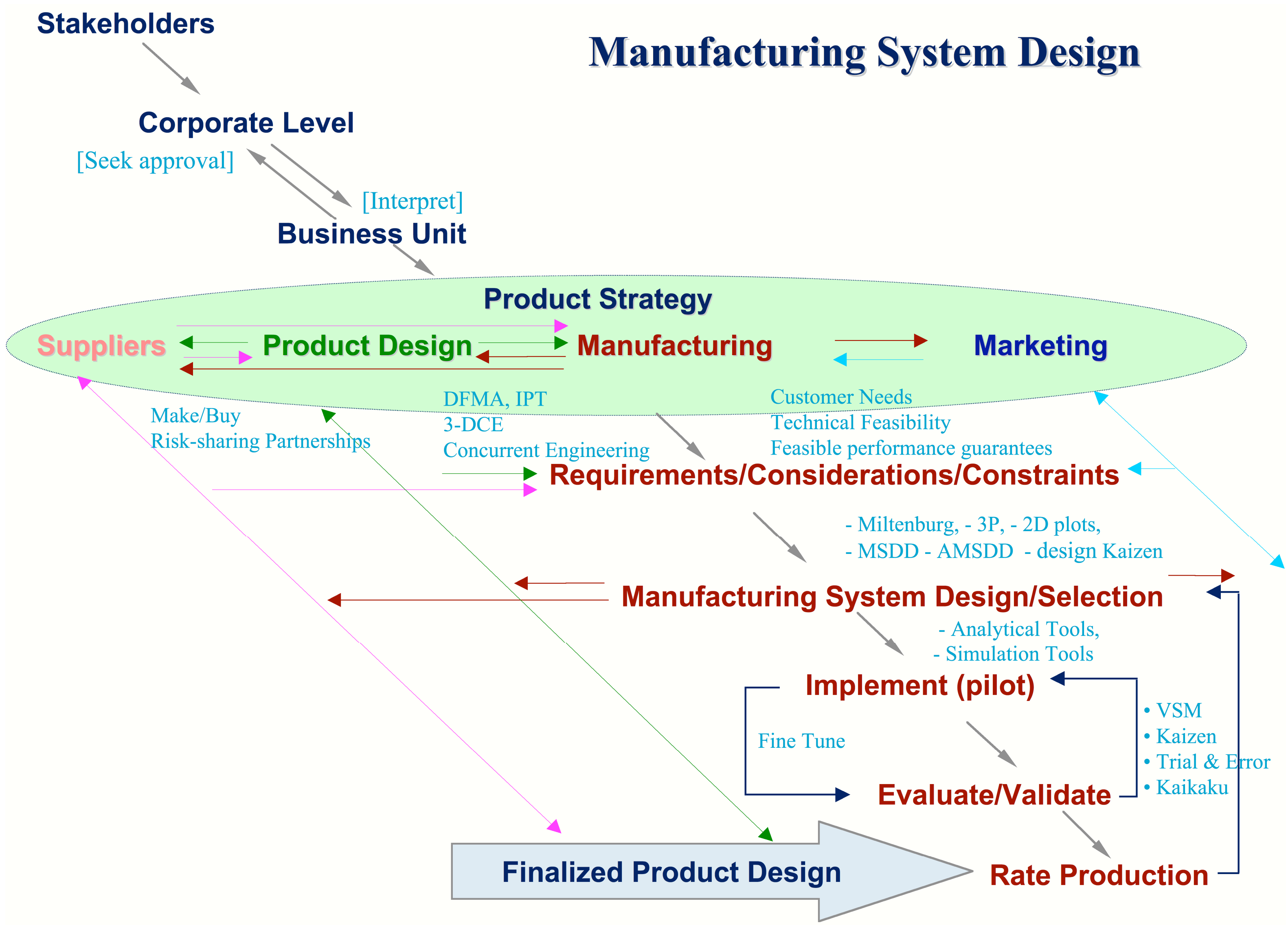

Figure 1: The Manufacturing System Design Framework

1.3 Infrastructure Design

The top portion of the framework is the manufacturing system "infrastructure" design. To review, the manufacturing system infrastructure contains all the activities associated with the overall operating environment of the system – the operating policy, organizational structure, choice of location etc.[9] The infrastructure design consists of the three levels: Stakeholders, Corporate Level and Business Unit. Together, these three units make up the Strategy Formulation Body.

The framework begins with this infrastructure section since the commitment of upper levels of management plays a key role in the manufacturing system design process, for better or for worse.[10] [11] Specific tools available to assist in infrastructure design are located in Appendix A.

Strategy Formulation Body

The strategy formulation body is where the needs are processed for the enterprise as a whole. The first level in the strategy formulation body is entitled "Stakeholders". This nomenclature was specifically used to de-emphasize a particular stakeholder for the overall system or enterprise. The manufacturing system has numerous stakeholders which could be the stockholders, the customers, the employees, society at large or the environment. Each different stakeholder has unique needs that the system must fulfill. These needs could conflict with one another and it becomes the responsibility of the corporate level leaders to balance the conflicting needs and establish priorities of how those needs will be addressed. This is the formulation of the corporate level strategy.

The corporate level strategy is transferred down to the different business units, or profit centers, throughout the corporation or enterprise. This corporate strategy helps maintain the common threads across the business units, as the corporate level links all the separate business units. But this is not a one way link. The business unit is responsible for accurately representing all the resident functions up to the corporate level. The business unit passes up to the corporate level its capabilities, potential future directions and what a reasonable strategy for the business unit may be. The corporate level strategists are responsible for balancing out the input of possibilities from the business units with the needs from the stakeholders to create the overall strategic focus and direction for the corporation.

Why is Manufacturing Strategy Necessary?[12]

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

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[9] Hayes, R.H. and S.C. Wheelwright, Restoring our competitive edge, Competing Through Manufacturing
[10] Monden, Y., Toyota Production System: An Integrated Approach to Just-in-Time
[11] Miltenburg, J., Manufacturing Strategy
[12] This section from P. Fernandes, *A Framework for a Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor.*

initiatives. These help the business gain and maintain a competitive advantage.[13] The key idea 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.[14] 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.[15]

This is especially true for the current status of aerospace industry. As argued by Utterback, the aerospace industry has possibly reached a phase where manufacturing capabilities 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.[16] This information can be used to design manufacturing systems to give the desired output to differentiate products in the market. 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.[17] 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,

[13] Schroeder, R.G., *Development of Manufacturing Strategy: A Proven Process*
[14] Buffa, E.S., Meeting the Competitive Challenge, Manufacturing Strategy for U.S. Companies
[15] Hayes, R.H. and G.P. Pisano, "Beyond World-Class: The New Manufacturing Strategy"
[16] Hayes, R.H. and G.P. Pisano, "Beyond World-Class: The New Manufacturing Strategy"
[17] Miltenburg, J., Manufacturing Strategy

- Provides for clear communication between management levels,
- Helps select improvement/capability building activities that will contribute to long-term enterprise success
- Creates an awareness of competition

Product Strategy

The next level in the framework, following the strategy formulation body, is the product strategy. This is a new concept, which aims to ensure congruence between the corporate level and business strategy including the different functional strategies. Fundamentally, the product strategy is an instrument to align manufacturing and other functions with the overall corporate strategy. This applies to a single product, or to a family of products. For example, the Boeing Company could have a product strategy for their Next Generation 737, or a product strategy for their narrow-body commercial airliners, or a product strategy for all commercial aircraft. The same concepts apply to all the various cases.

The concept of the product strategy is included in this framework for a few important reasons. First of all, product strategy emphasizes the importance of establishing manufacturing on the same level as the other functional areas of the corporation. Secondly, because the interaction of technological change, organizations and a competitive marketplace is much more complex and dynamic than most models describe.[18] The product strategy is an attempt to address the importance of these interactions.

