Aligning Technical and Organizational Aspects of Complex Manufacturing Systems

by

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Abstract

Learning rates are typically considered to be intrinsic properties of systems. As a result, little thought goes into "design for learning". Yet, in industries in which learning is extremely important (those with short product life cycles or low production volumes), the success of a new product or process can be greatly improved when learning is considered as a process is being designed. Doing this is a matter of understanding the different types of learning that can exist, and ensuring that the organization and technology are designed so as to create and take advantage of learning opportunities.

This research addresses the issue of aligning the technical and organizational parts of manufacturing systems. Learning – the ability to operate and improve a process – is used as the primary metric for the degree of alignment. Well aligned systems experience a greater amount of learning. In poorly aligned systems, potential learning is not achieved. Several tools were developed to allow manufacturing systems to be analyzed from a joint technical and organizational perspective. Foremost among these tools are the Contact Chain, the Process Interactions Matrix, and the concept of Process Architecture. Using these tools, the critical communications flows in a system can be determined. Process improvement activities, corrective action strategies, work teams, supply chain management techniques and outsourcing decisions are all affected by the communications patterns. Creating an infrastructure to allow necessary communications to occur is critical for the success of any implementation program.

Presented in this thesis are the results of two case studies performed at major aircraft manufacturers. In these case studies, the tools and methodologies developed here were tested and shown to add value to both process improvement and process/organizational design processes. The degree of potential learning in a manufacturing system can be identified, and weaknesses in existing or planned organizational infrastructure revealed. A particularly important finding is that the process architecture has significant implications for organizational strategy. For learning to occur in a process, and for the process to be improved, strong communications links and a high degree of systems knowledge must be present. This shows some of the limitations of the 'agile manufacturing' paradigm, in which companies form short term, ever-changing, 'virtual organizations'.

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Chapter 1

Introduction

1.1 Managing Flexibility

This thesis addresses the problem of improving the first-time success of new manufacturing systems by providing a method for concurrently designing its technical and organizational components. The method is described in the context of emerging flexible assembly methods in the aircraft industry.

In today's competitive environment, companies are increasingly looking to introduce more products in shorter periods of time. To deal with these new pressures, many corporations are aggressively pursuing flexible design and manufacturing strategies. In some industries, a suitable flexibility strategy might involve the design and production of modular components that can be assembled in any of several different combinations. Nippondenso, for example, designs flexibility into their products by carefully managing the interfaces between modular components. [41] Levi Strauss also pursues a similar type of 'mass customization' strategy. Each customer can be measured in the store, and the closest of over 8,448 different possible jean templates is then used to create 'custom made' jeans. [14]

The degree and type of flexibility sought by companies varies depending on the competitive forces in their particular industry. In the production of aircraft structures, for example, obvious cost issues prevent Boeing and Airbus from developing an aircraft structure customized for each customer. The final aircraft, however, can be customized for different customers. TWA, for example, may want to have more Coach or First Class seats than other airlines. To provide this flexibility, aircraft are designed to accommodate many different seat types and configurations. The degree of flexibility is limited, however. It is extremely rare for an aircraft structure to be designed to accommodate two different types of wing or fuselage.[1]

Despite the inflexibility in the design of aircraft structures, there are ways in which the production of these structures can be made more flexible. At present, most large aircraft structures are assembled using large, dedicated fixtures. These fixtures can only be used to produce a specific structure, take several months to build and can cost anywhere from a hundred thousand to a million dollars. In order to be able to increase the production rate of an aircraft, an adequate number of fixtures is needed. Because of the cost and floor space requirements of current fixtures, it requires great effort and dedication of resources to have the capability to rapidly increase production.

To solve this problem, many aircraft companies are trying to change the nature of aircraft assembly. Instead of using the dedicated fixtures, there is an attempt to use flexible fixtures and, in many cases, to eliminate the fixtures all together.

The elimination of fixtures allows the aircraft manufacturers to develop capacity flexibility. However, making the changes in technical features required to eliminate fixtures is not enough. If the organization is to remain aligned with the new business and manufacturing strategies, changes in the organizational structure must be made. Factors that must be addressed include organizational learning, continuous improvement, skill and responsibility requirements for factory floor workers, and the establishment of new information pathways.

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1. The USAF's Joint Strike Fighter is one example of an aircraft that is being designed to accommodate different types of aircraft structure. Each of the proposed designs for the JSF has versions suitable for the Air Force, Navy and Marines.

1.2 Organizations and Technology

About 30-40% of attempts to increase manufacturing flexibility fail. [4] While some of the reasons for this high failure rate are purely technical, the majority of failures are due at least in part to other factors. Some failures are the result of managers not understanding exactly what kind of flexibility they need to achieve their strategic goals. In other cases, the workers and support personnel do not have the skills necessary to properly use the advanced manufacturing technology in the flexible systems. In still other cases, the organizational structure of the firm inhibits the smooth operation of the manufacturing system. [39]

Most of the causes for the failure of advanced manufacturing systems stem from an incompatibility between the technical and the organizational systems within a firm. Here, elements of the organizational systems include the workforce management system, continuous improvement activities and infrastructure, the supply chain, and communication flows. An example of an incompatibility might be that workers are not given the roles and incentives necessary to promote the necessary communication flows.

In most cases, a great deal of time, money and effort is spent on the design of the technical elements of a system. Little effort is spent on explicitly designing the organizational system. If an effort is made to design the organizational system, it is most often independent of the technical development effort. The result is a manufacturing system with incompatible components. Leonard-Barton points out that "a technology almost never fits perfectly into the user environment." [22] Building upon this point, Tyre notes that "Successful technological change also requires active organizational efforts to adapt the new technology, the existing manufacturing system, and the organization itself to a new set of demands." [36]

To successfully implement new technologies into a manufacturing environment, **the technical and organizational systems must be designed concurrently.** The concept of concurrent engineering must be expanded from simultaneous technical development of the design and manufacturing systems to the development of the total design and manufacturing system. In this latter case, worker roles and skills, supply chain structure, communications flows, corrective action and continuous improvement processes would all be considered at the same time as the accuracy of the machine tools and the design of a product's components.

The research described here provides an initial framework for aligning the technical and organizational aspects of complex manufacturing systems. Using and building on this framework will allow firms to improve the first-time success of new manufacturing systems, and to improve productivity and process improvement on both new and existing programs.

1.3 Learning Across Organizational Boundaries

While the role of organizational structure in manufacturing systems is perhaps not questioned, the subtleties of its role are not widely appreciated. In most manufacturing environments, for example, the organizational structure is of secondary importance to the technical system. Yet, it is through the organizational structure that many of the most important elements of a manufacturing system are affected.

Learning is a case in point. Companies are increasingly discovering that learning is a major source of competitive advantage in today's business environment. There are numerous stories where a company that was doing poorly recovered and excelled by transforming itself into a "learning organization".[2] Books professing to teach companies how to become "learning organizations" are very popular, as evidenced by the success of Peter Senge's The Fifth Discipline. [28]

There are several elements to any learning system. Some of these are shown in Figure 1.1. First and foremost, people have to want and have the opportunity to learn. The environment in which the people find themselves is therefore extremely important. A company which provides the motivation, training and time – the corporate values – necessary for learning to occur has a much better chance at being successful than one that takes learning for granted and does not provide the proper environment. However, building this environment is not enough. In order for the maximum amount of learning to occur, the system needs to be designed to facilitate information and communications flows.

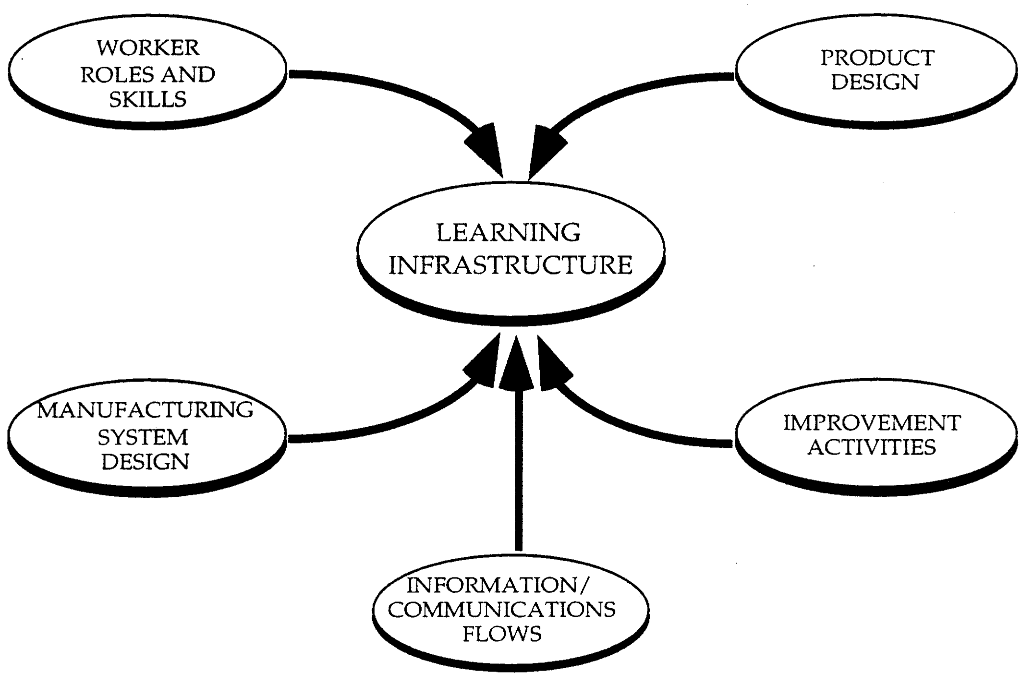

Figure 1.1: Elements of a Manufacturing System's Organizational Infrastructure.

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2. Analog Devices is one such success story. See Stata [29] for a more complete description.

Several studies [30] have noted that "all learning depends on feedback".[3] Feedback can occur in two ways. It occurs to some extent through the natural process of doing things. If you drill a hole, you learn something about how well you drilled it. This is a direct form of feedback. There is also an indirect form, in which information ripples through the entire system. Exactly how the feedback progresses through the system depends on the communications infrastructure present. To achieve the maximum amount of learning in a manufacturing environment, this infrastructure must be specially designed; it is not enough to accept the infrastructure that is created as a by-product of other decisions.

Creating this infrastructure is not easy. Elements of the infrastructure are dependent upon the technical features and capabilities of the system, the corporate culture, past and present organizational structure and the design and capabilities of the supply chain. Links must be created to span these and other factors. In order to avoid the waste of resources, links that do not need to exist should not exist. At the same time, any links that might be important should be checked to avoid overlooking an important factor.

Addressing the problem of designing and creating this infrastructure is one of the major themes of this thesis. The goal, alluded to above, is to improve the learning and improvement capabilities of firms, and particularly to improve the first time success of new manufacturing systems.

1.4 Program Background

The research presented in this thesis was performed as part of the MIT Fast and Flexible Manufacturing Program, under the sponsorship of the United States Air

3. [30], pg. 292.

Force Wright Laboratory Manufacturing Technology Directorate and the Advanced Research Projects Agency (ARPA). There are two primary goals of the project: to develop a conceptual framework for product realization within an intricate network, or web, of suppliers, and to improve the first-time capability of new products developed or procured in a complex web of suppliers. The definition of first-time capability includes: [11]

1. Delivering products to specification
2. Fast cycle times for product development
3. Ability to accommodate in-process changes in specifications
4. Low cost.
5. Minimum error rate in production.

Several industrial partners are involved with the project. Case studies performed at industrial sites have led to the development of tools and methodologies for managing product development on a web, as well as a sharing of knowledge between the aircraft and automobile industries.

Several theses and papers have been written on the work performed in the Fast and Flexible Program. A selection can be found in the Bibliography, including [6] [7] [12] and [21].

1.5 Thesis Roadmap

In writing this thesis, there are three ideas that I want to communicate. The first is learning is a source of competitive advantage, and that careful alignment of technical, organizational and business strategies can improve a company's ability to learn. To this end, this thesis describes techniques and tools developed through research performed at major aircraft manufacturers. The aim of these tools is to create a consistent framework upon which technical and organizational systems can be analyzed and compared to strategic objectives.

The second key idea is that of process architecture, which describes the degree of interaction between the process steps. Process architecture is an extension of a concept that is used in product design. It is developed in this thesis for two reasons. First, the analogy to product design is useful as it helps to clarify issues that are common to both contexts. It creates a common language between the product and process organizations. Second, process architecture encompasses and describes a number of other important points about manufacturing systems. It is a useful, integrative approach to thinking about such systems. In this thesis, the concept of process architecture is defined and described, as are the benefits of thinking in terms of process architecture.

The third idea presented in this thesis is that of Chains. Most things are achieved through flows and processes. Chains describe the ways in which the interfaces between the different elements in a process contribute to the achievement of the desired output. An assembly process involves parts flowing into a system and being linked together to achieve an output, which then flows out to the customer. A sales process involves several elements - financial transactions, logistics, manufacturing, and marketing - all coming together to produce the final output; in this case, a sale.

Viewing systems through the lens of chains – understanding what elements flow into a system and how they link together and affect each other – enables new solutions and efficiencies to be achieved. However, using an understanding of chains in this way is to partly waste the power of that understanding. The most dramatic results can be achieved through proactively designing the chain that is best for the system. Unfortunately, most chains are not explicitly designed at all.

They are, instead, locked into place by decisions made in other areas of the process. In a manufacturing process, for example, the choice of fabrication system, assembly sequence and tools lock in a particular chain. A colleague in the Fast & Flexible Design and Manufacturing Program, Timothy Cunningham, is currently conducting research showing how choices made as early on as the concept definition stage lock in certain chains. Designing and using chains to improve the operational and strategic effectiveness of complex manufacturing system is a major thrust of this thesis.

The following chapter highlights the importance of learning in manufacturing environments. In Chapter 3, organizational issues in manufacturing systems are discussed, with a focus on process improvement and workforce management. Chapter 4 provides an introduction to the various tools used to characterize and analyze a product development and manufacturing system. Case studies illustrating the links between several of the topics in this thesis are described in the following two chapters, Chapters 5 and 6. Finally, Chapter 7 explores the implications of the issues highlighted in the previous chapters.

Chapter 2

Learning

2.1 Learning is a Feedback Process

Learning is the fundamental process through which systems are improved and productivity increased. It is driven by experimentation. A child learns that a square block will not fit into a round hole by trying and failing. A person learns to ride a bike by actually riding one, starting with training wheels and perhaps falling a few times before he learns to balance.

Experimentation is not always enough to drive learning. Consider the case of a student trying to learn calculus. Practicing problems is perhaps one of the best ways to improve one's performance. However, a person could do hundreds of problems without improving her ability to do calculus if she could never check the answers. In this case, experimentation combined with feedback is important. A person performs a task; she then evaluate her performance and learn lessons based on how she did.

If we revisit the first two examples, the same process can be seen to be at work. A child learns that a square block will not fit into a round hole only so long as they obtain feedback from the system. The block must not fit through the hole, and the child must be able to see and feel that. The same holds for the bicycle. You cannot learn to ride a bicycle very well by riding an exercise bike. On an exercise bike, the sensations that come from a bicycle which is tilting in one direction or the other is absent. The stability that comes from moving forward is not seen or learned. All of these sensations constitute a kind of feedback.

The case of the person learning calculus demonstrates that the adage "practice makes perfect" is not entirely accurate. Practice – experimentation – is useless without feedback. The learning process, shown in Figure 2.1, is a never ending cycle of experimentation (operating the system), followed by the collection and evaluation of feedback, and the implementation of system improvements. Each of the elements in this cycle can be structured or unstructured. In some cases, the evaluation of the feedback is subconscious; in other cases, it is very explicit.

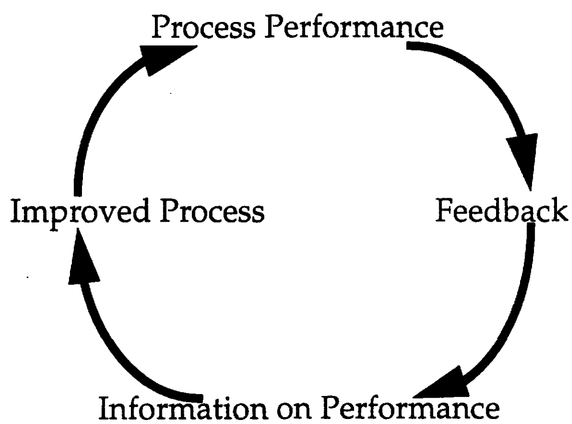

Figure 2.1: Practice, with Feedback, Makes Perfect

The speed of learning is primarily affected by two variables: the time it takes to perform a learning cycle, and the amount of improvement that each cycle yields:

$$\text{Speed of Learning} = \frac{\text{Improvement per cycle}}{\text{Time to perform each cycle}}$$

When learning occurs on a subconscious level, the time to perform each cycle is typically small; the learning speed is therefore large. The more explicit the experimentation and feedback evaluation periods, the longer the improvement time, all else being equal.

Understanding the improvement per cycle variable is more difficult. In part, it depends on the efficiency of the feedback loops. To a large degree, it depends on the level of understanding of the person doing a process. The deeper the understanding of what they are doing, the easier it is for them to evaluate the feedback and generate improvements. Conversely, a limited or incorrect knowledge of the system leads either to smaller improvements or to mistakes in interpreting the feedback and devising improvements. System performance suffers as a result.[1]

In this chapter, learning, and its role in manufacturing systems, is examined. Particular attention is paid to understanding the mechanisms at work when learning occurs in such environments.

2.2 Learning in Manufacturing Systems - The Learning Curve

Learning, and the increased productivity it brings, is particularly important in manufacturing systems. People naturally learn as they repeat certain tasks. In a manufacturing setting, this translates into reduced labor hours and lower costs.

While studying the production of aircraft in the early 1930's, Wright noticed that this 'learning by doing' phenomenon was a regular, quantifiable process. [44] Reductions in labor hours occurred at a predictable, regular fractional rate. This observation is the foundation of the learning curve.

Figure 2.2 shows two learning curves for different assembly processes. There is a large difference in the rate at which learning occurs in these two systems. In one, about an 80% improvement is seen between Lot 1 and Lot 30. At the same time, the other has only improved by about 50%.

1. The goal of the field of System Dynamics is partly to help people make better decisions by obtaining a better understanding of the systems in which they operate. For further information, see the literature by Senge, Sterman and Forrester. [28][30][13]

Learning curves come in several different flavors. All have some measure of cumulative output on the X-axis. On the Y-axis is a measure of productivity or, in some cases, quality. Historically, the measure of productivity has been labor hours. More recently, other measures of productivity that combine labor and capital (Total Factor Productivity) have been used. However, as discussed later in this chapter, most learning curve discussions still focus upon direct labor, even though this may no longer be a good indicator of system learning.