The structure of the product strategy is an extension of the Fine's 3-D Concurrent Engineering (3-DCE) model.[19] The traditional view of 3-DCE consists of suppliers, product design and manufacturing. Marketing is added to this model because of the impact marketing can have in the aerospace industry with things like foreign sales and is considered a core function in other literature.[20] The figure below is the representation used for the product strategy where the product strategy is the overlapping area between the different functions. The shape of the figure implies that interactions between the different functions occur and that all functions are represented together with the same status. This emphasizes that manufacturing system design is supported by these other functions of product design, supplier integration and marketing.[21]

[18] Utterback, J.M., Mastering the Dynamics of Innovation
[19] Fine, C. H., Clockspeed
[20] Ulrich K.T. and S.D Eppinger, Product Design and Development
[21] Reynal, V., *Production System Design and its Implementation in the Automotive and Aircraft Industry*

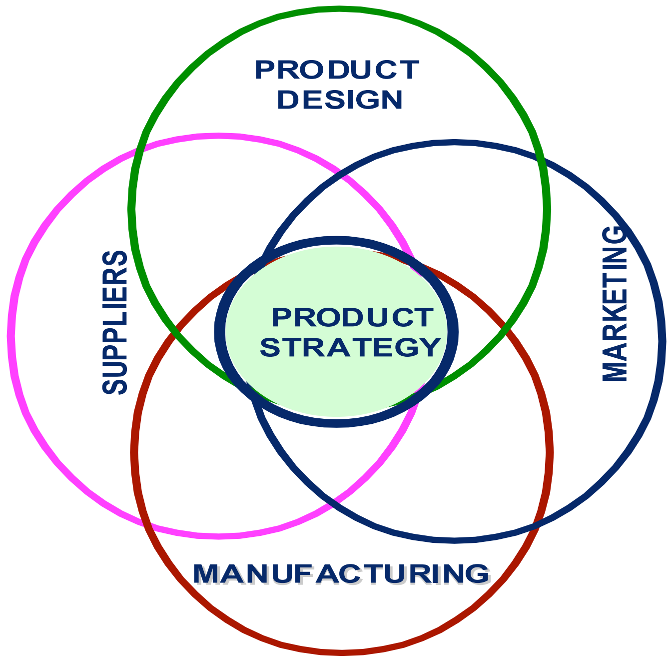

Figure 2: Product Strategy[22]

The formulation of the product strategy requires collaboration between these functions. Make/buy decisions and the formation of risk sharing partnerships can be formulated between product design, manufacturing and the suppliers,. The relationship between marketing, manufacturing and product design leads to an understanding of the true customer needs and technical feasibility of those needs.[23] The relationship between product design and manufacturing is what will lead to the design of a manufacturable product which will be more conducive to high performance in the factory.[24]

Utterback argues that products, as they mature, first experience predominately product innovation followed by a period where process innovation dominates. Where the product is in terms of its product and technology life cycle could shift the focus of its product strategy. For instance, a mature product may wish to choose a product strategy that emphasizes the incorporation of more efficient process technologies as its core objective to win market share or contract awards where price is the predominant discriminating factor.

For ease of incorporation into the framework, the product strategy is represented like an oval in the Figure 3. The arrows inside the oval depict the interactions between the different functions but not all the arrows are drawn between all the functions for clarity.

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[22] Fernandes, P., *A Framework for A Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor*
[23] Piper, L.J. and W. Pimblett, *A Systems Approach to Manufacturing System Design*
[24] Womack, J.P., Jones, D.T. and D. Roos, The Machine That Changed the World

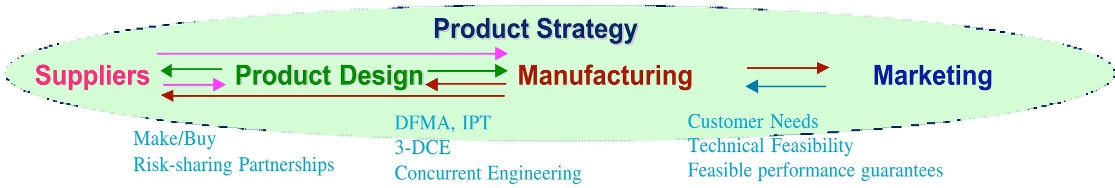

Figure 3: Product Strategy representation within the framework

In summary, a well-formulated product strategy provides alignment of manufacturing strategy (as well as other functional strategies) with business and corporate strategies and helps ensure that decisions made within the function are based on that strategy and long-term objectives of the corporation or enterprise. The structure of the product strategy ensures that manufacturing is an integral part of the corporate structure and allows for clear communication between functions and management levels. The goal of the product strategy is to ensure consistency between decisions made within each function and overall corporate goals.[25]

The product strategy provides the link between the manufacturing system infrastructure and structure design, corresponding to the top and bottom portions of the framework. It does this because the strategy itself, along with the input from the other functions, generates a set of requirements, considerations and constraints for the manufacturing system design.[26] This leads to the design of the manufacturing structure.

1.4 Structure Design

Below the product strategy, the actual physical manifestation of the manufacturing system design is conceptualized, piloted and refined. Each element is addressed as a separate phase with some specific characteristic events and a set of tools that are applicable in transitioning between phases. Each phase is one of the major demarcations on the framework beginning with "Requirements/Considerations/Constraints". Since this framework is primarily concerned with the design of manufacturing systems, it is the manufacturing portion of the framework that is presented in detail (see Figure 4). But following the product strategy formulation, design activities of all the functions would begin and proceed in parallel. The manufacturing system structure is made up of the activities that actually deal with the factory floor such as people, machines and processes.[27]

[25] Rosenfield, D., *Manufacturing Strategy*
[26] Maier, M.W. and E. Rechtin, The Art of Systems Architecting
[27] Hayes, R.H. and S.C. Wheelwright, Restoring our competitive edge, Competing Through Manufacturing

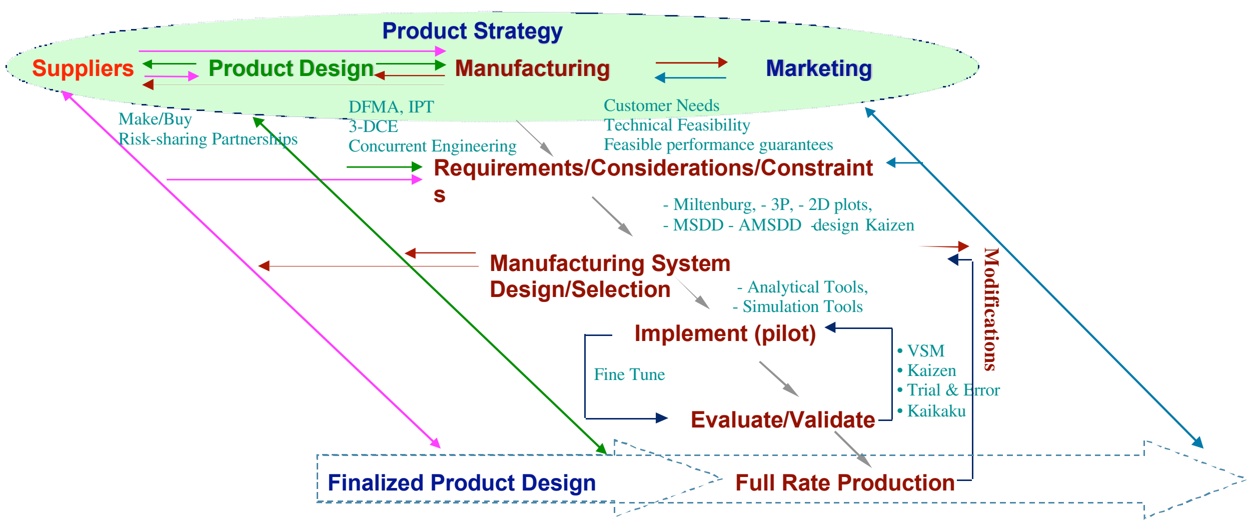

Figure 4: Manufacturing System "Structure" Design portion of framework

Each of the phases within the manufacturing system structure design process will be discussed in turn.

Concurrent Product Design, Manufacturing, Supplier and Marketing Activities

The concurrent design activities for the different functions are represented by the arrows extending from each function in the product strategy oval down to the rate production level. This indicates that the various design activities are all performed concurrently. For example, the product design is progressing at the same time as the manufacturing system design and the suppliers are designing or modifying their own systems or processes to incorporate the new part or components.

Another aspect of the framework and the concurrent design activities is the breadth throughout those activities. The same concept that derived the product strategy as being the intersection between the circles for the functions applies at each subsequent phase of the framework. This is represented by the arrows that extend from the phase of the manufacturing system design process to the arrow indicating the progression of the other functional design processes. The goal of this view of the framework is to emphasize breadth throughout the design processes. The product strategy was a result of a combination of the different functions, and this aims to emphasize that the breadth and communication should continue through the remainder of the design process, whether it be for the manufacturing system or the product.

Following this concept of breadth in the framework is important to alleviate the classic "thrown over the wall" scenarios in manufacturing system design. Previous research conducted in the aerospace industry illustrated that it is difficult to look at the manufacturing system in isolation from the product design.[28] This can be because the product design will determine most (estimated at 80%) of the cost of the product and will either directly, or indirectly, determine the

[28] Dobbs, D., *Development of an Aerospace Manufacturing System Design Decomposition*

tooling concept.[29] So, these consequences, which are frequently deemed to be in the manufacturing domain, are heavily influenced by the product design work and, therefore, should not be considered in isolation from the manufacturing system design. By incorporating more input from manufacturing into the early product design slows the product design considerably. But, the overall design time can still be reduced because the need for later (and more lengthy) iteration is lessened.[30]

Another benefit of the emphasis on breadth across the functions through the design process is the result of manufacturing emerging to be an equal member of the competitive skill set of the enterprise. It is no different than the product design or supply chain or any other functional necessity. Maintaining this perspective through the design process will make it easier to sustain it through subsequent improvement activities across the enterprise. This is beneficial in the long run since a full enterprise view encompassing all the different functional areas can be seen as a requirement to maximize the benefit of these improvements.[31]

One characteristic of these concurrent design activities is that they should all be completed, that is, they should all converge to the finalized product and system designs, at the same time. The finalized product design arrow represents that the product should be designed at the same time as the manufacturing system and the supply chain is ready to support its production. All too frequently in practice, however, one function will complete their design activities long before the others (meaning that part of the overall design effort is stalled waiting for the others to catch up). Frequently, the product design will be completed first and this results in using a low-rate system configuration to carry the company through the early high-rate production levels.

Requirements/Considerations/Constraints

The next phase in the framework is the determination and definition of the requirements, considerations or constraints that will guide the detailed design effort. These requirements, considerations or constraints could result from internal or external influences, be mandatory or voluntary, but the effect on the manufacturing system design process is the same. These are the goals that must be met for the system to be a success.

These requirements, in part, flow down from the complete product strategy as well as from the various component functions. There will be circumstances when the requirements from different functions, or external agencies will conflict and the framework aims to resolve these tensions. The framework emphasizes breadth across the different functions, as was mentioned earlier, throughout the design processes. This creates ample room for feedback between the different functional groups and reinforces the idea of collaboration between these groups for the purpose of achieving the strategic goals of the company rather than individual component goals.

The Manufacturing Systems Team has come up with a set of inputs to guide the requirements definition phase. These inputs to the manufacturing system design process are presented here and defined in more detail in Appendix C.

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[29] Al Haggerty, presentation for LAI
[30] Eppinger, S., Whitney, D.E., et. al., *A model based method for organizing tasks in product development*
[31] Kessler, W., Lean Enterprise presentation

- Market Uncertainty
- Production Volume
- Production Mix
- Frequency of Changes
- Product Complexity
- System Process Capability
- Type of Organization
- Available Worker Skill Level
- Time to First Part
- Investment

These inputs fit into the context of the manufacturing system design framework because they require input from the other functional areas. The product designers provide the information that translates into the product complexity, frequency of design changes and capability of processes to do what their designers require. Marketing provides the knowledge of needed production volume and mix and variability of those values. The suppliers and the capability of their processes could potentially impact the make/buy decisions or supplier selection for different components. Finally, the manufacturing component contains the information of the internal process's capabilities, available skill levels, core competencies, as well as what resources and investment are required to pull everything together.

In all, the different functional areas that make up the product strategy all impact the requirements set for the manufacturing system. A manufacturing system is then designed or selected to meet the established requirements.

Manufacturing System Design or Selection

A manufacturing system is either selected from existing proven systems or designed from scratch based on the finalized set of requirements. Some of the manufacturing systems that are used widely in practice include job shops, cells, Flexible Manufacturing Systems, transfer lines, project shops, flow lines, assembly lines and moving or pulsed assembly lines.

This phase is placed in the framework explicitly to emphasize the need to make a conscious decision when selecting or designing a manufacturing system. A strategy formulated for the product and for the manufacturing operation is useless if the associated manufacturing system is just chosen arbitrarily or simply using the previous system design. Careful analysis must be performed to design or select a manufacturing system that supports the strategy while simultaneously fulfilling the requirements.

This is not a trivial step and this is made more difficult because it is not a predictive step since a "manufacturing science" does not exist. But the framework includes tools that are available to assist in, or guide, the design or selection process. Cursory descriptions of these tools are located in Appendix B.

Implement (Pilot) ←→ Evaluate/Validate Loop

The implement and evaluate loop is the smaller loop in the framework which calls for implementing the chosen manufacturing system on a smaller scale, either in terms of rate or capacity, to test the concepts embedded within the manufacturing system design. This allows the system design to be tested, fine tuned and eventually brought to rate or full-scale production.

This can be accomplished using either computer simulations, scale models, full-scale models operating at a low rate, moonshine shops, physical mock-ups or pathfinders. Whatever the method, the objective of the piloting activity is the same: to subject the system design to practical tests to pinpoint problems. Like flight testing of a new aircraft, no matter how detailed and careful the analysis, things always turn up in flight test that were not anticipated.

But, also like in flight test, what is tested, or piloted is important.[32] The piloting loop is intended to find and fix problems so the system can function smoothly when it is brought up to rate-production levels. The piloting step allows an additional opportunity for creative, new ideas to make their way into the system. Throughout history, the "experimental" plant has played an important role in the development of radically new ideas for production concepts and the piloting activities help instill this creative atmosphere into the manufacturing system design process as well as helping to smooth the transition to rate production when the time comes.[33]

Rate Production

The next phase of the manufacturing system design framework is the rate production phase. The large arrow represents the finalized product design, and at this stage, the manufacturing system is ready to support the production effort. "Rate" production can be interpreted many different ways and does not necessarily mean "Full-Rate". In the aerospace industry, low-rate initial production (LRIP) certainly counts as rate production and should take place in a manufacturing system that will be used for full-rate production.

The arrow for the finalized product design spans all the different functions of the company maintaining the focus on breadth throughout this process. And as was mentioned in the need for concurrent design activities, these design activities should all converge at the point of rate production level. A mismatch in the timing of completing the design activities could delay the start of production, or require starting production in a system that was not intended to support rate production levels.