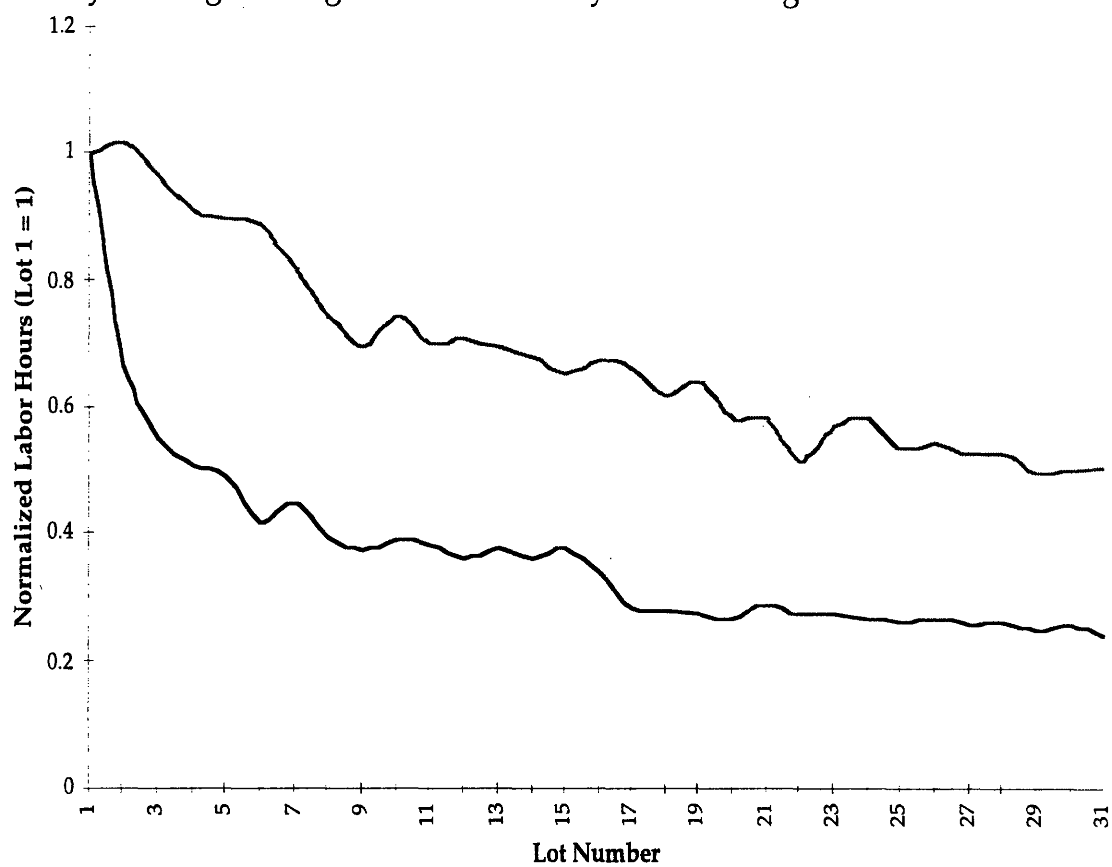

Figure 2.2: Two Learning Curves for Different Aircraft Subassemblies

When talking about learning curves, several terms are normally used. The most important of these is the **learning rate**. This is a measure of the rate at which learning occurs. It is the percentage of the input factors (labor, capital – the Y-axis) that is needed every time the cumulative output doubles. A 70% learning rate, for example, means that at lot **j**, only 70% of the resources needed for lot **i** are required, where **j=2i**. This nomenclature is quite counterintuitive; given this definition, **a lower learning rate is better**. Typically, learning rates range from 50% to 100% (no learning).

Several models describing learning curves have been developed. The most basic of these is the log-linear model:

$$\zeta = X^{\left[\frac{\log\Phi}{\log 2}\right]}$$

ζ is the percentage of the initial input factors needed to produce the Xth unit, X is the cumulative number of units produced, and Φ is the learning rate.

Notice that, while not completely independent of the actual production rate when measured in time units, it is the cumulative production, and the experience that has been built up through this production, that is important. It is for this reason that most learning curves do not contain a time variable. For further discussion of learning curve mechanics, see Belkaoui or Teplitz. [3] [34] A brief discussion of learning curves can also be found in most microeconomics textbooks.

Several important points about the learning curve are illustrated by Figure 2.2. Learning can have large consequences on the cost (and quality) of a product. It does not occur at the same rate in every system. Indeed, it can even vary between different plants making the same product with the same processes in the same company. [16] In addition, the learning rate can be greater than 100% – experience is lost (through, for example, lay-offs or reassignments) or items forgotten (as might happen if a line shuts down for a period of time). Lastly, although it is modeled as a constant, the learning rate does vary slightly throughout the process. The average learning rate is the value which produces the best fit exponential curve for the data.

2.3 Learning Curves and Cost

Learning curves have traditionally found the most use in the areas of managerial accounting and pricing. As learning occurs, costs decrease. Consider the two learning curves in Figure 2.2. Imagine that these represent the learning curves for the production of competing aircraft made by different aircraft companies. Further, imagine that the price of each aircraft is $60 million, and the unit cost of production is $120 million at Unit 1.

To begin making any profit on the sale of each aircraft, the companies must bring the cost of production below the selling price of $60 million. They must realize about a 50% reduction in cost just to break even. Based solely upon learning, Aircraft Manufacturer C, with the 75% learning rate, achieves this cost goal by about Unit 5. It takes Aircraft Manufacturer D, with the 85% learning curve, until about Unit 20. [2] The result of this difference is shown in Figure 2.3. Manufacturer C realizes much less risk (because of the sooner profitability) and greater rewards (as measured by cumulative profits) through the difference in learning rates. Indeed, the difference in cumulative profits by Unit 100 is just under $2 Billion! When the gap between learning rates decreases so that it is only 5% (80 vs. 85%), the cumulative profit difference at Unit 100 is still about $1 billion.

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2. C & D were chosen as manufacturer names instead of A and B to remove any possible confusion with real aircraft companies. The scenario described in this section is fictitious, although the issues raised and the orders of magnitude are accurate.

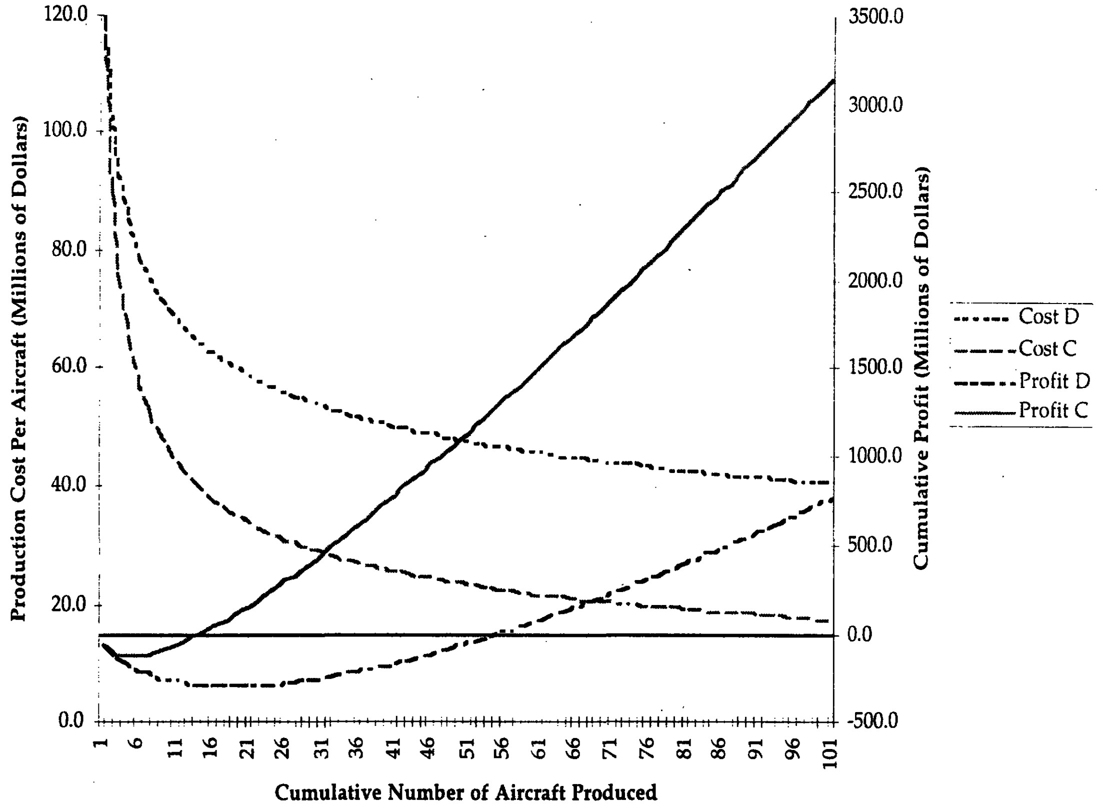

Figure 2.3: Effect of Learning Rate on Cumulative Profits and Unit Costs.

The aircraft industry is particularly concerned about learning curves for the reasons highlighted in this example. Volume and production rates are low (a typical production rate for an aircraft is 4/month), so the cost reductions achieved at an early stage have a huge impact on the bottom line. Typically, aggregate learning rates for aircraft production are in the range of 75-85%. In the high volume environment of automobile production, by contrast, most of the learning is accomplished early in the initial "launch" period, when "practice" cars which are not sold are produced. The number of practice cars produced is very small compared to the total cumulative production for a typical model. The practice automobiles make up perhaps 0.05% of a total production run. Learning curves therefore have less impact on total cost.

Learning is important in the aircraft industry for another reason. Unlike the scenario presented above, prices in the real commercial aircraft market do not remain fixed. Because the commercial industry is dominated by two large companies, prices are not set by a market; they are instead set through negotiations and bids. It is not unusual for aircraft companies to present customers with sizeable discounts to win a large order. Cost reduction is therefore even more important as it allows this price flexibility. In addition, the base price of an airplane is not set by the cost of producing that particular aircraft. It is typically set based on the average cost of the entire expected production run, which might consist of 400 units. Learning curves are taken into account when calculating this average cost. It is therefore extremely important that aircraft companies have the capability to predict and achieve targeted learning rates.

In military aircraft production, learning curves are even more critical as total production volumes are often much lower than commercial aircraft volumes. One of the major benefits of the new USAF Joint Strike Fighter program, with the high commonality of parts and single production line, will be the cost reductions that will come through learning, resulting in lower average prices. Obviously, if learning rate can be improved on this or other military programs by even 1-2%, very large savings can be realized. Part of the learning rate improvements in military programs may be achieved through improved producability studies. In addition, learning rates can be improved by making greater efforts to spread learning across programs. This, however, is difficult due to the competition among major defense contractors. Learning rates can further be improved by employing Design-for-Learning activities such as those described in this thesis.

2.4 Behind the Learning Curve

Because of the importance of learning curves to companies, there has been a great deal of research aimed at better understanding the mechanics of the curve. Most of the early work was on the modeling and predictive aspects of the curve. In these studies, the learning rate was taken as a constant property of a system. Mathematical models of the learning curve were developed, as were techniques to track and predict learning rates. However, in most of these studies, the mechanisms behind the learning curve were not examined. Instead, the all-inclusive "learning-by-doing" explanation was used – people performed tasks better the more they performed the task.

Only recently has a body of literature appeared that examines the mechanisms behind the learning curve. Much of this literature comes from the world of psychology and education. This literature has illustrated many of the key factors at play in learning in general. The individual learning process has been modeled, and techniques for promoting organizational learning have been developed. These techniques include: building a shared vision and common goals, creating an open learning environment and expressing mental models of various problems. [28] In addition, the psychology literature has been useful in understanding how to improve teamwork and interpersonal communication.

The groundbreaking work on learning organizations and the psychology of learning was by Argyris. [2] This work was the first to distinguish between single-loop and double-loop learning. Single-loop learning was defined to be learning in which the fundamental problem and approach remain the same; the mental model is unchanged. Double-loop learning, on the other hand, occurs when problems are redefined, and the underlying policies of the organization are changed. In double-loop learning, the mental models are altered, as are the paths to possible solutions.

Another, growing part of the literature is emerging from management realms. Pioneering studies by Hayes and Clark [16] and Adler and Clark [1] first examined the learning curve from a "microeconomic perspective". They examined the influence of different variables, such as location, training and engineering changes, on the overall learning rate. Their main findings were somewhat surprising. Training helps productivity in some cases, but hurts in others. The same is true of engineering changes. Furthermore, differences in day-to-day management were found to have a great impact on productivity (and, therefore, on the learning rate). Companies producing the same product in similar plants were found to have widely varying learning rates between the plants.

Perhaps the greatest insight that results from these pioneering studies is that there are no techniques for improving productivity and learning that will work in every situation. Management must tailor their programs and activities to the special circumstances of their plant and product.

Adler and Clark's work led to further research on problem solving and learning, particularly in the area of new process implementation. Among the major insights from this research has been the recognition of the need to adapt the organization to the particular technology being implemented [22], and on the need for workers to properly understand and structure problems as a step towards a solution. [28] [38]

A separate literature on learning has appeared under the guise of process improvement. It is interesting to note that only a small section of the learning curve literature has examined the lessons from the TQM movement. In part, this seems to be due to the fact that process improvement is not seen as part of the "learning-by-doing" process. Only recently has there been a recognition that quality, measured as defects-per-million, for example, improves at constant fractional rate with cumulative production (as does cost in the cost-based learning curve). [5] There have not, as far as I am aware, been studies linking the quality learning rate to the cost learning rate. In fact, the literatures on the two subjects are quite disjoint. Part of the aim of this thesis is to fill the gap between process improvement and learning literatures. By doing so, learning rate improvement techniques can be developed which build upon and extend these different literatures.

2.5 Who Does the Learning?

The first step in understanding how to improve learning in a system is to identify those who actually do the learning. In every system, all of the people involved do some learning, no matter how small their role. In manufacturing, both direct and indirect workers learn and improve processes. In product development, test engineers, designers and marketing representatives all learn from iteration to iteration, project to project.

Because learning is driven by feedback, the people who get the feedback the quickest have the potential to learn the fastest. This does not mean, however, that what they learn has the greatest impact on the system. Sometimes, the longer feedback loops provide the greatest leverage in improving a process. Because of this, care must be taken to include all people who are involved in the process in any way in the learning activities. On a manufacturing floor, this might mean including maintenance personnel and design engineers in the process improvement teams. In a product or process development setting, it might mean adding some manufacturing floor personnel to the design team.

Many of these issues have been recognized in the discussions surrounding Design for Manufacturability (DFM) and Concurrent Engineering. Indeed, the general motivations are the same. In DFM, benefits are obtained from sharing knowledge and learning between functions by shortening the feedback loops involved in the design iterations. Rapid prototyping is another case in which shortened feedback cycles improve the overall design and producability process. The improvements that these innovations have brought to many organizations are one element of proof that shortening feedback loops and **proactively designing** the feedback structure of the system can have dramatic effects upon efficiency, productivity, cost and time-to-market.

2.6 Explicit and Implicit Learning Loops

Process improvement and learning-by-doing have at least one thing in common: they both require feedback to be successful. However, the type of feedback that they require is different. The link between the two can be established by understanding and comparing the types of feedback loops that are necessary for each.

In this thesis, it is asserted that there are two types of activities account for all learning that occurs in any system: activities that provide implicit feedback loops, and activities that provide explicit feedback loops. These two types of loops are described below.

2.6.1 Implicit Learning Loops

Implicit-loop learning is what is primarily responsible for the basic 'learning-by-doing' phenomenon. It occurs 'naturally'. That is, only very limited special actions, if any, are need for the learning to occur. All of the feedback needed for learning is gathered and processed directly by the person doing the learning. The feedback is never made explicit. It is, instead, processed subconsciously.

Implicit learning loops exist any time a person works directly on a task. The loops are limited in scope to a single task, and typically contain little delay. Feedback travels through the system at a very fast rate. However, because the feedback is never made explicit, it is often the case that the improvement per cycle which results is quite limited.

2.6.2 Explicit Learning Loops

Explicit learning loops are those which have been specifically designed into a system. They are not a 'natural' part of a system; they are not normally performed in the most basic form of a process. Instead, time, policies and structures are required to create the feedback loops. Examples of this type of activity are continuous improvement and corrective action systems. The PDCA cycle in process improvement provides structure and creates the opportunity for feedback to be collected and evaluated. Corrective action procedures, which typically involve root cause analysis, also comprise explicit feedback loops that must be deliberately created. There is nothing inherent in the production of a widget that requires corrective action mechanisms. Instead, a conscious decision is made to try to identify and solve problems that occur, and a particular set of procedures is designed and resources allocated.

The distinction between implicit and explicit learning loops helps to fill some of the gap between the worlds of learning and process improvement. The former has traditionally been dominated by implicit-loop learning, while the latter has typically made use of explicit-loop learning. An examination of the similarities and differences between these types of loops can provide a guide for linking the process improvement and learning literatures.

2.6.3 Learning Loops and Knowledge

In order to fully understand the different learning loops and their implications, it is important to make a clear distinction between learning and knowledge. Learning happens when feedback is transformed into knowledge of how the system works. There are two types of knowledge: explicit and tacit. Tacit knowledge is defined by Nonaka and Takeuchi [26] as knowledge which is "highly personal and hard to formalize." Explicit knowledge, on the other hand, is that which "can be expressed in words and numbers, and easily communicated and shared."

Either of the learning loops can create either type of knowledge. Explicit learning loops can create tacit knowledge as well as explicit knowledge. Similarly, implicit learning loops can generate either tacit or explicit knowledge. The label describing the type of learning loop refers to the form of the feedback and feedback structures, not the type of knowledge generated.

For example, consider a person learning to play the piano. When she is beginning to learn, the learning is often explicit-loop. There are exercises which are practiced, and there is a teacher providing feedback to the student. However, the knowledge that is generated tends to be tacit in nature. Most piano players cannot tell you exactly how they play different pieces. Yet, they can play those pieces extremely well. This is an example of explicit loop learning translating into tacit knowledge. Of course, some explicit knowledge is learned in the process as well. As part of her lessons, the student might learn the difference between the minor and major scales, or how to play a C chord. Such knowledge is explicit.