Modification Loop

The last phase of the manufacturing system design framework is the modification loop. This is the cycle that represents continuous improvement showing that the manufacturing system design process is never complete. This loop is active as long as the manufacturing system is in operation. The modification loop can be active to fix problems that have emerged since the system entered rate production. This loop accommodates a manufacturing process or design change, or perhaps incorporates new technology into the product or the manufacturing system. The modification loop captures the essence of the Toyota Production System where the quest for perfection through continuous improvement never stops. As examples from Toyota illustrate, continuous improvement requires the continuous redesign of the manufacturing system. It is a way of life for companies striving to become lean.[34]

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[32] Da Silveira, G., *A methodology of implementation of cellular manufacturing*
[33] Karlsson, C., *Radically new production systems*
[34] Black, J T., *Lean Manufacturing Cell Design - Tutorial*

The modification loop, like the rest of the framework, also requires the different functions within the organization to be linked. Success in continuous improvement activities requires equal emphasis on product and process design, which must be closely integrated.[35] This also means that improvement activities don't necessarily have to occur on the factory floor. There is a potential of benefiting from improvements and modifications in the other functional areas.[36] Also, the improvement efforts cannot be done in isolation of the system strategy. Rather than improving the system for the sake of improving the system, the goals of the system that were established by the product strategy need to be revisited.[37] This will help ensure that the improvement activities will support the corporate strategy in the long run.

1.5 Greenfield and Brownfield Application

The manufacturing system design framework applies to both green and brownfield environments. True greenfields are rare; therefore, this framework was created to assist practitioners in either setting.

Brownfields are simply existing manufacturing systems or facilities. So, rather than designing a new system from scratch, an existing system is being re-designed or heavily modified. Since manufacturing systems and facilities are capital intensive, it is more common to accommodate new product introductions, manufacturing process changes, new technology insertions or system relocation within existing facilities using common machines and equipment.

The framework still applies by using the idea that a re-design of this magnitude is the same as a greenfield design effort, but with more constraints. A brownfield design activity will have additional constraints emerge in the requirements/considerations/constraints phase. Using the framework in a brownfield environment will help ensure compatibility between the new system or product being inserted into the existing system.

1.6 Framework Summary

This manual serves as an introduction to the manufacturing system design framework. In summary, the manufacturing system design framework is a visual meta-framework that contains many other useful tools. It aims to guide the manufacturing system design process and does not assume any particular solution. It is comprised of two halves which represent the design of the manufacturing system infrastructure and structure. These two halves are linked by a new concept of the product strategy that is based on collaboration between different functional elements of the company. This idea emphasizes the need to treat manufacturing as a source of competitive advantage for the enterprise. Each phase within the framework represents the necessary decision making activities that should be occurring at that point in the design process.

[35] Utterback, J.M., Mastering the Dynamics of Innovation
[36] Kessler, W., Lean Enterprise presentation
[37] Cool, C., *Journey To A Lean Enterprise*

There are also some key insights to be gained from studying the manufacturing system design framework. The breadth of the framework across the different functions and the inclusion of the high-level strategy formulation body, show that manufacturing system design extends beyond the factory floor and includes all functions of the corporation. The presence of the strategy formulation body emphasizes that the key decision-makers are part of this design process and the manufacturing system design process should have a strategy that supports the core competencies of the enterprise. The formulation of this strategy will have an impact on the product characteristics and requirements on the manufacturing system. Also, the modification loop of the waterfall emphasizes the fact that manufacturing system design never ends. There are always improvements to be made. This framework applies the principles of systems engineering in a rigorous manner to a domain where systematic principles have seldom been used.

2.0 Manufacturing System Design Process[38]

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.

2.1 Infrastructure Design

1. **What are the corporate goals?**
   - What is the corporate strategy?
2. **What is the business 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 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, or Specific?[39]
   - 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?[40]
   - 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?

[38] This chapter on the proposed Manufacturing System Design Process is taken from P. Fernandes, *A Framework for a Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor.*
[39] Utterback, J.M., Mastering the Dynamics of Innovation
[40] Hayes, R.H. and S.C. Wheelwright, Restoring our Competitive edge

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, etc.)	Cost

- How do you plan on using your suppliers?
    - Risk sharing partners?
    - Build to print contractors?
    - How do you plan on using your 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".[41] With the formulation of the product strategy, the infrastructure design is complete. Based on the strategy, a structure design can be attempted.

2.2 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 handy here to see how the combination of different factors affect the factory floor
    - Miltenburg's strategy sheet
5. **Receive requirements from product design. Give feedback to product design**
   This is not just a one way communication dominated by product design but the collaboration of the two. Depending on the status of the industry, the dominant component of a product strategy should be given more control. 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
    - Physical product characteristics/requirements
    - Tolerance requirements
    - New manufacturing technology development requirements
6. **Receive requirements from Marketing and Suppliers – Give feedback**
    - Get rough forecasts on volume and mix
    - Determine supplier location, transportation time, supplier quality etc.
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 etc.)**
    - Feedback up the chain to eliminate contradictions
    - A check and balance system to keep strategy as the priority and not the design

[41] Miltenburg, J., Manufacturing Strategy

- Establish a 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	Process Capability
Production Volume	Worker Skill
Production Mix	Type of Organization
Frequency of Changes	Time to first part
Product Complexity	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?[42]
   - 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 features of different systems be combined to design a suitable system?
     - Tool: Axiomatic design/MSDD/AMSDD

   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
   - 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 the rest of the company. Manufacturing managers should make their decisions based on this policy, which ensures compliance with the underlying manufacturing, business and corporate strategy.
    Operating Policy should determine:
    - Factory control mechanism
    - Inventory levels
    - Daily decision guide
    - Metrics
    - WIP
    - Required skill level
    - Quality checks/quality levels
    - Employee freedom for innovation

11. **Implementation plan**
    Implementation depends on type of system chosen
    - Use known implementation methods, if possible

[42] Miltenburg, J., Manufacturing Strategy

- 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 cannot 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 simulations

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.

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Appendix A: Manufacturing System "Infrastructure" Design Tools

A.1 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[43 44]
- Product-Process Matrix[45]
- 3-D Concurrent Engineering[46]
- Nine Components of Manufacturing Strategy[47]
- The Strategic Manufacturing Planning Process

"Focused Manufacturing" Approach

Skinner recognized the need for a top-down approach to manufacturing system design as early as 1969.[48] 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.

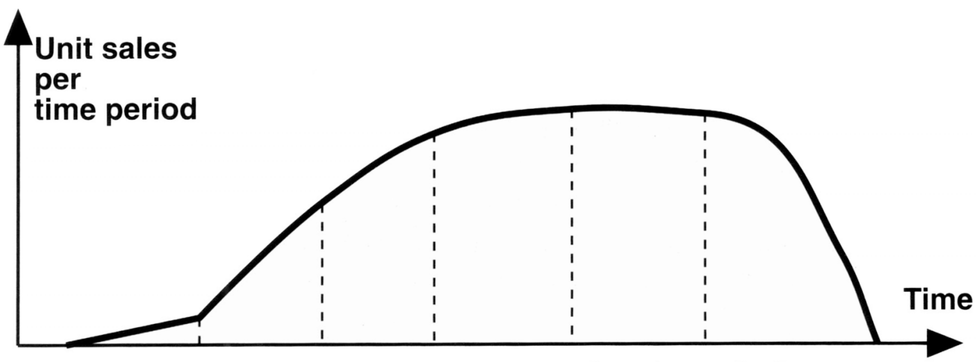
An improvement on this thought is the focus on certain competing elements such as cost, quality, flexibility, innovation, and velocity rather than the entire product.[49 50] There could be more of these elements. The idea here is to focus on some of these elements depending on the business environment 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

[43] Skinner, W., "Manufacturing – Missing Link in Corporate Strategy"
[44] Skinner, W., Manufacturing: The Formidable Competitive Weapon
[45] Hayes, R.H. and S.C. Wheelwright, "Link Manufacturing Process and Product Life Cycles"
[46] Fine, C.H., Clockspeed
[47] Fine, C.H. and A.C. Hax, "Manufacturing Strategy: A Methodology and an Illustration"
[48] Skinner, W., "Manufacturing – Missing Link in Corporate Strategy"
[49] Hayes, R.H. and S.C. Wheelwright, Restoring our competitive edge, Competing Through Manufacturing
[50] Miltenburg, J., Manufacturing Strategy

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.