Implicit loops also play a role in this example. As the person plays the piano more, she begins to recognize some of her own mistakes, and correct them. Thus, tacit knowledge is generated through the normal act of playing the piano – through implicit learning loops.

2.7 Improving Learning through Design

There are two ways to improve learning in a system. First, a greater number of high leverage loops can be created during the product or process design phase. Doing this is the subject of this section. Second, existing loops can be strengthened; that will be addressed in the following section.

All learning in every system happens through a combination of implicit and explicit learning loops. There are, however, diminishing returns from the use of any particular loop. To see this, consider the structure of a loop. Every loop, whether explicit or implicit, passes through a set of tasks and processes. It provides workers a certain perspective on those tasks. This perspective opens doors that had previously been closed, allowing new approaches to problems to be seen. Once the door has been opened for a period of time, the perspective becomes part of the standard problem solving toolkit. Most of the problems which can be fixed using this new, expanded toolkit are slowly fixed, and soon the situation returns to how it was before the door was opened. Problems exist, but the toolkit cannot solve them efficiently. However, when there are doors that have not yet been opened, the process can begin again.

It is possible to argue that there are some loops that can continuously provide new information, and which will always present new ways of attacking problems. This argument, however, does not consider the human side of the equation. Much of the impact of a new perspective comes merely from the fact that it is new. Often, the new information help people to think 'out-of-the-box' – they begin to think more innovatively. [26] The process of opening new doors not only allows a worker to add to their toolkit. It helps them to make more innovative and creative use of their existing toolkit. A greater number of loops therefore helps to improve learning simply through the fact that it makes the environment more dynamic.

A more serious argument against increasing the number of loops is that of complexity. Indeed, complexity in both organization and technology is one of the greatest obstacles to learning. This is illustrated in Figure 2.4.

As the number of loops in a system increases, the organizational complexity of the system likewise increases. Information needs to travel to an increasing number of different places, making information management a much more difficult task. There are more ways in which a particular organization can be affected. Sorting through all possible causes therefore becomes more challenging as well.

Indeed, left unchecked, the complexity that new loops introduce into a system can destroy any possible benefits. In some cases, the situation might actually become worse. The situation with few loops might become preferable. As Francis Bacon once noted, "truth comes out of error more easily than out of confusion".

This need not be a death sentence for the concept of improving learning through increasing the number of loops. Several steps can be taken to alleviate the problem. In particular, there is a trade-off between complexity and loop proliferation (see Figure 2.5). The critical challenge for managers is to recognize the level of complexity that can be effectively managed, and then to design a system that has the right number of loops to provide this complexity.

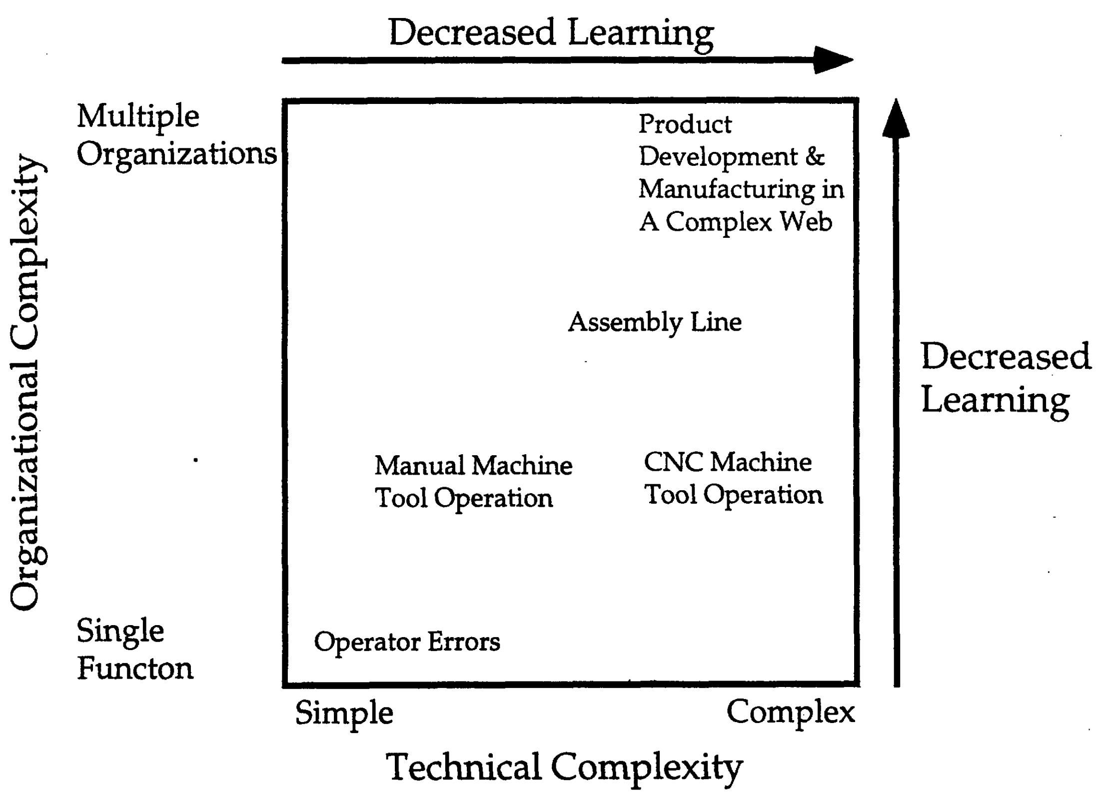

Figure 2.4: Complexity Increases the Learning Rate (Decreases Learning)

Obviously, this is easier to say than to actually do. Exact numbers cannot be put to the levels of manageable complexity or optimal loops. Indeed, because the strength and scope of different loops vary, the latter is impossible to define without going into great detail.

Yet, while these figures cannot be specified which much certainty, the concepts can be useful to managers. The dangers of uncontrolled loop proliferation are shown, and the need to focus management attention on reducing complexity recognized. In fact, because a lower the level of complexity for a particular combination of loops results in greater learning, the goal of management should be to reduce complexity as much as is possible and practical while maintaining the explicit loops. Tools exist which can aid in this process. One such tool, that of structured correlations, is developed in Chapter 5. Computerized information systems can also greatly reduce the complexity of information flows.

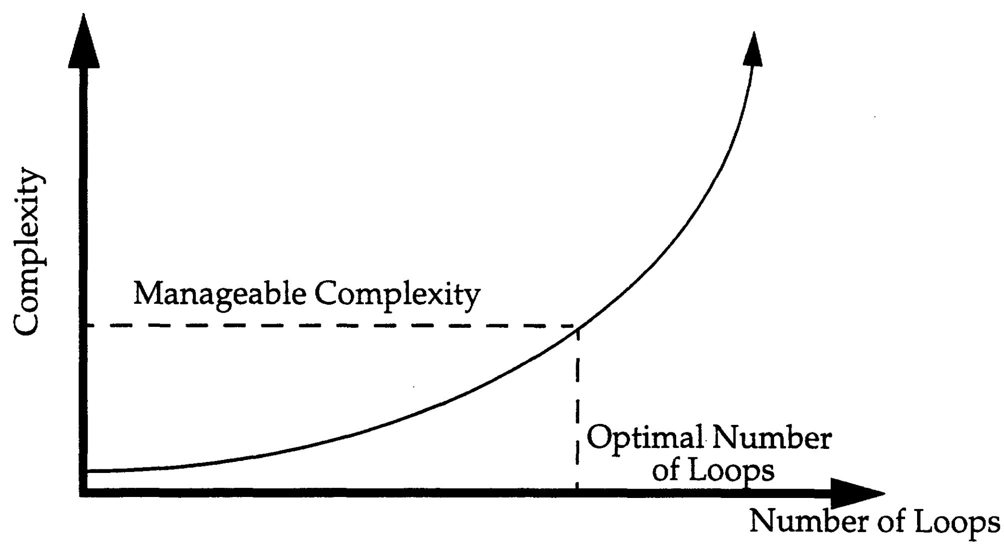

Figure 2.5: Trade-off between Complexity and Learning Loops

2.8 Improving Learning by Strengthening Loops

Another way to improve learning in a system is to make better use of the existing loops – to <u>strengthen</u> the loops. Techniques for doing this differ depending on the type of loop. Implicit and explicit loops will therefore be considered separately.

2.8.1 Implicit Loops

Learning through implicit loop really depends on only one thing: the ability of the person to gather, process, understand and act upon feedback. All of this processing must happen during the normal performance of the worker's tasks.

There are two basic factors that affect a worker's ability to gather and use feedback efficiently. First, the worker must have the proper roles to allow him to actually act upon any feedback, and he must be encouraged to utilize these roles. Second, he must have the necessary skills to recognize and utilize the feedback. Here, the effect of roles and skills upon loop strength will be considered. Many of the issues regarding actually designing workers roles and skills will be dealt with in Chapter 3.

The effect of worker roles on the strength of an implicit loop is straightforward. If a worker is not given the freedom to make improvements, improvements will not be made. In the more extreme case, if a worker is punished for taking the time and resources necessary to make improvements, they will not make any improvements. In order for an implicit loop to be useful, workers must be given the incentives and opportunity to 'go the extra mile' and actually improve their system.

Understanding how skills affect implicit loop strength is more difficult. The level of skill required depends upon the level of technical complexity in the system. Because of the limited nature of implicit loops, organizational complexity is not as important an issue.

As a system becomes more technically complex, it becomes harder to understand what is going on. Consider, for example, the case where a mechanic who used to drill holes using spray dots as a guide now drills the same holes using a computer controlled laser pointer as a guide. In the first case, the worker might be able to recognize that the dots are in the wrong place. Because she is the one who positioned the template and sprayed the paint, she might have noticed that the locating surfaces on the template were bent out of position. The implicit learning loop – noticing that the dots were in the wrong place, making the connection to the templates and solving the problem by bending the template to its original position – is effective because the worker could understand how all the of steps in the process work.

In the second case, the same worker might have a greater problem understanding why the laser pointer that worked well for the last 100 units is suddenly not working properly. Say, for example, that one of the bearings in the laser positioning system was worn. Noticing this fact, and understanding its implications, is difficult unless one has the necessary skills. In this case, when the technology becomes more complex, a higher level of skill is needed. In order for implicit loop learning to remain effective when the a system's technical complexity increases, the skill level must also increase. Technical complexity and skill level must remain in balance.

Training and management innovation are the most effective ways to improve the strength of implicit learning loops. Training can be provided to aid in the learning process. In most company settings, such training involves a mix of operational training (learning how to operate different types of machinery, for example) and 'soft skills' training in areas such as teamwork and communication skills. This helps both skill and role development. However, training must be accompanied by management innovation. In particular, management must design and manage broader worker roles and provide an incentive structure that promotes learning. Most importantly, managers must become comfortable operating in an environment in which a certain level of complexity exists. What is simplest to manage may not be optimal for system performance.

2.8.2 Explicit Loops

Strengthening explicit loops involved many of the same actions as those required for implicit loops. However, there are some critical differences. When dealing with explicit loops, organizational complexity is extremely important. Technical complexity is also important, although a great deal of it can be reduced through techniques such as Design of Experiments.

When explicit loops are contained within a team, many of the observations made with implicit loops are exactly true, so long as the team is considered the work unit instead of the worker. The team as a whole must have the skills to identify and solve problems. Similarly, they must have roles broad enough to allow them to solve problems. They must be allowed to meet as a team, to conduct experiments and to brainstorm and implement solutions.

Once the explicit loops cross organizational boundaries, the situation changes. This is because the communication between organizational elements does not happen automatically. When communication does occur, it is often with some delay. Also, because the teams are not familiar with every aspect of the system, understanding the information from other teams is more difficult. In short, the organizational complexity increases.

A related problem also exists. In implicit loops, and in explicit loops contained within a team, both tacit and explicit knowledge is available to the problem solvers. However, once organizational boundaries are crossed, the presence of tacit knowledge is no longer automatic. Thus, greater effort needs to be spent in identifying the knowledge that is important to other teams, and in converting the tacit knowledge into explicit knowledge which can be transferred. This is, of course, an extremely difficult proposition. Indeed, it is one of the chief barriers to the success of many 'virtual' and 'agile' organizations, where there are many, quickly changing organizational boundaries and little time for system-wide learning.

The problem of knowledge creation and transfer is increasingly being recognized and discussed.[3] As this work becomes further developed, techniques for managing knowledge will be developed. However, one thing is clear from the current work. Knowledge sharing can only happen when management and workers both actively try to identify and manage knowledge. From the perspective of this work, that has a profound implication for systems with explicit loops. System knowledge must be fostered at all levels in the organizations. This means that people must be allowed to communicate directly, to visit each other and observe processes in action, and to take the risk of reducing their own performance for the sake of overall system performance.

In terms of training and worker roles, the implications are clear. In addition to the technical skill training that is necessary to reduce the technical complexity seen by workers, training in systems issues must also exist. Such training will reduce the organizational complexity seen by the workers, enabling faster and more efficient learning.

3. See, in particular, Nonaka and Takeuchi, [26].

Other techniques for reducing organizational complexity can further strengthen explicit loops. Some of these were mentioned above: using IT systems to facilitate information flows, and using techniques, such as structured correlations, to aid in information processing. Others include the creation and use of Integrated Product Teams (IPTs) and the implementation of performance metrics that make communication between organizations easier and more attractive.

It is worth noting that while both implicit and explicit loops can be improved, explicit learning loops tend to have more avenues and opportunities for learning associated with them. While implicit loop learning can typically be improved only through training, explicit loop learning can be improved by a myriad of techniques, including training. While additional training is often a good first step in improving learning in systems, once that avenue has been explored, most of the learning improvements will have to come through improved explicit loop learning. Because of this, the emphasis in the cases discussed in this thesis tends to be on improving explicit loop learning in systems.

2.9 Learning and Human Content

At this point, it is necessary to point out an assumption that runs through all of the arguments presented above. The assumption is that only people can learn. It may seem strange to focus upon this point. At the most basic level, it may seem to be an indisputable truth. Yet, as simple and obvious as the assumption is, it has led to a great deal of confusion in the world of learning and learning curves.

The confusion stems from the fact that the statement "only people can learn" has been translated in many circles as "processes which have the greatest amount of manual content have the fastest learning rate." This statement is central to many of the arguments surrounding learning and learning curves. Here, it is argued that it is flawed.

To see how it is flawed, the statements that are normally made about learning curves need to be examined. There is a notion widespread in the learning curve literature that the ratio of labor intensive activities to machine intensive activities is a good indicator of learning rates. When the ratio is high, learning is high, and vice versa. Machine intensive processes are said to not enjoy the same learning rates as labor intensive processes. Rules of the thumb include:

75% assembly labor, 25% machine labor => 80% learning rate
50% assembly labor, 50% machine labor => 85% learning rate
25% assembly labor, 75% machine labor => 90% learning rate[4]

This notion stems from the beginnings of the learning curve, and in many ways makes sense intuitively. Yet, it is not accurate. Adler and Clark [1], for example, have found no difference in learning rates inherent between capital and labor-intensive processes.

How can this discrepancy be explained? Why has the notion that there is a difference between capital intensive and manual processes been so widely accepted if it is not true? These questions can both be answered using the concepts of implicit and explicit learning.

All learning happens because the people involved in a process learn. In an implicit learning loop, learning occurs because the person is directly involved with all aspects of the process. Because of the nature of implicit learning, with its reliance on 'natural' learning, the more opportunity a person has to be exposed to the problem, the more they will learn from it. Therefore, as far as implicit learning

4. Belkaoui, [3], pg. 5.

is concerned, the more manual content in a task, the more leaning will happen. Labor-intensive processes, by definition, have greater manual content than capital-intensive ones. They will, therefore, have more learning through implicit loops.

Historically, most of the learning in manufacturing systems has been through implicit learning loops. Only fairly recently has the idea of work teams and structured problem solving by workers gained widespread acceptance in U.S. companies. Before that, workers tended to work on processes that were designed so that interactions with other processes were limited. Implicit learning was the only kind that could exist.

As we have seen, however, there are two types of learning: implicit loop and explicit loop. The latter has historically only seen a limited amount of use. Perhaps the greatest manifestation of explicit loop learning has been the process improvement/total quality movement. Standard process improvement techniques involve the creation of explicit loops, such as the Plan-Do-Check-Act cycle of Deming.

Now, while implicit loop learning works most effectively in situations where the manual content was the greatest, explicit loop learning is not bounded in this way. In fact, explicit loop learning often happens best in capital-intensive situations. The only constraint is that a person needs to be involved somewhere in the loop.

Consider the case of robotic assembly. Under the standard rules of learning curves, a robotic assembly station would be expected to have a very high learning rate, i.e., low learning. However, most robotic assembly systems involve people in some way. For example, position data is taken from the robot and fed, through a computer, to a quality control engineer. In addition, a machine vision system inspects the final product to ensure that the robotic assembly has worked correctly. This information is also passed to the quality engineer. Through the use of this explicit learning loop – the robot position data and machine vision data forming the links to the engineer – problems can be spotted and fixed. Suboptimal performance can be addressed, and performance enhanced through reprogramming of the control algorithms. Costs can be reduced and quality improved. In other words, the robotic assembly system can learn.

There is no reason why the learning which happens through explicit loops should happen at a higher learning rate than that which happens through implicit loops. Recall that there are two variables at play: the improvement per cycle, and the time to complete each cycle. Compared to implicit loops, explicit loops have a longer 'time to complete each cycle'. However, they can, and often do, have greater amounts of 'improvement per cycle'. This is because with explicit loops, problems can be better understood and more effective and innovative solutions devised. In the end, there is no clear advantage to either implicit or explicit learning loops. Each situation will be different.

Unlike implicit loops, which happen to some degree regardless of the amount of resources spent on it, explicit loops need attention. They must be designed and utilized effectively. The creation and use of explicit loops – for example, by starting a process improvement system based on Deming's work, or by providing sensor feedback from critical capital equipment – will allow capital-intensive systems to have learning rates comparable or even better learning rates than labor-intensive systems.

Chapter 3

Workforce Management

3.1 Using Workers to Gain Competitive Advantage

There is much discussion in the popular business press about the changing nature of business. A common link through all of these discussions is the general agreement that people ultimately provide a company with competitive advantage. In almost every industry, workers are gaining a greater stake in the success of their companies. They are gaining more responsibilities and more freedom to improve their work. This is a dramatic change from the situation that has existed since the introduction of mass production around the turn of the twentieth century, and certainly since World War II

This chapter describes some of the major changes in workforce management techniques that have occurred in the last 100 years. These changes are described to give the reader an understanding of some of the advantages and disadvantages of different workforce management systems, as well as to provide an indication of the historical trends. Issues involved with designing an efficient system are then discussed, with a focus upon understanding the importance of worker roles and skill levels. This understanding of roles and skills will then be used to aid in the development of manufacturing teams. Lastly, the links between process improvement and workforce management techniques are discussed.