Manufacturing System Linked to Product Life Cycle[51]

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 5 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 5: Stages in Product Life Cycle[52]

Hayes and Wheelwright introduced the famous product-process matrix[53] suggesting a strong link between manufacturing system capability needed and the current stage of product in the product life cycle. Several other authors have since endorsed this concept in various forms.[54] [55] [56] In

[51] Hayes, R.H. and S.C. Wheelwright, "Link Manufacturing Process and Product Life Cycles"
[52] Miltenburg, J., Manufacturing Strategy
[53] Hayes, R.H. and S.C. Wheelwright, "Link Manufacturing Process and Product Life Cycles"
[54] Chase, R.B. and N.J. Aquilano, Production and Operations Management – A Life Cycle Approach
[55] Miltenburg, J., Manufacturing Strategy
[56] Utterback, J.M., Mastering Dynamics of Innovation

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 6: Product Process Matrix. 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 on 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.

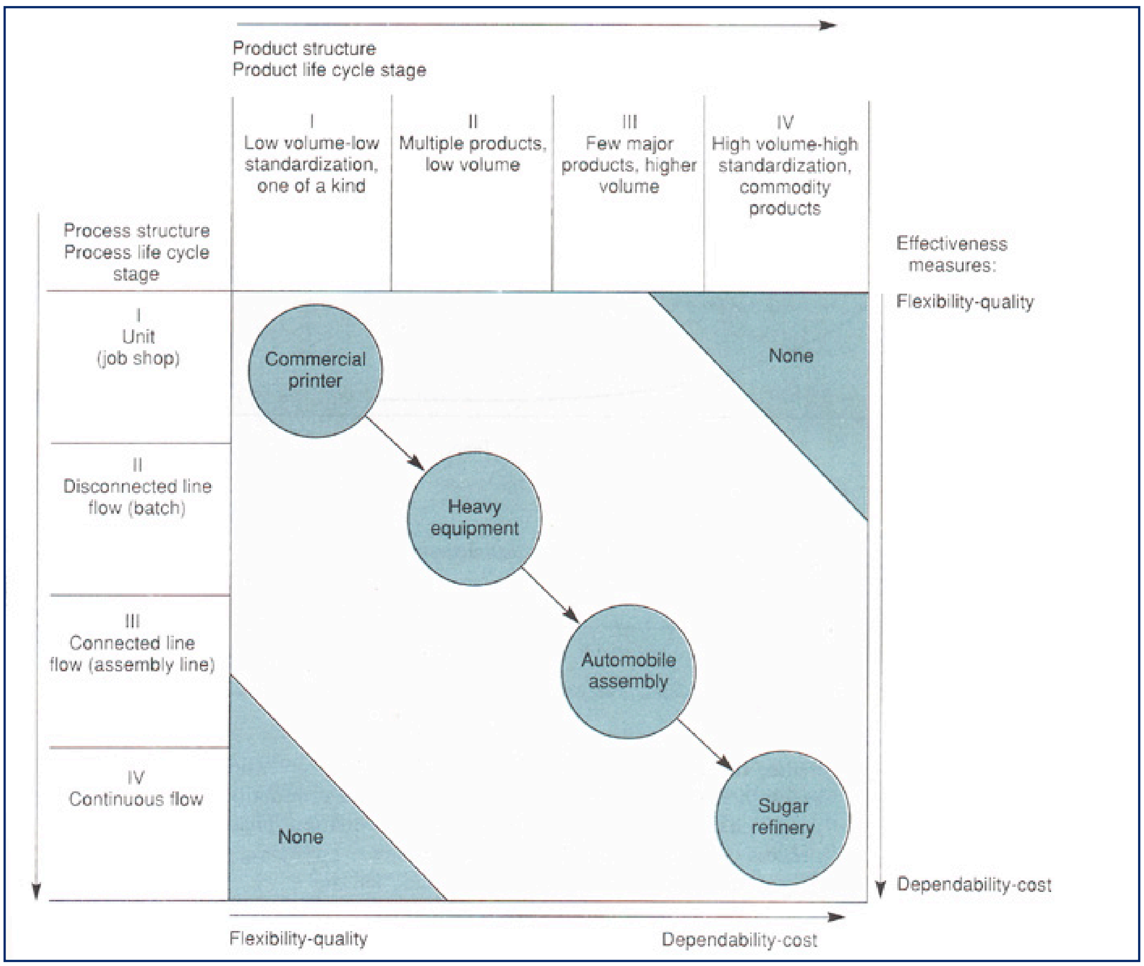


Figure 6: Product Process Matrix[57]

[57] Hayes, R.H. and S.C. Wheelwright, "Link Manufacturing Process and Product Life Cycles"

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 Skinner's focused factory approach. Skinner advocates product focus but Hayes and 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.

3-D Concurrent Engineering[58]

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: Overlapping responsibilities across Product, Process and Supply Chain development activities

The intersection of the three ovals in Figure 7 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.

[58] Fine, C.H., Clockspeed

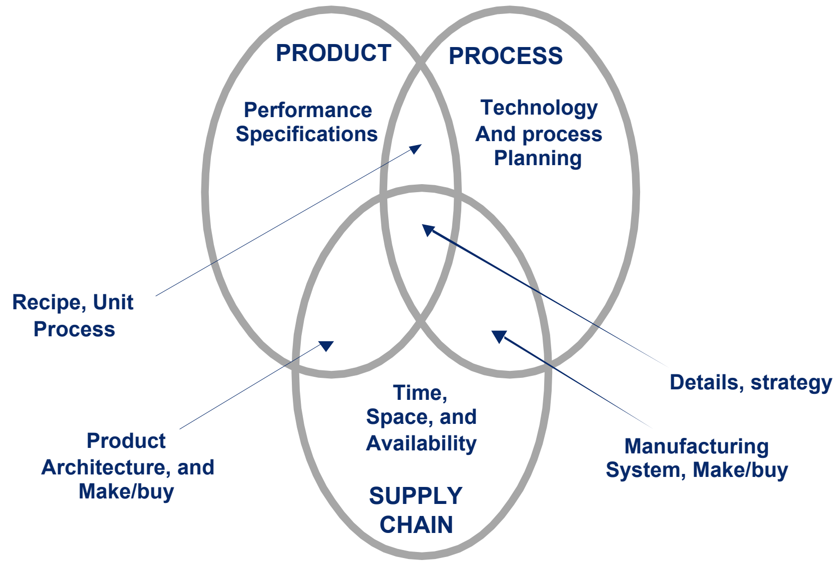


Figure 7: Overlapping responsibilities across Product, Process and Supply Chain development activities[59]

Nine Components of Manufacturing Strategy[60]

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.[61] 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.

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

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[59] Fine, C.H., Clockspeed
[60] Fine, C.H. and A.C. Hax, "Manufacturing Strategy: A Methodology and an Illustration"
[61] Buffa, C., Meeting the Competitive Challenge, Manufacturing Strategy for U.S. Companies

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 earlier.

A.2 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.