3.2 The Changing Roles of Workers

For most of history, products were produced by skilled craftsmen, working alone or in small groups. A highly skilled blacksmith would forge iron into useful products; talented and skilled weavers would make cloth; skilled 'fitters' would file and form parts until they all fit together.

This changed with the advent of mass production. The key to mass production is not, as most people believe, the moving assembly line. Even more fundamental is the ability to produce interchangeable parts. By making parts so that they fit together the first time, the skilled fitters alluded to above could be eliminated. Instead, only workers with very limited skill sets were needed. Only after interchangeable parts became possible did the assembly line become practical. The assembly line built on the changes produced by the production of interchangeable parts by allowing further deskilling of the direct production workforce. Production workers no longer needed to understand the whole process of building a car. They only needed to have an understanding of their small part of the process. Frederick Taylor pursued this work model to the limit. Jobs were broken down as much as possible, until workers were performing only simple, repetitive tasks. [33] [43]

The changes introduced by Ford and Taylor quickly spread into other industries. By World War II, mass production was the normal mode of production for most major world industries. In the aftermath of the War, however, this slowly began to change. Faced with the task of completely rebuilding their industrial base, but lacking the resources with which to effectively do so, Japanese companies, led by Toyota, began to change their model of production. The end result was lean production.

Lean production is a system based on the Toyota Production System.[1] The central aspect of lean production is the elimination of waste. Inventory buffers are

1. A detailed description of lean production and the differences between it and mass production can be found in [43].

eliminated as much as possible, replaced with the Just-In-Time (JIT) inventory system. Workers are organized in multi-skilled teams and allowed to fix problems as they arise. They are encouraged to continuously find ways to improve their processes. Through these and other policies, lean production allows waste to be eliminated, costs to be reduced and quality to be improved.

Lean production was an important factor in the success of Japanese companies competing in the U.S. market. In response to this new challenge, U.S. companies have begun to adopt lean practices, and to create new paradigms such as 'agile' practices and 'mass customization'.

One of the largest components of both the mass and the lean production systems is in the way in which they manage and utilize their workers. There is, however, no inherent need for the two systems to employ different workforce management philosophies. Indeed, the philosophy used in lean production was spelled out by Douglas MacGregor as early as the 1960's as a way to manage mass production. MacGregor described two theories of workforce management, Theory Y and Theory X. [24]

3.3 Theory Y vs. Theory X

Theory X was the name given to traditional, Taylorist forms of worker management. The underlying assumptions of Theory X are:

1. Most people dislike work, and will avoid it whenever possible.

2. People must therefore be coerced, controlled and closely supervised if management objectives are to be achieved.

3. "Further, most people prefer to be controlled and directed, wish to avoid responsibility, have relatively little ambition, want security above all." [2]

The assumptions of Theory X lead to some natural conclusions about work-force management. It leads to organizational structures where each level of worker is watched and supervised by the level above them. Such an environment is often confrontational and is, in many ways, self-fulfilling: if people are treated in a manner consistent with these objectives, the result is often that they do not perform as efficiently as possible, and they are not motivated to improve their performance. As a result, the outcome of a Theory X environment is often the belief that removing workers completely is the best solution, leading to large investments in automation. Note, however, that the promises of automation have not been fulfilled. In the auto industry, for example, plants with less automation are often more productive and produce higher quality goods than other, more automated plants.

In contrast to this, consider the assumptions and implications of Theory Y:

1. "The expenditure of physical and mental effort in work is as natural as play or rest.

2. "External control and punishment are not the only means for bringing about effort towards organizational objectives. Man will exercise self-direction and self-control in the service of objectives to which he is committed.

3. "Commitment to objectives is a function of the rewards associated with their achievement.

4. "The average human being learns, under proper conditions, not only to accept but to seek responsibility.

5. "The capacity to exercise a relatively high degree of imagination, ingenuity

2. [24], pg. 33-34.

and creativity in the solution of organizational problems is widely, not narrowly, distributed to the population.

6. "Under the conditions of modern industrial life, the intellectual potentialities of the average human being are only partially utilized."[3]

Theory Y represents a set of beliefs that have only recently been accepted by the general U.S. business community. Although some companies used these principles in throughout the 1960's and 70's, it is only recently that they have achieved widespread attention in the U.S. In the early 1980's, People Express was founded in part on these beliefs, and was one of the first companies in the U.S. to eliminate hierarchies as much as possible, and to make employees partial owners in the venture. [40] Much earlier, in the 1950's and 60's, a form of Theory Y was practiced by many Japanese companies, who used its principles in its lean production systems.

The system developed under lean production is not the only way to implement Theory Y. Several attempts were made in the 1960's and 70's to employ 'socio-technical work systems' and other 'quality of work-life' programs. [35] What both of these worker management methods have in common is the use of teams to expand the roles and responsibilities of workers.

Roles and responsibilities are critical notions when thinking about workforce management. Each of the innovations described in the above discussion involved some changes in worker roles – how they worked (in teams or individually), the scope of their work (individual stages or multiple broad tasks), and the breadth of their work (administrative and improvement activities in which they are expected

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3. [24], pg. 47-48.

to participate). Theory X tends to argue for extremely limited roles, while Theory Y argues for more expanded roles.

3.4 Skills

A description of desired worker roles does not provide a complete description of the workforce. To complete the picture, an understanding of the skills the workforce has is necessary.

For the purposes of discussion, it is useful to differentiate skills into two broad categories. Here, these categories are called micro- and macro-skills:

- Micro-skills

These are operational and analytic skills uses to directly complete the tasks assigned to a worker. Included in this category are skills such as drilling holes, using a spreadsheet, operating a lathe, and loading a fixture. Such skills tend to be used often and to be the subject of training and skill level certification courses. In addition, as noted in Chapter 2, it is improvements in this type of skill area that account for the majority of the implicit loop, 'learning by doing' phenomenon.

- Macro-skills

This category consists of more intangible skills that are not directly associated with any particular task or function. These skills are conceptual in nature, and often involve an understanding of the ways in which several distinct elements come together. They are often referred to as 'systems thinking' or 'integration' skills. [28] [20] However, these descriptions do not capture the full description of macro-skills, which also include human relations and team building skills.

Multi-skilling, as it is usually practiced in lean production, normally involves giving a person a wide set of process specific, micro-skills. A result of multi-skilling, however, is to encourage the development of some macro-skills. As a person is exposed to more steps in their group's process, they increasingly gain the ability to relate these steps to each other. Even in this setting, macro-skills are typically difficult to learn. This is due to the fact that the complexity of the environment in which these skills are used is much greater than that for micro-skills, where feedback is direct and quickly processed.

3.5 The Model of Competence

Roles and skills are independent, but they should not be considered as such. In order for workers to be the most productive, an optimal combination of roles and skills is needed. A skilled engineer should not be confined into the role of a lab technician. Similarly, effective multi-skilled workers need broader roles than those with narrow skill sets.

To understand the necessary mix, the model of competence is useful. [17] As the name suggests, competence is an indication of the ability of a worker to perform the necessary assigned tasks. It is a function of both roles and skills. The ideal situation is to have people who are competent at performing their assigned or chosen tasks. They should be neither overskilled or underskilled for their roles.

Figure 3.1 shows how competence is built for individuals in different work models. The meanings of the axes of this graph are important. Functional Tasks refers to the breadth of different tasks and assignments that a person is expected to perform. It is an indication of the amount of macro-skills (integration skills in particular) needed, as well as the scope of the roles. Depth of Expertise refers to the level of operational and analytic knowledge (micro-skills) required to perform particular jobs. Managerial/Administrative Activities indicates the degree of responsibility a person has to manage communication and information flows, and to plan and manage their production and improvement activities. These activities contain a combination of macro and micro-skills.[4]

Each model presents a different combination of roles and skills. The lean model uses teams with multi-skilled members. As shown in the figure, this means that people in the lean model need a high degree of knowledge of the functional tasks involved in their system. They also need some detailed expertise. In contrast, in the craft model, people who are highly trained in particular jobs are used.

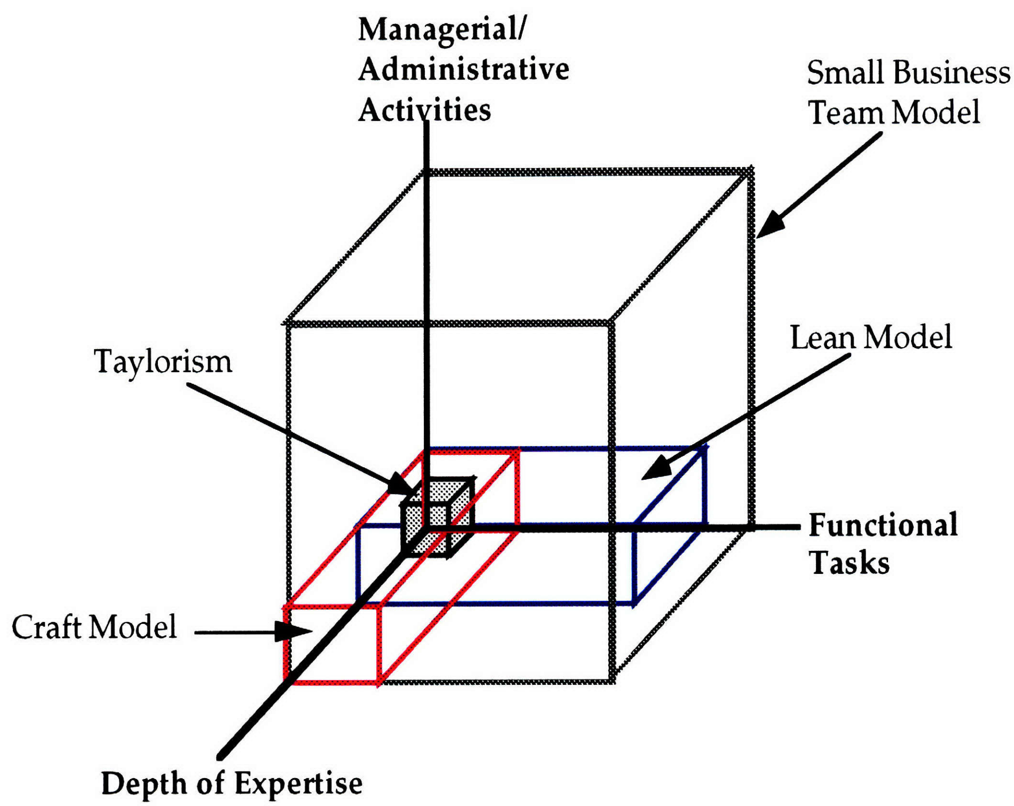


Figure 3.1: Work Models, Shown as a Combination of Roles and Skills. [20]

4. For a description of the meanings of the various axes, please refer to Klein [20].

Such people need little knowledge of the functional tasks involved in producing a complete product. They do, however, need to have a great deal of skill in their particular job. In Taylorism, workers are deskilled as much as possible by reducing their role in the system to the greatest possible degree. A fourth model, described by Klein [20], is the small business team model. In this model, teams are constructed so that they function as relatively autonomous groups, possessing the depth of expertise not found in the lean model, the awareness of functional tasks possessed by teams in the lean model, and the ability to perform the managerial and administrative tasks necessary for the group to operate.

3.6 Building Teams

No matter which of the models is chosen, no person operates alone in a complex manufacturing system. Every person works with others, either as a collection of individuals performing their tasks, or as members of a team. The idea of competence does not only apply to individual workers. It also applies to teams. Teams are assigned a particular role, and they must be given the right combination of skills to perform these roles. Team must be competent at performing their tasks.

In building an appropriate, competent team, roles and skills must be considered in light of best practices, union rules, incentive systems, existing structures, and company capabilities, strategies and policies. Using the representation shown in Figure 3.1 provides some insights into the strengths and weaknesses of any team. The roles and skills of each of the team members should be drawn on one graph. Once this has been done, the graph can be examined to discern the roles and skills that are present in the team. This information can be compared to the desired state, and any needed changes made.

Understanding the considerations that are important when building teams will be useful when the Precision Assembly case is discussed in Chapter 6. Using a mental picture of Figure 3.1, conclusions about how roles and skills should be designed, and what training is necessary, can be deduced.

3.7 Continuous Process Improvement

One of the greatest innovations in workforce management has been the rise of improvement programs. These programs typically involve workers identifying problems and improving the processes on which they work. Changing from an environment in which this participation was neither sought nor offered to one in which it is a critical part of the job is a difficult transition for many workers and organizations. Several elements are necessary in any successful transition effort. All of the workers must believe in and understand the reasons behind the new programs. They must see commitment from management and believe that the new programs are not just another management fad that will soon pass. Appropriate performance measures and incentives, perhaps based on a "Balanced Scorecard" methodology, must be put into place. [18][19] Time must be set aside to ensure that improvement does not fall victim to schedule pressure.[5]

Since the early 1980's, U. S. companies have adopted methodologies created by Deming and others to improve their processes. These methodologies include risk and root cause analysis, statistical process control, the Deming Plan-Do-Check-Act cycle and Taguchi Design of Experiments. These tools all aid in the identification and solution of problems or possible improvements. However, in many cases, the continuing usefulness of these tools is questionable, and probably

5. Many of the issues involved in the dynamics of improvement programs are discussed in detail by Sterman et al. [31]

declining. Two examples are that of Statistical Process Control (SPC) and Root Cause Analysis using Ishikawa Fishbone Diagrams. The very success of standard SPC tools is what makes it of diminishing value. At first, SPC implementation and use is carefully thought out. However, as it becomes more successful at solving particular problems, it tends to be implemented on a larger scale. Eventually, it gets to the point where more data is taken than is either useful or possible to analyze through traditional techniques. The focus that existed in the beginning is lost.

A similar situation exists with root cause analysis. Ishikawa diagrams are useful for identifying a certain set of problems, specifically those in which the problem arises from discrete parts or simple actions. However, as the Ishikawa approach becomes more successful, people and organizations typically tend to assume that the only problems that can exist are those that are captured in these diagrams. Thus, a particular focus and philosophy becomes ingrained into the organization, hampering efforts to solve different types of problems. The dynamic here is similar to that of Core Competencies turning into Core Rigidities, as described by Leonard-Barton [23].

Chapter 4

Tools and Methodologies

4.1 Characterizing A System

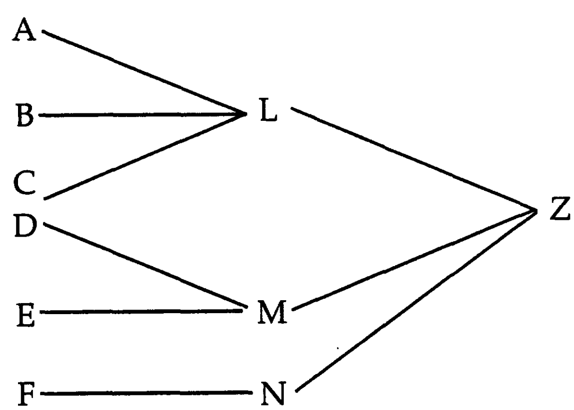
Manufacturing systems, and indeed, most business systems, are very complex entities. They have been built up over years (in some cases, decades), and preserve remnants of past organizations and decisions. In order to begin improving such systems, tools and methodologies to aid in understanding the system are needed. These techniques will help the observer to understand the key elements at work, and to characterize the essential essence of the system.

The starting point in understanding any system is to draw boundaries around it. Here, the boundaries of the supply chain for a particular product is taken as the system boundaries. The supply chain was chosen to allow all of the technical elements contributing to a product to be included. Included in this representation are suppliers, designers and manufacturers; not included are separate finance and marketing organizations, or the final customer.

The aim of this chapter is to present tools that can be used to describe the technical elements of a manufacturing system. In the chapters which follow, these tools will be linked with organizational concepts which have already been discussed to provide a coherent and consistent framework for a complete organizational-technical analysis. All of these tools are structured around the concept of the supply chain or, more accurately, the product development web.

4.2 Understanding a Supply Chain

Most manufacturers spend a great deal of time and energy thinking about and managing their supply chain. For many simple products and services, the supply chain can be thought of as a 'tree' process. Parts start out from several different places, and gradually come together. However, this image is not an accurate representation of the supply chain for complex products. In general, as a product gets more complex, so does its supply chain. For most complex products, the linear 'tree' image breaks down. Such products are developed and manufactured over a network, or web, involving many complex systems and structures. The web, illustrated in Figure 4.2, describes the physical and information flows necessary to develop and produce a product.



SUPPLIERS SUBASSEMBLY FINAL PRODUCT

Figure 4.1: A 'Tree' Representation of a Supply Chain

Every complex product is designed and produced within a web similar to that shown in Figure 4.2. A firm's ability to proactively manage this web is critical to its success. Failure to coordinate tooling, part and assembly suppliers will inevitably result in wasted resources, higher costs and a lower quality product. Unfortunately, the complexity of most product development webs makes this management task very difficult.