Appendix B: Manufacturing System "Structure" Design Tools

Overview

A holistic approach to manufacturing system design yields thinking in terms of manufacturing system structure design and infrastructure design. This appendix 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 earlier.

B.1 Types of Manufacturing System Design Aids

There are three different types of factory design aids encountered 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 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

B.2 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 8.

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 8. 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.

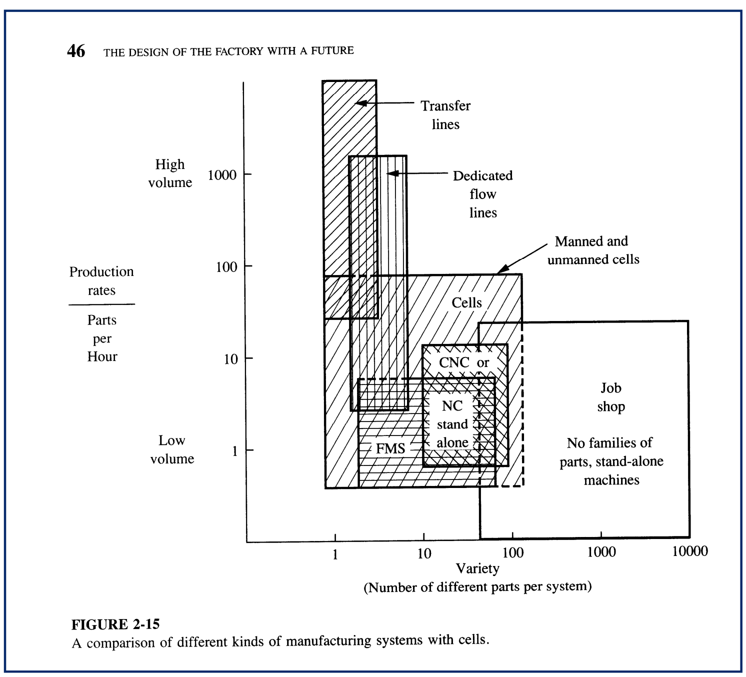

Figure 8: Characterization of Manufacturing Systems[62]

[62] Black, J T., The Design of the Factory with a Future

Observed Manufacturing System Design/Implementation Methods

Even though manufacturing science is nacent with no comprehensive formulas to design facories, 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

Trial and Error/Experimentation Techniques

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 a definite manufacturing science.

There are three differed common trial and error design methods:

- 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.

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 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.

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. 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 satisfies 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 using trial and error, then fine-tuned to the desired level.

Structured Design Methodology

The idea here is to use a disciplined design process such as the one used for a product design. One such approach is to design a manufacturing system using a known design methodology such as the Axiomatic Design.[63] The Manufacturing System Design Decomposition (MSDD)[64], developed by the MIT Production System Design lab, 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).[65]

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[63] Suh, N.P., The Principles of Design
[64] Cochran, D.S., et. al., "Decomposition Approach for Manufacturing System Design"
[65] Dobbs, D.C., *Development of an Aerospace Manufacturing System Design Decomposition*

B.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 or structure design.

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)[66]
2. Toyota Production System Framework by Monden[67]
3. Integrated Manufacturing Production Systems[68]
4. Manufacturing System Design Decomposition[69]
5. The Manufacturing Strategy Worksheet[70]

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

As the name indicates this framework specifically describes the Toyota Production System (TPS). As shown in Figure 9: Toyota Production System Framework, 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.

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[66] Duda, J.W., *A Decomposition-Based Approach to Linking Strategy, Performance Measurement and Manufacturing System Design*
[67] Monden, Y., Toyota Production System: Practical Approach Production Management
[68] Black, J T., The Design of the Factory with a Future
[69] Cochran, D.S., et. al., "Decomposition Approach for Manufacturing System Design"
[70] Miltenburg, J., Manufacturing Strategy

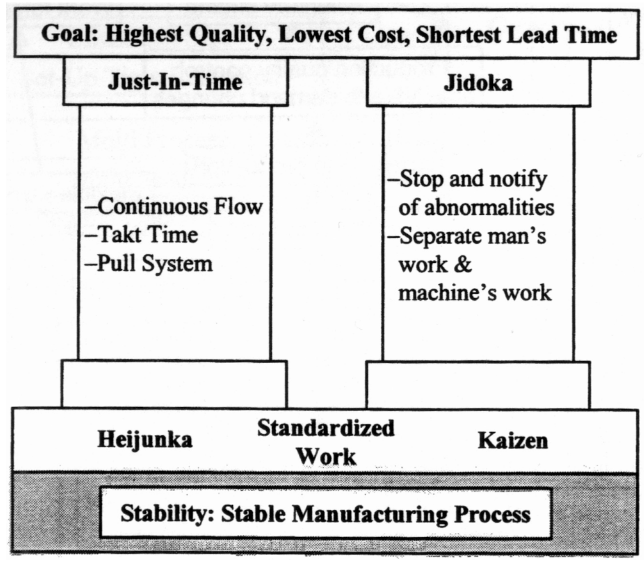

Figure 9: Toyota Production System Framework[71]

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.

Toyota Production System Framework by Monden

The framework developed by Monden, shown in Figure 10, 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.

[71] Duda, J.W., *A Decomposition-Based Approach to Linking Strategy, Performance Measurement and Manufacturing System Design*

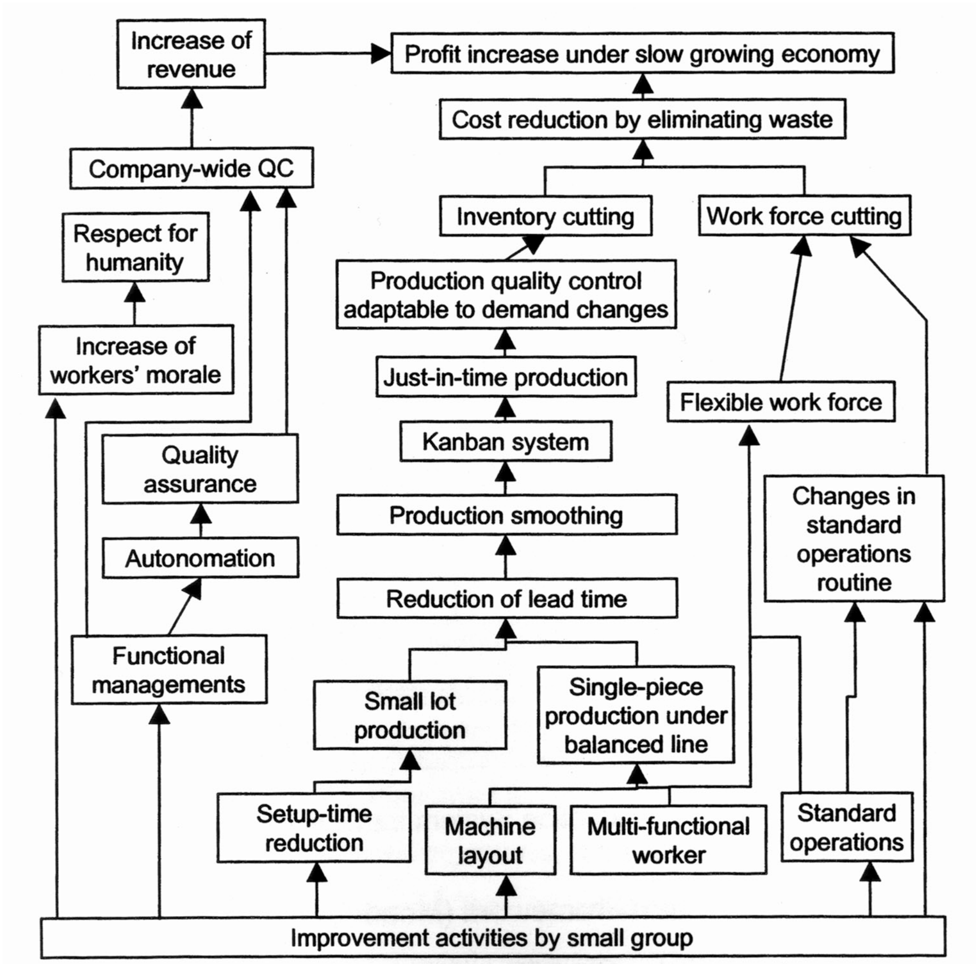

Figure 10: Toyota Production System Framework by Monden72

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. 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.

Integrated Manufacturing Production Systems Framework

J. T. Black recommends a 10-step process to implementing what he calls an integrated manufacturing production system (IMPS).[73] 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

[72] Monden, Y., Toyota Production System: Practical Approach Production Management
[73] Black, J T., The Design of the Factory with a Future

11) 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.

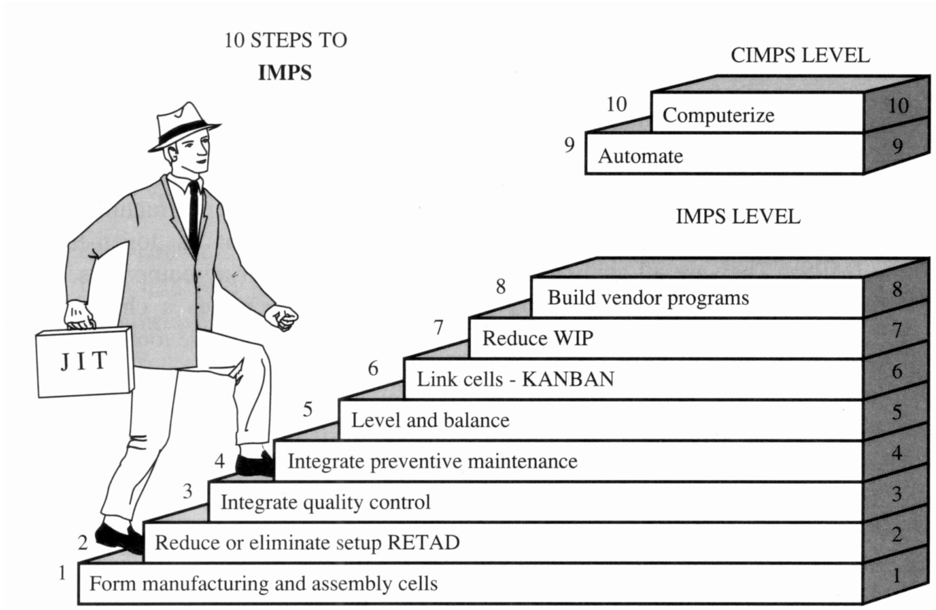

Figure 11: Ten Steps to Integrated Manufacturing Production Systems[74]

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.

Manufacturing System Design Decomposition (MSDD)

This is the first tool we came across that clearly, as the author[75] 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.[76] 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,

[74] Black, J T., The Design of the Factory with a Future
[75] Cochran, D.S., et. al., "Decomposition Approach for Manufacturing System Design"
[76] Suh, N.P., The Principles of Design

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. A schematic of the entire MSDD is shown below in Figure 12. (See web site http://psd.mit.edu/MSDDFrameset.htm for expanded view of 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.

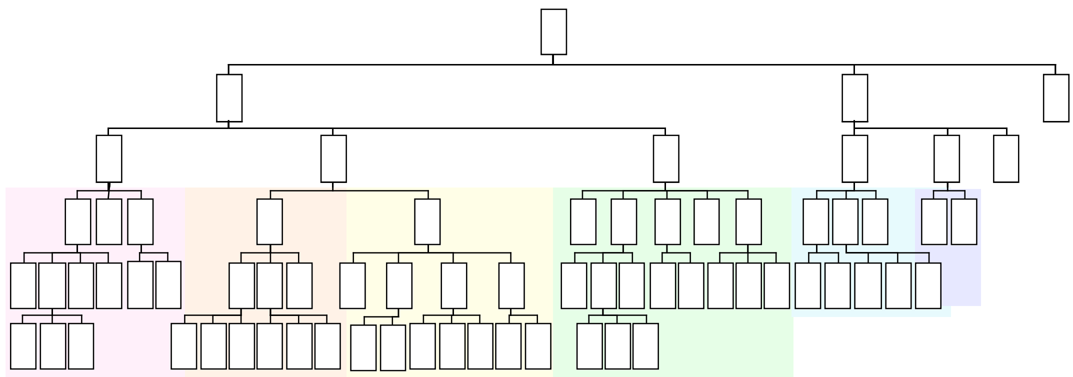

Figure 12: Manufacturing System Design Decomposition (MSDD)[77]

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 may not be a universal one, 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.[78]

The MSDD is not based on a business strategy or a manufacturing strategy. 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. The message being conveyed is that no matter what the market or competition conditions are, a

[77] Cochran, D.S., et al., "Decomposition Approach for Manufacturing System Design"
[78] Fernandes, P., A Framework for a Strategy Driven Manufacturing System Design in an Aerospace Environment- Design Beyond Factory Floor

manufacturing system, based on general best practices and designed to satisfy the overall corporate goal, is sufficient for the company to compete effectively. In the aerospace industry, however, product design often dictates manufacturing system design choices and objectives. 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, the 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. The first step in this effort to include the product design was the creation of the Aerospace Manufacturing System Design Decomposition (AMSDD).[79]

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.[80] However, the assumption makes the tool a specific tool rather than a general manufacturing system design tool.

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.[81] 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 13: The Manufacturing Strategy Worksheet shows Miltenburg's manufacturing strategy worksheet. The recommended use of the worksheet is as follows:

1. Determine the Product to be offered to support corporate goals
2. Determine if the product is planned to be marketed as a *Order Winning* or *Market Qualifying* product
3. Perform competitive analysis to determine which manufacturing outputs are needed to achieve goals in (2) and to assess the strength of competition
4. Select the one or more outputs and see which system provides those outputs
5. Perform a company capability analysis to determine if the current manufacturing system can fulfill the new requirements
6. Determine which manufacturing levers need to be adjusted

[79] Dobbs, D.C., *Development of an Aerospace Manufacturing System Design Decomposition*
[80] Miltenburg, J., Manufacturing Strategy
[81] Miltenburg, J., Manufacturing Strategy

7. 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 concept behind the whole framework is very useful, but its validity needs to be verified. The tool does not provide an implementation plan but does point to the appropriate system and exposes the requirements to get to that system.