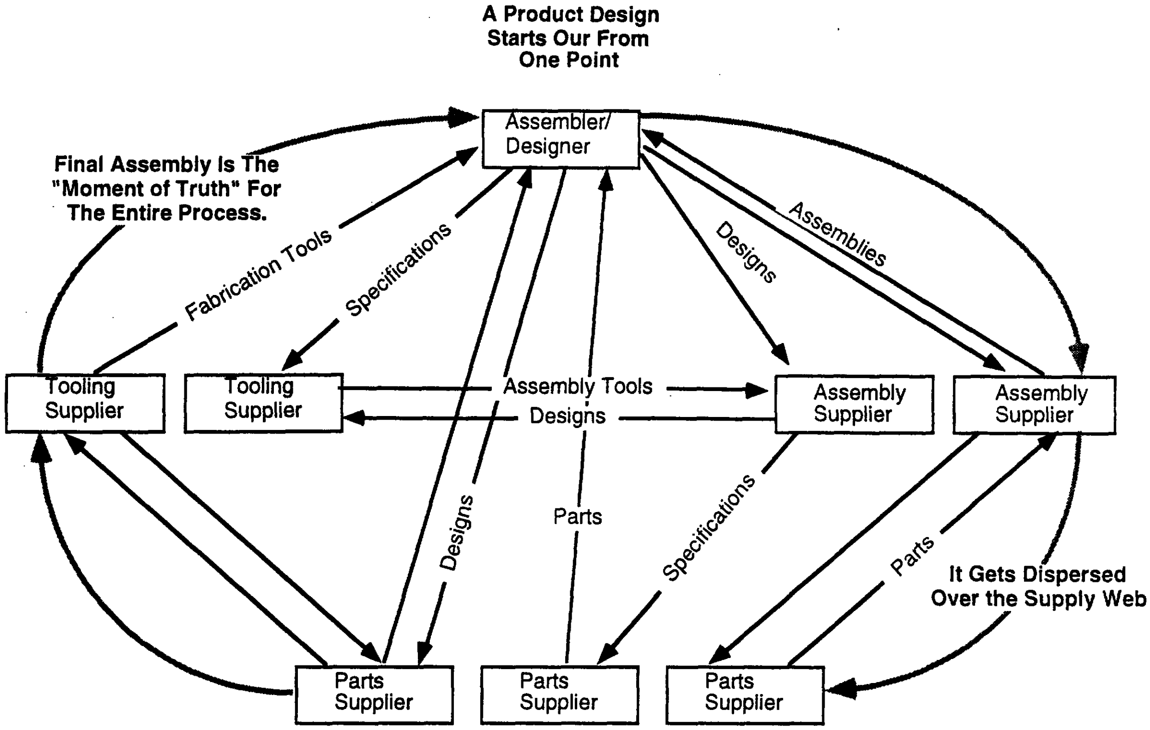


Figure 4.2: Product Development Web Map (Source: Dr. Daniel Whitney) [11].

Compounding this problem is the fact that complexity does not stop with this single web. The product development web is similar to a fractal in nature – it holds at a very macro, industry level, and appears whenever you examine each element more closely. For example, the web gives a good overview of the product development and manufacturing processes of a large company such as Boeing. Additional levels of complexity can be seen as the level of detail is increased. Similar web pattern can be found at each of the other elements, describing a supplier's own supply network or their internal manufacturing operations. Consider, for example, the case of Northrop Grumman, a major Boeing supplier. In addition to using tools and designs provided by Boeing, Northrop Grumman has its own tooling, parts and raw material suppliers, as well as some design capability.

Going to an even greater level of detail, to one of Northrop Grumman's parts supplier, will result in a repeat of the same general pattern. In addition, each manufacturing plant in the network, and each team on every manufacturing floor, has a complex supply and communications web associated with it.

The fractal nature of the web is important because it means that an analysis that works at one level has a good probability of working at another. Most of the tools described in this chapter fall into this category. They can be used to analyze the web at a very high level, or to focus in on one particular process that makes up an element of the web.

Understanding and managing the web at any of these levels is a challenging task. For good decisions to be made, two key elements must be described and understood- the structure and semantics of the system. The structure is the 'what' of the system. It consists of the elements of the system and their interconnections. Often, the structure of a system is depicted in terms of a graph (as used in network theory) or a causal loop diagram, as shown in Figure 4.3. [32]

Knowing the structure of a system is not enough to completely characterize it. It only provides information on what elements are in the system and how they interact. Two systems that are identical in structure might behave in very different ways. To gain a complete picture, the semantics of the system – the 'how and why' – must also be understood. The semantics are normally represented as a set of relationships linking the various elements. They describe how and why the interconnections affect the various elements.

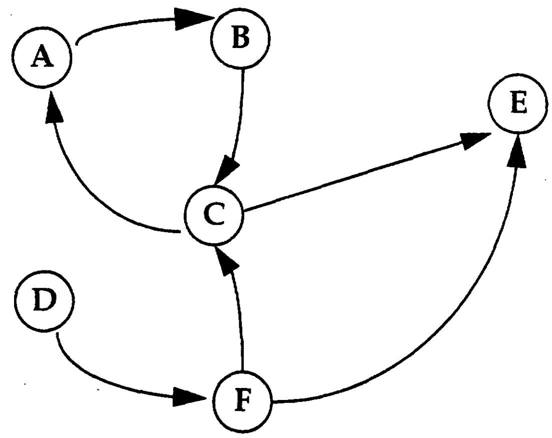


Figure 4.3: System Structure, as represented by a Graph.

4.3 Key Characteristics

The first part of identifying the structure of a system is to identify the elements involved in the system. For a mechanical product, this translates into identifying the parts, subassemblies and features that comprise the product. In software, the elements might be the various software modules and libraries that are brought together when the program is compiled.

Complex products, such as automobiles, aircraft or laser printers, consist of a large number of different parts, and have a great variety of features. Some of these are needed to provide the proper functionality or appearance; others are needed in order to be able to fabricate and assemble the product. Identifying which of these features are the most important to the product's success is critical if resources are to be well allocated.

The method of Key Characteristics allows these features to be identified. Key Characteristics (KC's) are the features that most significantly affect the performance, function and form of a product. For the purposes of this discussion, it is useful to identify three type of KC's:[1]

- **Product Key Characteristics (PKC's):** PKC's are the set of geometric and kinematic features and material properties that most significantly affect the ability of a product to meet customer, regulatory and safety requirements.

- **Manufacturing Key Characteristics (MKC's):** MKC's are the features or manufacturing process parameters that most significantly affect the fabrication of the product's components. MKC's can be associated directly with the product, or with the machine tools and fixtures used to fabricate the product's components.

- **Assembly Key Characteristics (AKC's):** AKC's are features on the tools, fixtures or product that most significantly affect the outcome of an assembly process.

The above list is by no means meant to be exhaustive. For some problems, it may be useful to define additional types of KC's, such as Business KC's (BKC's), which can help identify time, cost or other issues that are not considered in the above categories. BKC's are beyond the scope of this discussion, and may be the topic for further research. Here, only the three types of KC's defined above are considered.

1. These distinctions and definitions are due largely to the work done by Don Lee and others on the MIT Fast and Flexible Manufacturing Program. For a more complete discussion of Key Characteristics, see [21].

The advantage in using Key Characteristics is that they provide a focus. In a product where there may be thousands of different features, parts and parameters, this focus is invaluable. By knowing which of the features is important, technical and managerial organizations can focus on maintaining and improving their ability to produce them. Effort is not expended in areas where it will do little good.

4.4 Contact Chains

Key Characteristics provide some of the information necessary to understand the structure of a system. Using Key Characteristics, the important elements of a system and some of their interconnections can be understood. However, more information is needed before a complete description of a system is possible. The semantics of the system then need to be described. Contact Chains help in both areas.

Contact chains show how various elements of a product come together to achieve the KC's. Several types of information are provided by Contact Chains, including:

- The critical interfaces, features and tools for a given process
- The organizations which contribute to the process.
- The links that cross organizational boundaries.
- The activities that contribute to the cost of the process.

The following chapters contain examples of Contact Chains. A example contact chain is shown in Figure 4.4. In this figure, the KC is the angle between the centerlines of the Plus Chord and the Aft Skin. These two parts are both located to the assembly fixture by their edges; the angle is set once the parts have been located properly. Further contact chain examples can be found in [6].

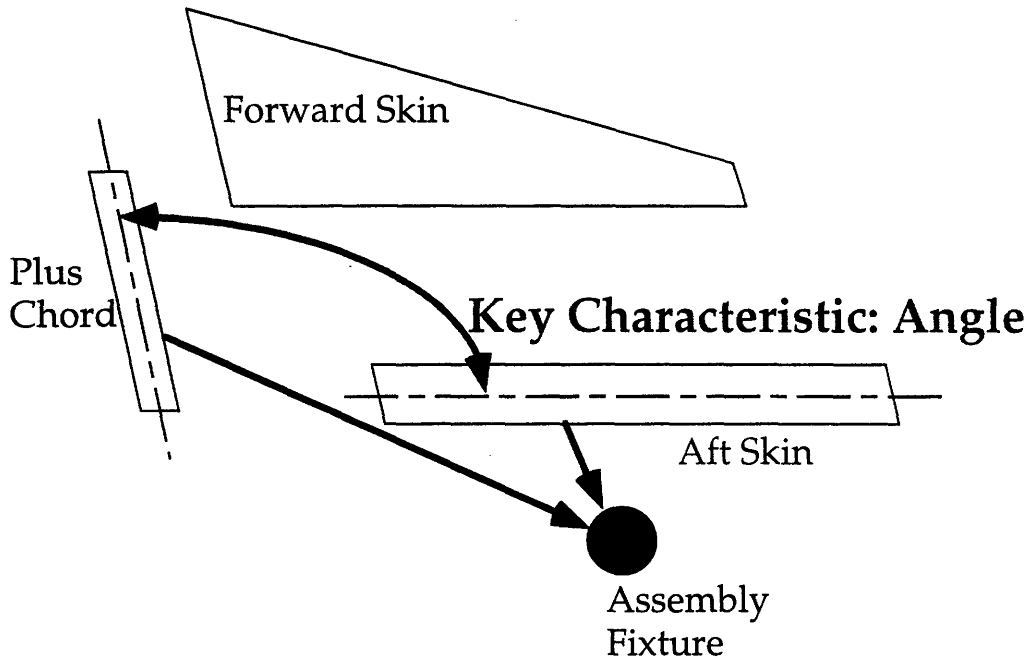


Figure 4.4: Contact Chain showing how the angle KC is achieved.

Contact Chains are fixed once the product architecture, assembly process and assembly sequences are decided. Like Key Characteristics, they are important tools in that they provide a simple and convenient way to communicate essential information about a product or process. Both tools help people to focus on the important aspects of a system. This information is useful in several ways. Essential engineering information is contained within the Contact Chain. However, the power of the Contact Chain is in its ability to simultaneously provide organizational, cost and technical information, and to show how this different information is related.

A second reason why the Contact Chain is an extremely important tool is that it focuses on systems and processes. Many of the existing engineering tools focus on discrete elements. They do not provide any information on how the elements relate to each other. Consider some of the tools used to solve problems in manufacturing and design. For example, Ishikawa diagrams are often used to identify the potential causes of a problem. However, a completed Ishikawa diagram is merely an organized list of the elements of the system and the ways in which variation might occur within these elements. It provides some value, but is lacking some important aspects. There is no sense of how the elements are connected to each other or how problems in one or a group of elements might ripple through the system. There is no sense of which variations are more likely or which elements are more important. In short, there is no focus or systems view. Contact Chains help fill the void left by such tools.

4.5 The Design Structure Matrix

One way to represent a system structure is to use a graph, as discussed above. Another is to use the Design Structure Matrix (DSM), developed by Steward [32]. DSMs are matrices that show how various tasks or elements in a system are connected to each other. They have been used in a variety of ways, some of which are described below.

4.5.1Design Structure Matrix as a Project Management Tool

One of the areas in which the DSM is used is project management. [10] In any complex project, such as a product development effort, there are tasks which can only be completed when information obtained from another task is known. For example, certain design parameters can only be set after tests on prototypes have been run. When needed information is not available, preliminary assumptions are made which are then revised as the information gaps are filled.

This dynamic is the cause of a great deal of project iteration and rework. If there is a large time delay between when the information is available and when it is needed, many of the tasks completed in the interim must be reworked to reflect the more accurate information. This consumes valuable resources, and greatly slows down the project.

In Figure 4.5, a DSM is shown. Two loops are explicitly illustrated on this figure. There is a feed-forward loop connecting task B and task C. This loop is indicated by the presence of a marker (X) in row C column B. This marker indicates that task C requires information from task B.

In addition, there is a feedback loop connecting task H and task A. The marker for this loop is in the upper triangular region of the matrix, at row A column H. Because H is performed after A, this loop indicates that some iteration is required. As task A can only be completed after task H has been completed, an estimate must first be made at task A. Tasks B through H are then performed, at which time A is revised again using the updated information from H. This needs to continue until a stable solution for A is achieved. The presence and length of the feedback loop introduces significant delay to the system, and consumes valuable resources.

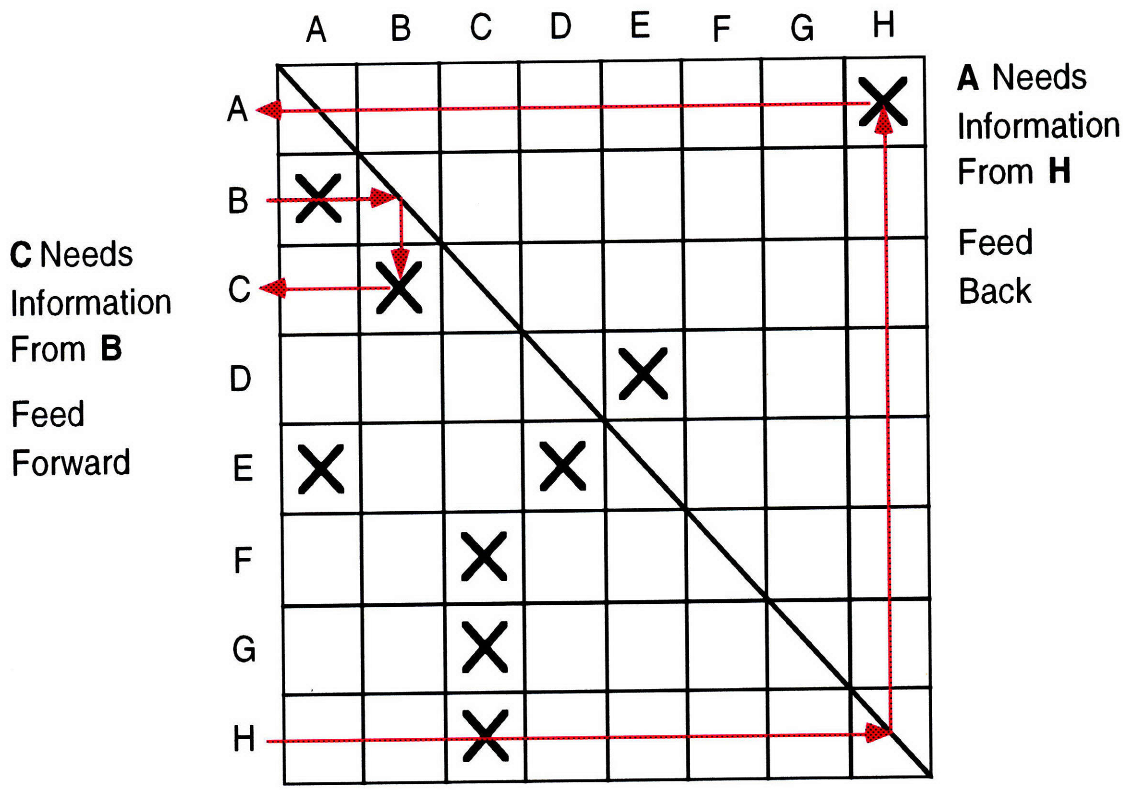


Figure 4.5: Design Structure Matrix (Source: Whitney et. al. [42])

Once the tasks and their interdependencies are documented in a DSM, the system can be understood and optimized. This is done by rearranging the tasks to minimize the number and length of iterations necessary to complete the project. Ideally, the length of any feedback loops would be minimized. Seen visually on a DSM, this would mean that the tasks would be reorganized so that any communications markers (X) in the upper triangular region of the matrix lie as close to the diagonal as possible.

By designing the system instead of accepting the system that already exists, great improvements in project completion time can be made. In a product development setting, this translates into shorter product development cycles and lower development costs.

4.5.2The Part Interactions Matrix

Another use of the DSM is as a Part Interactions Matrix. [27] In this case, the DSM is used to document the interactions between various elements in a product. The goal is similar to that in the project management case. Whenever two parts interact, communications and design iterations are necessary. This leads to slow development times and wasted resources.

By explicitly understanding and documenting the interactions between different parts, this problem can be alleviated. Rearranging the matrix often yields configurations with large clusters of interactions. Teams can be created to work on tasks that make up these clusters. These teams are often different from those that would have existed based solely on functional groups within the company. By organizing teams around interactions, much of the communications and iterations delays in the system are reduced, yielding much faster product development cycles and lower costs.

4.6 Process Interactions Matrix

An extension of the Part Interactions Matrix, called the Process Interactions Matrix (PIM), has been developed in this research to document the structure of manufacturing systems. In a PIM, the steps of a manufacturing process, along with their interactions, are recorded. An interaction occurs whenever what happens in a given step affects another step in the past or future. For example, if a part that was put into place in one step has to be slightly moved for another part to be added, an interaction would be noted. Similarly, if the location of a part, B, is set by the location of another part, A, the step at which the part B is located is connected to the step at which part A is located. Any error in locating A will necessarily result in an error in B's location.

The general principles of the PIM are similar to those for the DSMs described in Sections 4.5.1 and 4.5.2. There is, however, one important difference. While the order of tasks in a product development process or the members of teams can be changed quite easily, changing the order of tasks in a manufacturing process is much more difficult. In an assembly process, for example, the sequence is set by other factors such as precedence relations, tolerance propagation consideration, and physical proximity of the equipment and parts.

Given this constraint, the PIM cannot be used alone to optimize manufacturing processes. Instead, the value of the PIM derives from its ability to convey important information about the technical and organizational aspects of manufacturing systems. While the technical system cannot be optimized, many operational aspects can.

4.6.1 Reading a Process Interactions Matrix

Figure 4.6 shows an example of a PIM for a general manufacturing system. Each row of the matrix is assigned a particular step in the manufacturing process, as is each column. First, the rows and columns are grouped by organization. In the figure, they separated into fabrication and assembly groups. In a detailed

PIM, these groups would be broken down further into particular processes and subassemblies. The rows and columns are then arranged so that the process steps are in the sequence in which they occur within each particular process. Once arranged, the diagonal should represent the cells of the matrix where the steps on the rows and columns are the same.