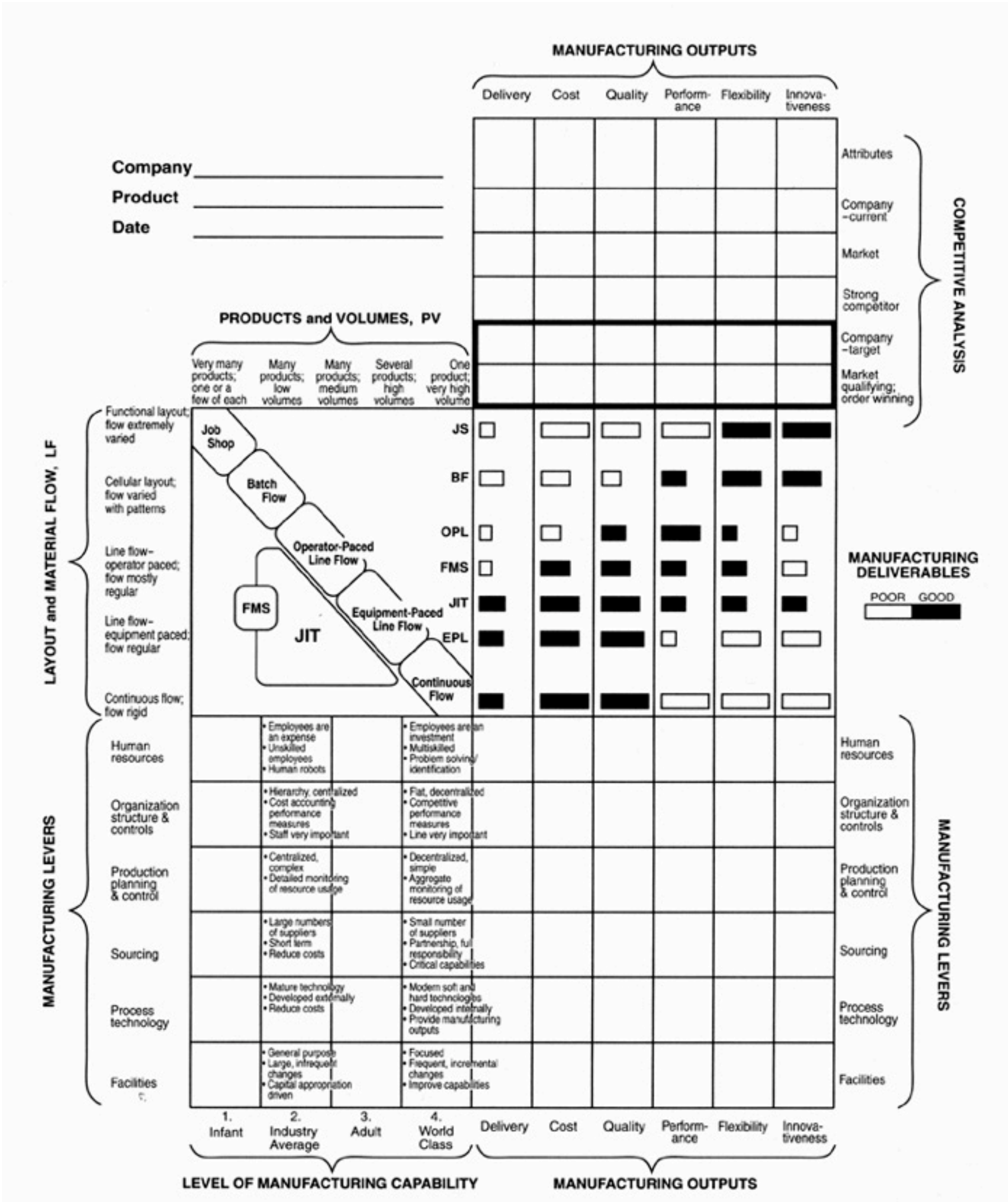

Figure 13: The Manufacturing Strategy Worksheet[82]

[82] Miltenburg, J., Manufacturing Strategy

B.4 Summary of Structure Tools

In this appendix 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	1 Range of available systems 2 System selection based on volume and variety 3 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

Appendix C: Manufacturing System Design Inputs

C.1 Introduction

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 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.

Table 1: Considerations in Manufacturing System Design

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 Regulations	Customer Price (Target Price)
Product/Program Nature	Product Quality
Product Volume	Resources Available
Product Mix	Existing Resources
Product Design	Performance Goals
Frequency of changes	Management Culture
Payback Period	Product Life Expectancy
	Level of Product Maturity
	Response to change

The list in Table 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 1 were sorted into the following broad categories: enterprise Needs/Objectives/Strategies, external factors, controllable factors and constraints/targets.

C.2 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 2 lists the items in Table 1 divided into categories.

C.3 External Factors
The enterprise does not have complete control over these factors, yet they must be accounted in order 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. 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 act truly external to the manufacturing system design decisions. Manufacturing system designers must, however, make design decisions concerning compliance realizing that decisions may affect other enterprise strategies. Table 2 shows the factors that are considered external to the enterprise.

C.4 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 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 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.

C.5 Constraints/Targets

Constraints and goals are set by the management or the decision body to ensure that the manufacturing system 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 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."

Table 2: Manufacturing System Design Considerations by Category

Enterprise Needs/Objectives/Strategies Stakeholder Satisfaction Corporate Strategy Make-buy/Outsourcing Strategy New Product Introduction Strategy	***Controllable Factors*** 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 Market Uncertainty Geopolitical Considerations Offset Requirements Environmental/Government Regulations Product/Program Nature	***Constraints*** Investment Time to first part Payback Period Customer Price (Target Price) Performance Goals Existing Resources

C.6 Major Factors in Manufacturing System Design

Even though all of the factors that are mentioned in Table 1 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)*

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. 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 may 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 are incentivized to buy all materials needed to produce the entire order at once. They hold inventory and start producing products as needed.[83] 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.

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 oversell 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

[83] Wang, A., *Design and Analysis of Production Systems in Aircraft Assembly*

researchers in the past have used volume as one of the two factors to describe the entire manufacturing system.

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 to 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.

Frequency of Changes

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

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 a 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. It is also unrealistic to force manufacturing system designers to design systems with infinite flexibility. 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 a 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 product, the manufacturer will be required to make the necessary changes. The changes can be structural or upgrades to existing systems and can occur as the product 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.

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 somehow (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.

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 a 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 may 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.

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.

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, 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.

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 14, below, 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 14: Schematic of Investment versus Time and Feasible Design Regions

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.

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 16, 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.

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.

Appendix D: Types 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.

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.[84] 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.[85] [86]

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.[87] [88]

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.[89]

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[84] Black, J T., The Design of the Factory with a Future
[85] Guerindon, P.C., Continuous Flow Manufacturing: Quality in Design and Processes
[86] Miltenburg, J., Manufacturing Strategy
[87] Black, J T., The Design of the Factory with a Future
[88] Guerindon, P.C., Continuous Flow Manufacturing: Quality in Design and Processes
[89] Chryssolouris, G., Manufacturing Systems Theory and Practice

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.[90]

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.[91]

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 to the 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.[92]

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.[93] [94] [95]

[90] Williams, D.J., Manufacturing Systems – An Introduction to the Technologies
[91] Williams, D.J., Manufacturing Systems – An Introduction to the Technologies
[92] Black, J T., The Design of the Factory with a Future
[93] Black, J T., The Design of the Factory with a Future
[94] Chase, R.B. and N.J. Aquilano, Production and Operations Management – A Life Cycle Approach
[95] Miltenburg, J., Manufacturing Strategy

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 and 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.[96]

Convertible Transfer Lines
Convertible transfer lines can be changed as part design changes. Modular transfer lines are used to speed up conversions.[97]

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.[98]

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:

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.[99]

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[96] Williams, D.J., Manufacturing Systems – An Introduction to the Technologies
[97] Williams, D.J., Manufacturing Systems – An Introduction to the Technologies
[98] Williams, D.J., Manufacturing Systems – An Introduction to the Technologies
[99] Reza, M.A., Flexible Manufacturing Systems: The Technology and Management

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, and materials are moved to the product rather than vice versa. In construction industry, bridges and roads are good examples of project shop. 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.[100] [101]

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 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 are produced (line is interrupted to change over). The change over can take from hours to days. Flow shops are not flexible by design.[102] [103]

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 the 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)

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[100] Black, J T., The Design of the Factory with a Future
[101] Chase, R.B. and N.J. Aquilano, Production and Operations Management – A Life Cycle Approach
[102] Black, J T., The Design of the Factory with a Future
[103] Williams, D.J., Manufacturing Systems – An Introduction to the Technologies

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 at each workstation then moves to the next workstation simultaneously. 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 3 and Table 4 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.

Table 3: Attributes of Fabrication Systems

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

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 4: Attributes of Assembly Systems