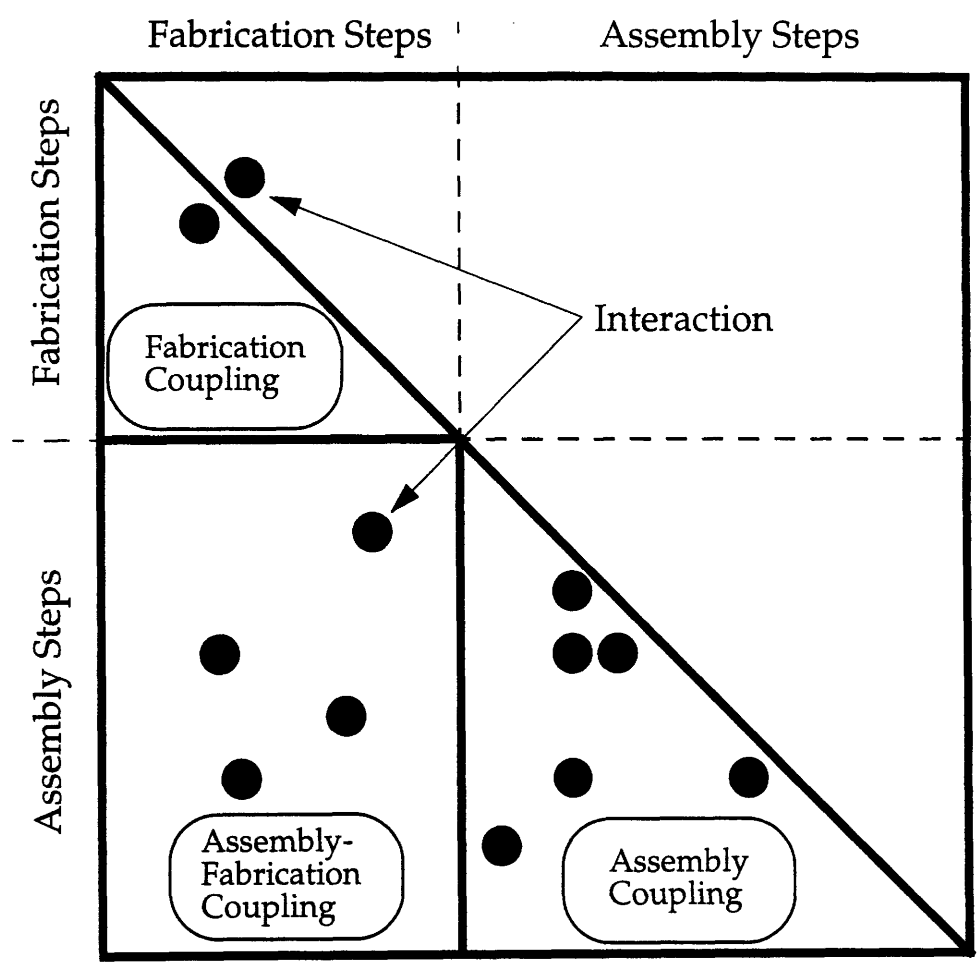


Figure 4.6: An Example of a Process Interactions Matrix

Interactions between different steps can be noted once the basic matrix structure is complete. Interactions are those events that affect the outcome of a particular step. A particular step, Y, might affect the outcome of another step, Z, but the reverse might not be true. When an interaction occurs, it is noted on the matrix; in the figure, the circles represent the interactions. Each column represents a possible interaction, whereas each row represents the step of interest. For example, if there is an interaction in row j, column i, this means that step i interacts with step j, i.e., i affects the outcome of step j. By looking down a particular column, one can tell how much a particular step interacts with other steps. Looking along a row shows which and how many other steps affect the step assigned to that row.

Because of the nature of the interactions, the matrix is normally not symmetric. In fact, if the steps are arranged in strict chronological order, it is likely that there will be few, if any, interactions in the upper triangular region.

The figure is divided into three main regions. Each of these regions represents a different type of interaction block. Whereas the term 'interactions' is used here to represent the linkages between individual steps, 'coupling' is used to denote types of possible interactions. The 'assembly coupling' region, for example, shows the area of the figure in which assembly steps might interact with each other. Similarly, 'assembly-fabrication coupling' denotes the region where assembly steps might interact with steps in the fabrication process.

4.6.2 Creating a Process Interactions Matrix

Process Interactions Matrices combine three types of information – process sequences, 'physical' interactions from a contact chain, and 'service' interactions from organizational maps. The process of constructing a PIM involves several stages:

1. Identify the organizations which contribute to the manufacturing process, including internal and external suppliers and maintenance, engineering and other support elements.

2. Document the tasks through which the product is produced. The tasks should be grouped by the organization responsible for them, and should be recorded in the order in which they are completed.

3. Understand the Key Characteristics and create the Contact Chains for the system. Use this information to understand how the steps in the process interact. Further review the system, talking to indirect and direct workers, to gain a more complete understanding of the interactions. If a process does not yet exist, imagine the process in operation.

4. Understand the interactions. This is the step at which the semantics of the system become completely defined. It may or may not be necessary, depending on the goals of the user. Further details on this step are presented in Section 4.6.7.

Once a PIM is constructed, a great deal can be learned about the technical and organizational aspects of the manufacturing system. The uses of the PIM are described in the sections below.

4.6.3 Communications Flows

The most direct use of the PIM is in understanding the communications flows that must occur within a system in order for it to operate efficiently. As noted in Chapter 2, all learning in any system occurs as a result of feedback. Interactions represent potentially valuable feedback channels. The ability of an interaction to stimulate learning is determined by the speed with which relevant information is conveyed.

Whenever an interaction occurs within a team boundary, learning can occur at a rapid pace. The feedback is immediately available. However, when the interactions transcend organizational boundaries, learning is much more difficult. In these cases, an organizational (communications) infrastructure must exist. The purpose of this infrastructure is to reduce communications delays, providing timely feedback to allow learning, and therefore process improvements, to occur.

Of course, not all interactions are equal. Just as in any process improvement activity, the processes which will have the highest impact should be improved first. Identifying the important interactions is a matter of understanding the structure and semantics of the system. Interactions which fall within a KC Realization chain (i.e., the set of steps that affect the step at which a KC is realized) have a greater effect on the outcome of the manufacturing process than those that are not. Interactions in the KC Realization Chain represent higher leverage areas for improvement activities.[2]

2. The KC Realization Chain is, in many cases, identical to the Contact Chain. However, there are cases when factors not normally accounted for in a Contact Chain, e.g., maintenance, are found in the KC Realization Chain.

4.6.4 Process Architecture

Products are often categorized by their architecture. They are described as being either modular or integral. A modular product is one in which parts have minimal interactions with each other. All interactions occur through standard interfaces. In a modular product, individual parts or subsystems can perform their functions independently of each other. Conversely, an integral product is one in which several or all of the parts share functions. The success of the product depends upon the performance of the system as a whole. [37]

Process architecture is a concept similar to product architecture. Processes can be categorized as modular or integral. A modular process is one in which there are few interactions between the process steps. Of course, there are different shades of modularity. No process is ever completely modular, and few processes are completely integral. Nevertheless, the distinction is a useful one when thinking about processes.

Both types of processes present opportunities for learning. However, in a modular process, the learning is limited to each individual step. In an integral process, on the other hand, learning happens on several different levels. As in the modular case, there is learning at the individual step level. Unlike the modular case, learning in an integral process is also possible at an organizational level. At this level, a deeper understanding of the system is gained, resulting in increased opportunities for learning. The amount of learning that actually occurs is a function of several variables, including the time it takes for information to travel from one organization to the other, the roles of the work teams, the skill level of the team members, and the clarity of the relevant chains.

4.6.5 Defining Worker Roles

Process architecture has a number of other consequences throughout a manufacturing system. One area in which it is particularly important is work design. For the most part, work teams have been created without analyzing the detailed technical requirements of the system.[3] However, an understanding of the technical requirements is critical if the team boundaries are to be drawn correctly. The PIM and process architecture framework described here allow us to easily incorporate technical considerations into the design of work teams. The learning issues presented above provide a guide for work team design. In order to have the maximum amount of learning in a manufacturing system, communication times should be minimized. This is best accomplished by making a small team responsible for all of the processes that interact with each other. That is, clusters of interactions should be internalized within a work team whenever possible, much as design teams were created based on interactions in the Part Interactions Matrix. [35]

There are, of course, constraints upon worker roles imposed by the physical location of equipment and organizations. Trade-offs must be made between learning efficiency and operational efficiency. If this were not done, the time and money saved through increased learning would surely be spent in travel time! However, just as worker roles would not be defined without thinking about the proximity issues, they should not be designed without some attention to learning opportunities.

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3. A notable exception is the socio-technical work design system, described in Trist [35].

The other effect of process architecture in workforce management is in the identification of worker skills. As mentioned in Chapter 3, competency is a function of both roles and skills. As we define the role of a worker, we also define the skills that worker needs to be competent at their job. In general, the more integral a process, the greater the level of macro-skills needed to effectively perform the job. The more feedback loops that are present, the more a worker needs to be able to think about the system as a whole. The worker also needs greater communications skills in order to be able to operate in the complex organizational infrastructure. Micro-skill requirements are generally the same as in the modular case – they are defined by the specific tasks (e.g., drilling, riveting, placement, programming) and do not depend to a great extent on the interconnections.

4.6.6 Make-Buy Decisions and Supply Chain Management

The discussion of work team design naturally leads into another, broader topic, that of supply chain design and management. Like product architecture, process architecture is important when making make-buy decisions. As the case study on the C-17 Nacelle will show, learning across organizational boundaries is difficult. Most organizations do not do it well, even when the organizational boundaries lie within the same building. An integral process should therefore give some pause to the make-buy decision maker. If one or more organizational boundaries cut through an integral process, the ability of a company to learn could be greatly hurt. To minimize this risk in such situations, a well-managed communications infrastructure and well trained personnel are needed.

4.6.7Human Content of Work

The concept of the Process Interactions Matrix can be extended further, to include more detailed information about the way in which the process works. Of particular interest here is the use of the PIM to capture information about the amount of human content in the process.

It has been noted several times in this thesis that learning occurs through feedback. A point that was implicit in that discussion is that, for feedback to be useful, it has to be processed, understood and acted upon. In terms of modern technology, this means that humans must be involved in the feedback processes. They must either be directly involved through manual labor, or indirectly involved through the reading and analysis of data on a computer screen or print-out.

The interactions that are documented in the basic PIM do not provide a complete description of feedback opportunities. To gain the complete picture, the interactions must be differentiated. There are four dominant forms of interactions in manufacturing systems:

1. **Worker-to-Worker (or Organization-to-Organization)**: This type of interaction occurs whenever two organizations interact directly. Examples of this might be transportation of parts from one location and group to the another, or the interaction of a maintenance team with a production team.

2. **Part-to-Part**: These interactions occur whenever one part directly affects another. They are almost always accompanied by a part-tooling or part-worker interaction. Tolerance propagation and parts which are located using features on other parts are examples of part-to-part interactions.

3. **Part-to-Tooling:** Interactions of this nature occur when the location or shape of a part is directly affected by the action of some tool, whether a cutting tool or an assembly fixture. An example of a part-tooling interaction might be a case where a part is located on a fixture using surface locators.

4. **Part-to-Worker:** This interactions class refers to cases in which a worker directly alters some feature of a part, or in which worker judgement and decisions greatly affect the shape or location of a part. The assembly of flexible parts, where parts must be bent and aligned by a worker, is an example of this interaction.

Each type of interaction has different degrees of learning associated with it. In general, the amount of learning is determined by the level of human content of work. A guide to this level can be obtained by considering two factors: error absorption and planning. The latter refers to the amount of systems knowledge and proactive activity necessary for a given interaction to occur successfully. For example, in some cases, rivets must be inserted in a particular direction or order for all of the rivets to be successfully inserted. The former, error absorption, refers to the ways in which deviations from the desired state are brought to light. In some cases, it is obvious to a worker on the process that an error has occurred. This might occur when, for example, two parts fail to snap together as they had been designed to do. In other cases, errors are absorbed by other elements of the system, and are not noticed at the time by the workers. Such a case might occur when a part is added to a system by placing it in a fixed location on an assembly jig.

In considering both the location and planning issues, it is useful to ask the question "How can the step fail?" Consideration of these failure mechanisms often highlights the critical factors at play.

Based on these ideas, some general rules of thumb can be generated to approach the question of learning in a manufacturing system:

• **Worker-Worker:** Highly dependent on the exact tasks. No rule.

• **Part-Part:** There are two types of part-part interaction – those accompanied by part-worker interactions and those accompanied by part-tooling interactions. When the part-part interaction is accompanied by a part-worker, the general level of learning is **high**. When it is accompanied by a part-tooling interaction, as in robotic assembly, the level of learning is **low**.

• **Part - Worker:** The learning in this case is **high** because the interactions occur directly as a result of a workers actions and decisions.

• **Part - Tooling:** Here, the level of learning is generally quite **low**, because the tool often does much of the work in locating and 'planning'. However, the exact level of learning does obviously vary depending upon the type of tool. Robotic assembly is much different from assembly using a fixture. The latter is often accompanied by a small degree of part-worker interaction.

As noted, few of these interactions occur in isolation. However, to avoid unnecessary confusion, only the interactions that greatly affect the outcome of a task should be considered. Part-part and part-tooling interactions must always be evaluated with any accompanying interactions in mind.

Using these rules of thumb to code the PIM, a rough learning map is obtained. Regions of high learning potential can be identified, and infrastructure building activities focused there.

4.7 Towards a Framework

In this chapter, several tools for understanding a technical system were described. Of particular importance are the concepts of Key Characteristics, the contact chain, and the process interactions matrix.

In the following chapters, the uses and importance of these tools will be demonstrated. Using these tools and the concepts described in Chapters 2 and 3, a comprehensive system for aligning technical and organizational aspects of complex manufacturing systems will be developed. This system will focus on how to ensure that an efficient organizational infrastructure which matches the technical requirements of a system is in place. By putting such an infrastructure in place, learning will be improved, allowing the performance of systems to be improved, and aiding in the successful implementation of new manufacturing systems.

Chapter 5

Case Study: Perceived vs. Physical Chains

5.1 Introduction

The case study described in this chapter describes the assembly process for the cascade subassembly of an aircraft nacelle. The major components of this nacelle are made by a major U.S. aircraft subcontractor, here known as ZipAir. The nacelle is made by ZipAir for a major U.S. aircraft company, referred to here as BigPlane.

There are several goals for this case study. One is to show how the concepts of explicit learning loops and contact chains can be linked and used to improve manufacturing operations. A second aim is to examine and understand some of the organizational dynamics that exist in complex manufacturing systems, particularly focusing on issues surrounding learning and problem solving in environments with complicated customer-supplier relationships.

The overall theme of this case study is to illustrate the nature and uses of different kinds of chains. Two kinds of chains are discussed: physical chains and perceived chains. Both of these chains exist in every manufacturing system. In some systems, they are explicitly designed and closely match. In others, one or both are created indirectly, a result of many decisions in various areas of an organization. The latter case is prevalent in the manufacturing world. Most design and manufacturing technologies today focus upon discrete elements. Chains are not recognized at all. Hence, they not explicitly designed, nor do many organizations spend resources thinking about chains. Much of the time, if a chain is recognized to exist, the chain that actually exists is misunderstood. Recognizing when this is the case is a critical part of process improvement.

In this chapter, the various parts and key characteristics that are important to the case are described. A brief discussion of the research approach follows. Physical chains in the KC realization process are discussed next. The perceived chains for the system are then presented, followed by a comparison of the two types of chains. Based on this comparison, conclusions about the nature of different chains are put forth. Lastly, the use of the different types of chains for learning are examined, and implications for process improvement and new process implementation are discussed.

5.2 Description of the Nacelle and Cascade Subassembly

The nacelle is the part of an aircraft that houses the engine. It is connected to a wing through a structure known as a pylon. A schematic drawing of a nacelle and pylon is shown in Figure 5.1. Also shown on this figure is the location of one of the joints between the nacelle and the pylon, known as Joint 6.

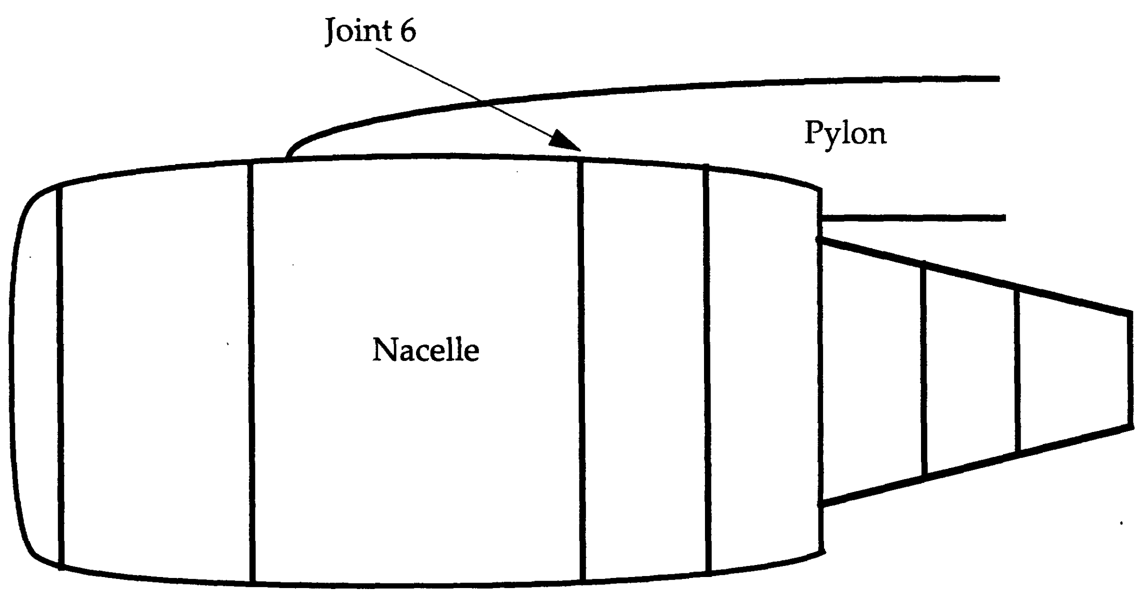

Figure 5.1: Nacelle (Not to Scale)

Joint 6 is the focus of this case study. It is formed when the two halves of the nacelle are brought together at the final assembly stage. Here, the focus is on the step, that is, the difference in height between the two halves at Joint 6. This step has been designated a Key Characteristic because of its structural and aesthetic importance. It is particularly interesting because the efforts to control it have not been successful to date.

Joint 6 is made up from parts that are first introduced into the system at the cascade subassembly stage. Figure 5.2 shows the assembled cascade subassembly. In Figure 5.3, the cascade subassembly is shown as it is at the final assembly stage, as part of the translating sleeve assembly. The two halves of this assembly join at the final assembly stage.

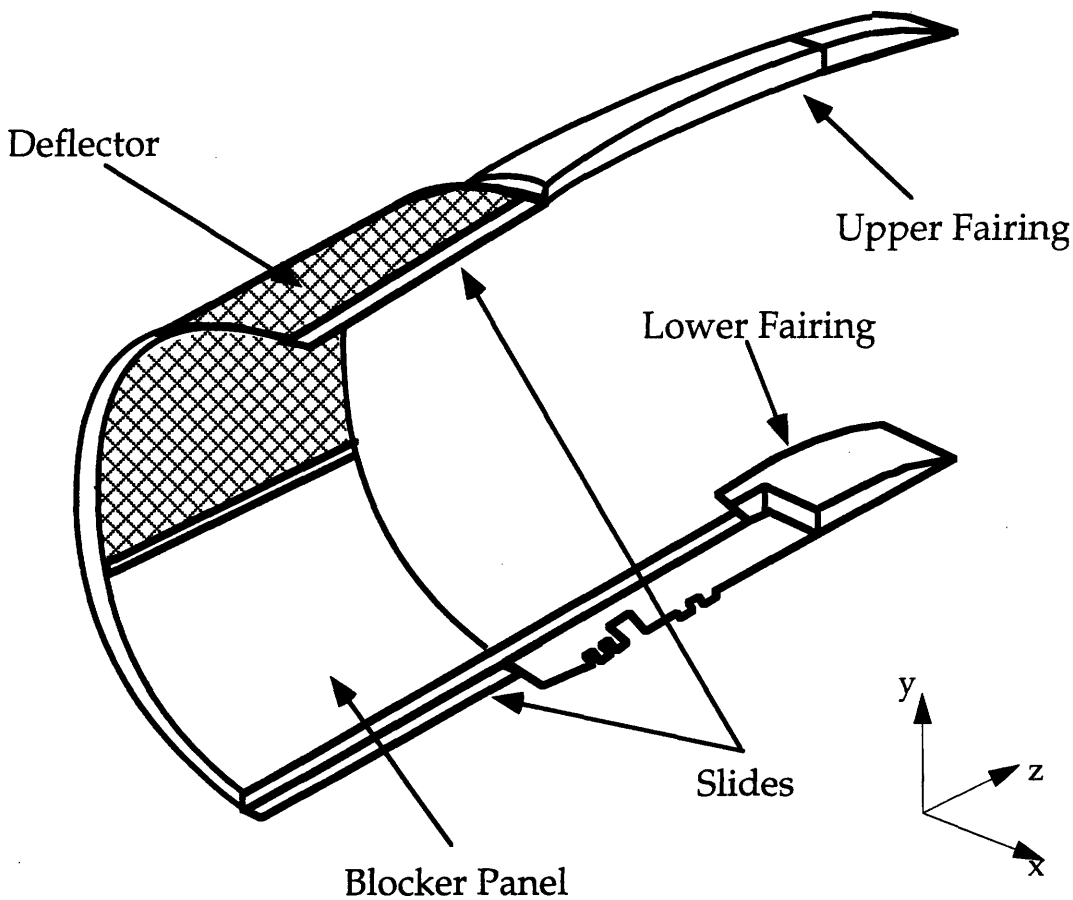

Figure 5.2: Cascade Subassembly (Left Side)

The main elements of the cascade subassembly, shown in Figure 5.2, include:

- **upper and lower fairings**

These are cast parts, obtained from suppliers. In the completed nacelle, the mate of the upper fairings is Joint 6. The step is therefore the difference in the vertical (y) positions of the upper fairings.

- **slides** (attached to the upper and lower fairings; obtained from suppliers.)

The slides attach along the length of the fairings. They are later inserted into tracks on the inner fan duct assembly, allowing the translating sleeve assembly to move parallel to the nacelle axis.

- **deflector**

The deflector is a metal grating. During normal operation of the engine, the deflector is not visible, hidden behind the access door.

- **blocker panel**

Sheet metal panels that form the shell of the nacelle.

5.3 Approach

In order to ensure that this case study would provide useful and accurate insights, a careful, structured approach was adopted. The main danger faced during the investigation was that of biased results. To avoid the possibility that one line of investigation would contaminate the results from another line, the different types of analyses were ordered so as to minimize possible interactions and biases.

Two different lines of investigation were pursued. First, the manufacturing process was examined, and the physical contact chain documented. The physical contact chain is that derived from a direct analysis of the physical elements of the process; it does not depend on worker perception. Once this was completed, the perceived chain was examined. This is the chain representing the information pathways that are used in the daily operation of the manufacturing system.[1] Having documented both the physical and perceived chains, a comparison was possible. Conclusions on how to improve the process followed from this comparison.

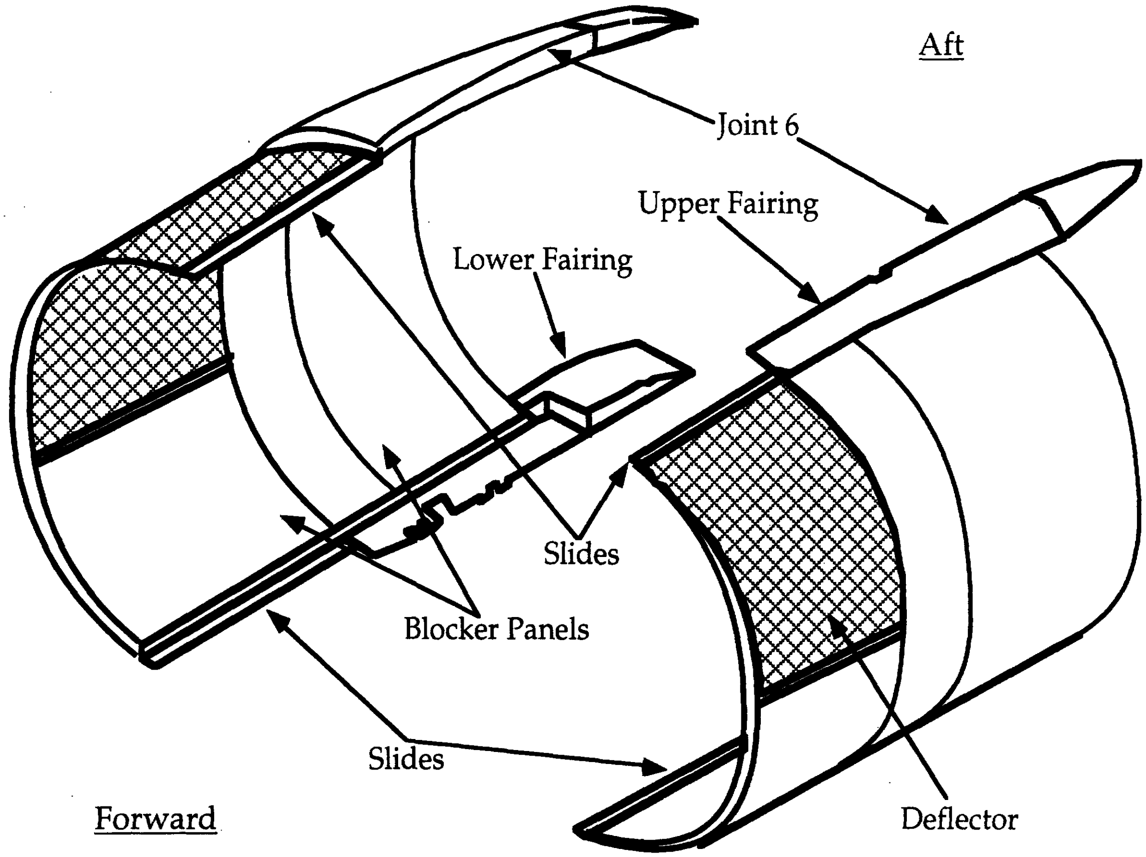

Figure 5.3: Two Halves of the Translating Sleeve Assembly.

If the two lines of investigation were pursued in the reverse order, it is possible that the documentation of the physical chain could have been influenced by the perceived chain. This is much less likely when the investigations are performed in the proposed order because, as described in Section 5.5, the documentation of the

1. Note, however, that the term "perceived chains" may not be accurate in many situations because, as mentioned earlier, many organizations do not think in terms of chains. The organization therefore does not perceive a chain. In these cases, the term "perceived information pathways" may be more appropriate. Here, however, "perceived chains" is used for simplicity.

perceived chain has virtually no dependency on the physical situation. Much of the perceived chain can be discovered by following a visible paper trail. Knowledge of the physical chain does not, therefore, affect the perceived chain documentation process. In contrast, the physical chain relies much more upon in-depth analyses of the process, some of which may be biased by other people's perceptions of what is happening in the system.

5.4 Physical Chain

The physical chain is the chain that exists as a result of the physical interactions between elements in a system that contribute to the achievement of a KC. As noted earlier, the focus of this case study is on the Joint 6 Step KC. In order to determine the physical chain, a number of steps were required. The physical chain for any system cannot be documented until the system is understood to some degree. Therefore, for this analysis, an understanding of the complete assembly system was needed.

Figure 5.4 shows the assembly map for the nacelle. This assembly map shows the physical flow of parts through the assembly stations. What it does not show, however, is the influence of 'service' components of the production process. For example, production technology and manufacturing engineers are critical parts of the system. They are a major source of problem solving, as well as a conduit through which information can be passed from one group to another. To some degree, service elements such as these transform the linear assembly map of Figure 5.4 into a complex assembly web. This assembly web will be particularly important when perceived webs are discussed. However, the physical web is based almost completely upon the physical system. The influence of service elements is very limited.

Figure 5.4: Nacelle Assembly Map

Once the assembly map is understood, a contact chain can be constructed. This is done by walking through the assembly processes in several directions. Starting at Joint 6 in the final assembly stage, for example, it is useful to identify the critical parts and interfaces, and to then move upstream to the systems that contribute to those parts and interfaces. Similarly, it is also useful to start at the point where a critical part enters the system, and to follow that part as it flows through to the KC achievement stage and final assembly, paying particular attention to anything that affects that part in any way.

As alluded to above, several criteria are important when constructing a contact chain. First, the key characteristic must be identified and understood. In this case, the KC was the Joint 6 step. Second, understanding the parts and features is critical to the successful documentation of a physical contact chain. When the KC relates to position, such as a tolerance or, in this case, a step, particular attention must be paid to the means by which contributing parts are located throughout the system. Because the upper fairings' positions determine the KC, the ways in which those positions could be altered need to be understood. Notice that this does not mean that the investigation should be limited to the fairings. A part-oriented, fairing based approach will likely not provide a complete picture. Instead, a systems view, incorporating not only the fairings but the features used to locate the fairings and other parts which might affect their position, is the better approach. As the Sufi saying goes, "Just because you understand *one* does not mean that you must understand *two* because one and one makes two. You must also understand *and*." The part-oriented approach fails to consider the 'and', whereas the links in the contact chains explicitly represent it.

The physical contact chain developed using the methodology described above is shown in Figure 5.5. At the cascade subassembly station (385), the slides are located to the assembly fixture. The deflector panels are positioned using the fixture and the slides. Similarly, the forward end of the fairings (nearest to the deflector panels) is located to the slide and the fixture, whereas the aft end is just positioned to the slide. From 385, the cascade subassembly moves to the Translating Sleeve station (380), where it is placed on an assembly fixture using the slides and the forward rim of the deflector panels as locators. Additional panels and the fairing tip are attached here, after which the subassembly is moved to the 370 station. At this station, it is attached to the Inner Fan Duct by placing the slides on the translating sleeve into tracks fabricated onto the inner fan duct. Note that at this stage, the Inner Fan Duct is located to the fixture using a series of locating pins. From this stage onwards, the locating method for the assembly remains those pins.

The last stage involves moving the Fan Duct/Translating Sleeve Assembly to the final assembly station (300B/D), where it is brought together with the other half. Final assembly measurements on the KC are taken at this stage. Finally, at 300D, the engine is attached to the nacelle.

5.5 Perceived Chains

Perceived chains are those that are actually used in the day-to-day operation of a system. They represent the information flows that are used to control KCs in the system. Unlike the physical chains, perceived chains are a function of the organizational policies and history associated with a system. They incorporate not only the physical parts, tools and processes, but also the perceptions of the people working on and around the chain. Many of the service elements alluded to above come into play in perceived chains. As such, while the physical chain for a given process must be the same regardless of where the plant is located or who is managing it, the perceived chain can vary from location to location.[2]

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2. Of course, for the physical chain to remain the same, identical equipment and parts must be used in each location. This is not always the case, as equipment is often modified as part of the problem solving process.

Naturally, given the additional elements contributing to the perceived chains, their structure can be extremely complex. What might have been a straightforward process in the physical chain may be a complicated tangle of feedback and

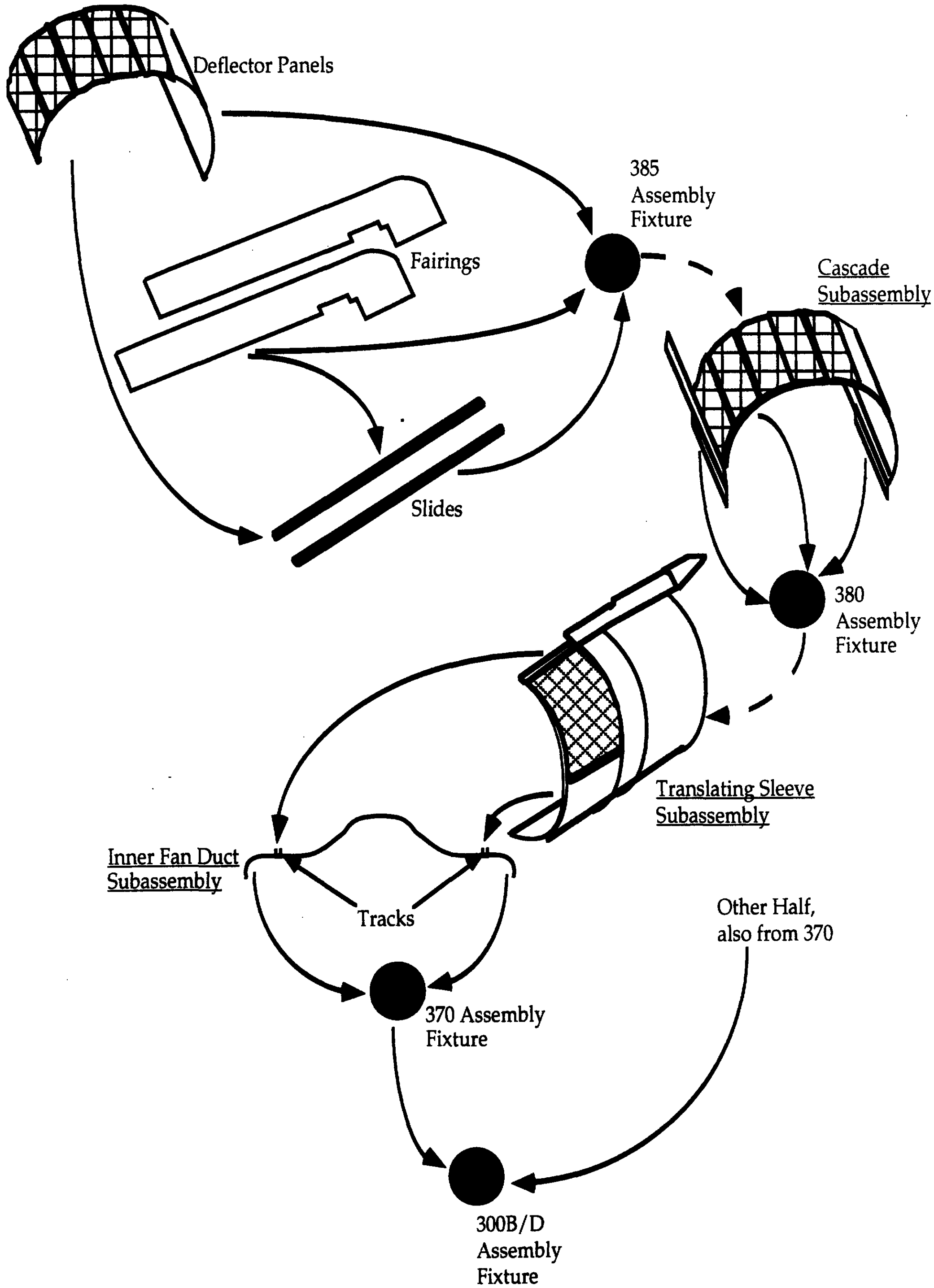

Figure 5.5: Contact Chain for the KC (step) at Joint 6

feed-forward loops in the perceived chain. However, the complexity in itself is not the largest problem that accompanies perceived loops. Instead, it is the tacit nature of the perceived chain, in which complexity is a factor, that presents the challenge.

Physical chains are solely a factor of 'tangibles', and can thus be definitively defined through proper, careful analysis. Perceived chains, on the other hand, are seen in a different way by each person, depending on their mental model of the system. For example, a worker at Station A might have no idea that Station B and C communicate with each other. A's perceived chain therefore lacks this link. Further, Station B might itself not be aware of the communication occurring between itself and Station C. This might happen if information at B is passed to a manufacturing engineer, who then passes it on to C without informing B. While this structure is relatively simple, one can easily imagine a situation in which the information from B is passed through several different hands before ending up at C. As a result, B's perceived chain is also incomplete. The opposite situation might also exist. If information goes through several hands between B and C, C might incorrectly have the impression that the information really came from A. In this case, physically non-existent links exist in the perceived chain.

Because the perceived chains are different depending on who one talks to, a methodology is needed for reconstructing a composite perceived chain – the chain through which information actually flows. Such a methodology should be built on several different structures, so as to ensure redundancy and improve accuracy. The first step in documenting the perceived chain is to understand the organizational and physical elements of the system. This is similar to the first step in the physical chain documentation. Unlike that case, however, the organizational aspects – the work assignments and the indirect support structure, for example – are critical here. Understanding the system by walking through and observing it, as well as through interviews, will yield an organizational map similar to Figure 5.4, but perhaps with additional organizational elements and information included (e.g., work team size for each station).

Once the system is understood, workers must be interviewed (informally or formally) to gain their perspective on what they are doing. This is the first step in identifying the information pathways in the system. By making the workers explain their mental models, areas of conflict can be identified. In addition, by interviewing workers, one is made aware of the types of information that are available.

Armed with the knowledge of what type of information is available, the paper trails can then be followed. This is the most critical part of the process. Most communication between teams happens in some structured manner. In some cases, information is passed in on paper in the form of control charts and customer complaint forms. In other cases, the same information is passed through a computer. In addition, teams often communicate through meetings (such as IPT meetings). Understanding what information is transferred where can provide a very accurate guide to the aggregate perceived chain.

The fact that perceived chains can be documented through the information 'paper trails' is extremely important. The argument in support of this assertion is as follows. The primary purposes of information flow in a manufacturing system are to fulfil a need or to provide a metric of performance (required, for example, for safety records). Consider the former. Information about a given process, in the form of production data, for example, is needed by a team only when that process is perceived to possibly have an effect on the team's work. By definition, when one element of a system has an effect on another, they are linked in a chain. Therefore, tracking the information flows that are required to control interactions in a system can give a good snapshot of the composite perceived chain – the chain that the organization as a whole sees.

Of course, figuring out what information flows are required is not a trivial task. The information gathered to serve simply as a metric of performance must be filtered out, as must information that is simply not relevant to the KCs of interest. Accomplishing this requires the knowledge of the overall technical and organizational system that was acquired during the first two stages in perceived chain documentation. Care must be taken when filtering out the metric-related information to ensure that the information does not have a dual purpose. In other words, only single purpose, metric-specific or non-process related information must be removed.

One technique for evaluating what information should be filtered out is to examine the measurement points throughout the system. Again, the critical KC should be the starting point and focus of the investigation. Any measurement points that in any way affect KC realization should be included. When in doubt, it is better at this stage to include the metric-specific or irrelevant information rather than leaving out potentially important links. Further pruning of the chain will occur at a later stage.

In this case study, the assembly map shown in Figure 5.4 was again used as a starting point for perceived chain documentation. Measurements are taken at several different stations; some of this data flows to other areas and is used to help improve processes. Virtually no structured communication between teams was observed to occur. Most of the communication happens through the indirect workers, such as manufacturing engineers, who are each assigned to several stations in the web. All of the analysis and comparisons of the information provided between the teams is performed by indirect personnel.

Five stations were found to be candidates for perceived chain elements. These stations were 385, 380, 370, 374 and 300B/D. The measurements taken at each station are described in Table 5.1. Of these five stations, only three were actually found to contribute to an actual chain. The perceived chain is shown in Figure 5.6.

Measurement Station	Parts Measured	Consistent Measurement Points With Stations	Data Compared With
385	Fairing	380, 300	380, 300
380	Fairing Fairing Tip	385, 300	385, 300
370	Fairing	No	None
374 (Before Coke Bottle Attachment)	Track	No	None
300B	Fairing Fairing Tip	385, 380	385, 380

Table 5.1: Perceived Chain for Joint 6 Step Based on Information Pathways

At the 385 station, the fairing position is measured at several locations. This measurement is repeated at 380 and 300B. In addition, once the fairing tips are added at 380, their positions are also measured. At each of these three stations, effort is made to keep the measurement points the same, although the subassemblies are located using different features at each of the stations. The information collected at these three stations are all passed (with some delay in the information loop) to support personnel who maintain records and perform some SPC calculations on them, mostly checking whether the points are in or out of control.[3] In no case does a team see the data taken at other stations. The direct communications between teams is limited to warning labels (attached by inspectors) indicating that various parts are out of specified ranges.

Data on the fairing is taken at the 370 station as well. However, here, the measurement points differ from those at the other stations. In addition, the data does not travel beyond the 370 and record keeping teams. Finally, at 374, data on the track location is taken. However, this data is collected before the coke bottle assembly is welded to the fan duct structure. This welding operation may introduce some variation to the track location after the measurements have been taken. Regardless, the track information is only checked to determine if it lies in specified ranges (before welding); it does not travel to any other teams.

Information flows in the production system indicate that the perceived chain is rather disjoint. The approach to the chain is to leave the data collection and immediate SPC analysis to the assembly teams, and to leave the analysis to the indirect personnel. This fact explains some of the results of the informal interviews, which indicated that teams had only a vague idea of what happened to their data after if left their work areas.

3. Note that the control chart information and the raw data are also maintained at the stations at which the data is taken.

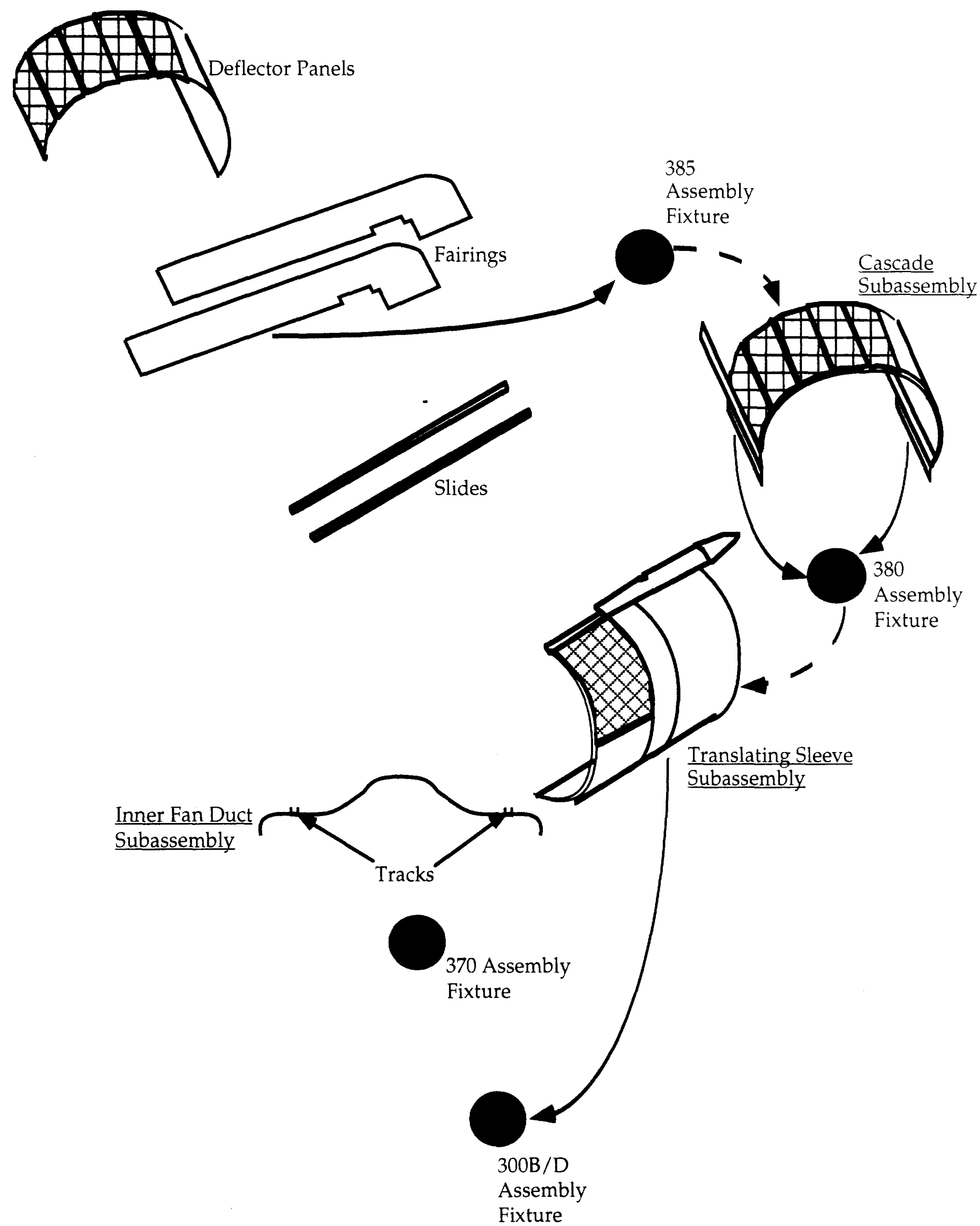

Figure 5.6: Perceived Chain for the step at Joint 6.

The disjoint nature of the perceived chain confirms the hypothesis presented earlier that the presence of service elements in the manufacturing converts the assembly map into a complex web. Information which is gathered at stages which lie on the map are then transferred to other organizations that do not fall on the map. A result of this added complexity is that people are not aware of the whole system. They are not aware of how their process affects others in the system, and therefore, they are not in a position to adequately judge the effects of local changes or improvements on the overall system. Given that most process improvement activities at ZipAir focus on such local improvement, it seems logical to wonder if the local improvement activities can in fact worsen the overall system learning rate, in both quality and cost. This question will be examined in detail in the following section.

5.6 The Meaning of the Chains

Once both the physical and perceived chains have been documented, one is in a position to compare the two. However, before that is done, the meanings of the chains, and the implications of differences between them, should be understood.

Physical chains map the physical interactions that occur throughout the system. In a more complex system in which service elements play a greater role in the physical system, tools such as the Process Interaction Matrix may be necessary to fully capture the physical chain. (A kanban-based, pull manufacturing system is an example of a physical system in which service elements – the communication of the need for particular types of parts – play a critical role. Such communication would be represented as worker-to-worker interaction on a PIM. Here, these interactions are empirically found to be quite weak, and so the contact chain representation is sufficient.)

No matter how the physical chain is represented, it always represents the communication links that need to exist in order for explicit-loop learning to occur. To see this, consider the meaning of the links in the chain. They represent the key interactions between elements of the system (part-part interactions and part-tooling interactions, for example). It is these interactions that have the most significant affect on the realization of the KC at the end of the chain.

If a KC is out of control, there are two possible sources: the parts themselves, or the way in which the parts come together. The former are generally monitored at the time of their fabrication, using standard SPC methods. However, the latter are much harder to monitor and improve. The interactions between different elements are important. When such interactions cross organizational boundaries, the different organizations must work together to monitor and improve the system. While the ideal situation would involve both organizations working side by side on the problems, this rarely happens at ZipAir. Instead, information is passed back and forth between the different organizations. Links in the physical contact chain therefore map the pathways through which information must pass. Interactions are improved using the information and knowledge stemming from communication along those pathways.

Now, explicit-loop learning is, by definition, learning that occurs as the result of specific actions outside of the normal performance of the task at hand. All of the efforts to control interactions between parts require specific control efforts, especially when the interactions cross organizational boundaries. Information on each of the interactions is needed at, and must travel through, every step in the chain. Thus, **the physical contact chain maps the information and the pathways which can generate explicit-loop learning for the KC associated with that chain.**

Having realized this fact, it is a straightforward task to understand the link between the perceived chains and the physical chains. The latter shows what information should flow through a system, and the pathways that should be used, whereas the former shows how information actually flows through the system. Once this is understood, a method for aligning technical and organizational processes of complex systems becomes apparent. Information pathways must be designed according to the physical chains, as shown by a PIM (or a contact chain in simple cases). **In the optimal case, the composite perceived chain should be identical to the physical chain.**

5.7 Comparing the Chains

With the implications of the different chains understood, the chains documented in this case study can be compared. A first pass shows that the two chains are markedly different in several places, while they closely mirror each other in other places.

Consider the similarities. The fairings are introduced into the system at 385. From this point, they travel through 380 and 370 before arriving at 300B/D. Some of these links are found on the perceived chains. Links between 385, 380 and 300B/D exist. At each of these stations, data is taken at identical points using similar references. While the locating scheme varies slightly from one station to the other, on the whole the measurements have been designed to be consistent.

However, the similarities break down at 370. While data on the fairings is being taken here, it is taken at different points than at the other three stations. In addition, the data is not compared at all to the data from the other three stations, effectively breaking the chain between 370 and the other stations.

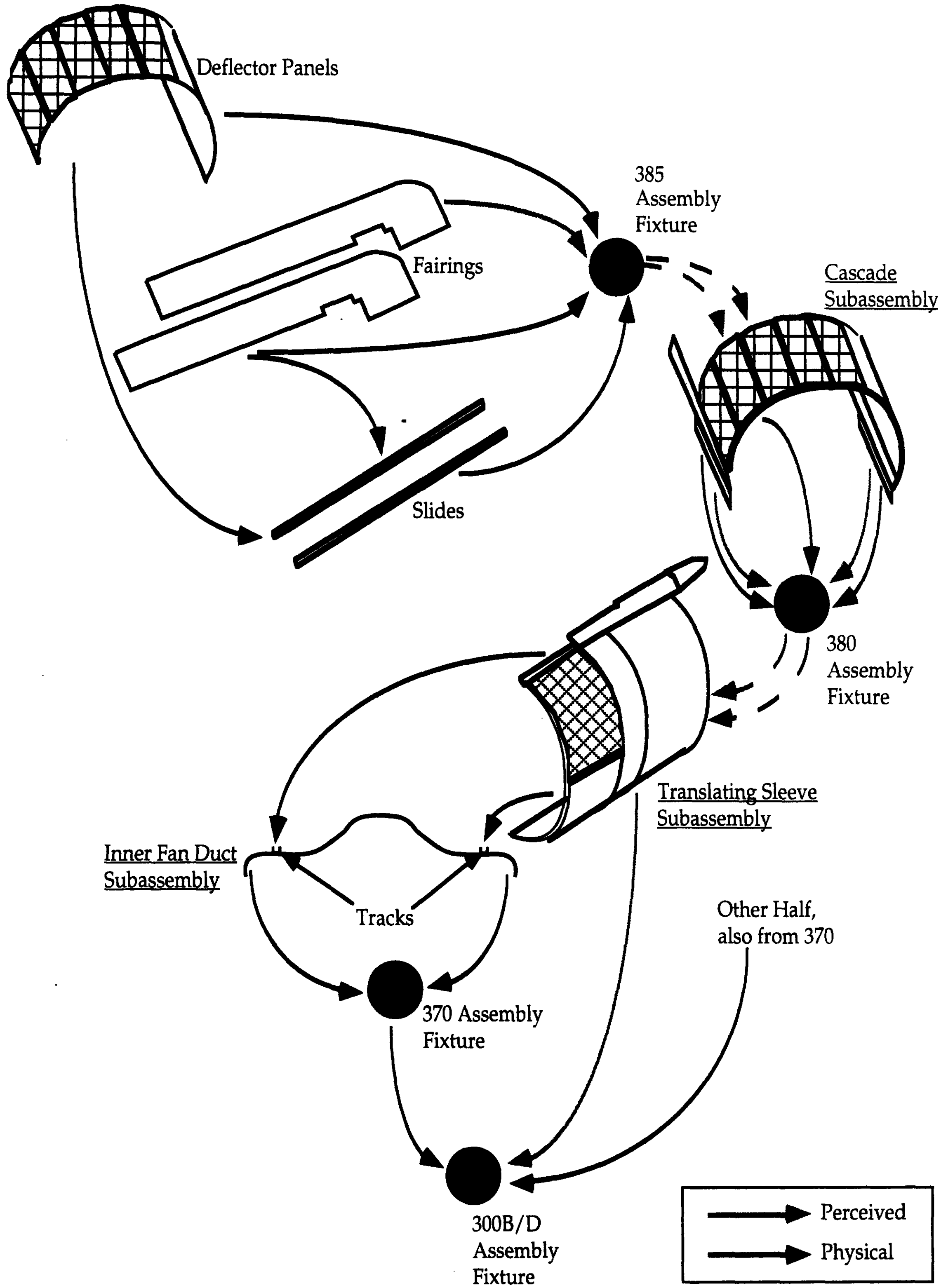

Figure 5.7: Comparison of the Perceived and Physical Chains

The second difference between the two chains is at the slides. The physical chain suggests that the slides play a critical role in the system. However, this link is not present in the perceived chain. Nowhere through the system are the slide locations measured. Instead, the slides are located using some reference surfaces at 385, and are assumed to be in the correct position there and throughout the rest of the chain.

Lastly, the physical chain suggests that the track position at 370 is important. While recognition of the importance of the track is found in the perceived chain, the needed link is not present. The track is instead measured before it is attached to the inner fan duct assembly. Yet, after it is attached, other parts are also attached which could potentially distort the tracks. In other words, there are interactions that occur between the stage where the tracks are attached and the stage where they are important in the process. So, in this case, the link in the perceived chain is not the needed link. Instead, a measurement should be taken at 370 itself, and this information should be passed along with data on the slides and fairings to the final assembly and other analysis groups.

This comparison illustrates some of the problems with the existing process. There are avenues for improving the KC (through which explicit-loop learning can occur) that are not being utilized. This fact is especially important due to the fact that the efforts to bring the KC into control using the perceived chain have not been successful.

5.8 Improving Processes

The case presented in this chapter is quite simple. However, one can easily imagine a situation where the complexity involved in an analysis such as that presented above quickly becomes unmanageable. In a world of limited resources, techniques for identifying the areas where resources well be best spent is needed. Such techniques are presented in this section.

In describing these techniques, it will be assumed that the perceived chain that actually exists is correct and being used. This is done for the sake of simplicity. Obviously, to get the most out of the process, the perceived chain should first be redesigned so as to match the physical chain. Only then should these techniques be used.

The most important point to realize about perceived chains is that they are dynamic. While the links in the chains tend to remain the same, the importance of these links changes. At one point in time, the link between station A and B might be the greatest source of variation. Once the problem at that link is fixed, or if a new problem arises elsewhere in the system, the importance of that link will be reduced.

Optimal allocation of improvement and learning resources depends on the proper identification of the links that are the greatest source of error at any given time. Because this is not constant, the identification process must be one that can be quickly performed.

Identification of the critical links is possible using a system of structured correlations. Simply put, all of the data taken at each link are compared to each other and to the final KC using a statistical correlation analysis. By doing this, the links which contribute the most to the trends at the KC are identified. In addition, solutions can quickly be found by looking at the correlations at links throughout the chain.

While correlation analyses such as this have been tried in the past, and are in fact part of the TQM toolkit [8] [9], the innovation here that greatly improves the usefulness of the technique is the use of the chain to focus the analysis. Other attempts at correlation analysis have tended to lack structure and focus. In these analyses, it is difficult to differentiate between causal relationships and correlations. The chain provides this information at the start of the correlation process. In addition, instead of performing limited, structured correlations on important links, other techniques use correlations performed either only on specific parts (comparing, say, two dimensions), or on every process that is part of the manufacturing system. Such analysis is overwhelming on even moderately complex systems, and extremely difficult to perform when several different organizations (e.g., suppliers) are involved.

As an example of how structured correlations would work, consider the Joint 6 Step KC. As mentioned earlier, several steps have been taken to attempt to bring the KCs under control. These efforts have focused on the 385-380-300B/D perceived chain discussed earlier in this chapter.

Figure 5.8 shows a graph of the predicted steps on the forward end of Joint 6, based on part measurement at the subassembly level, compared to the actual steps measured at final assembly. As the figure shows, the actual steps are not predicted with great consistency. The correlation factors for this data set are shown in Table 5.2.

Assembly	Forward Measurement Correlation Factor (R^2)	Aft Measurement Correlation Factor (R^2)
Predicted at 385 vs. Actual	0.29	0.33
Predicted at 380 vs. Actual	0.41	0.23

Table 5.2: Correlation Factors (R^2) of Predicted Steps vs. Actual Steps for Joint 6. (Based on direct part measurements and calculations by the author.)

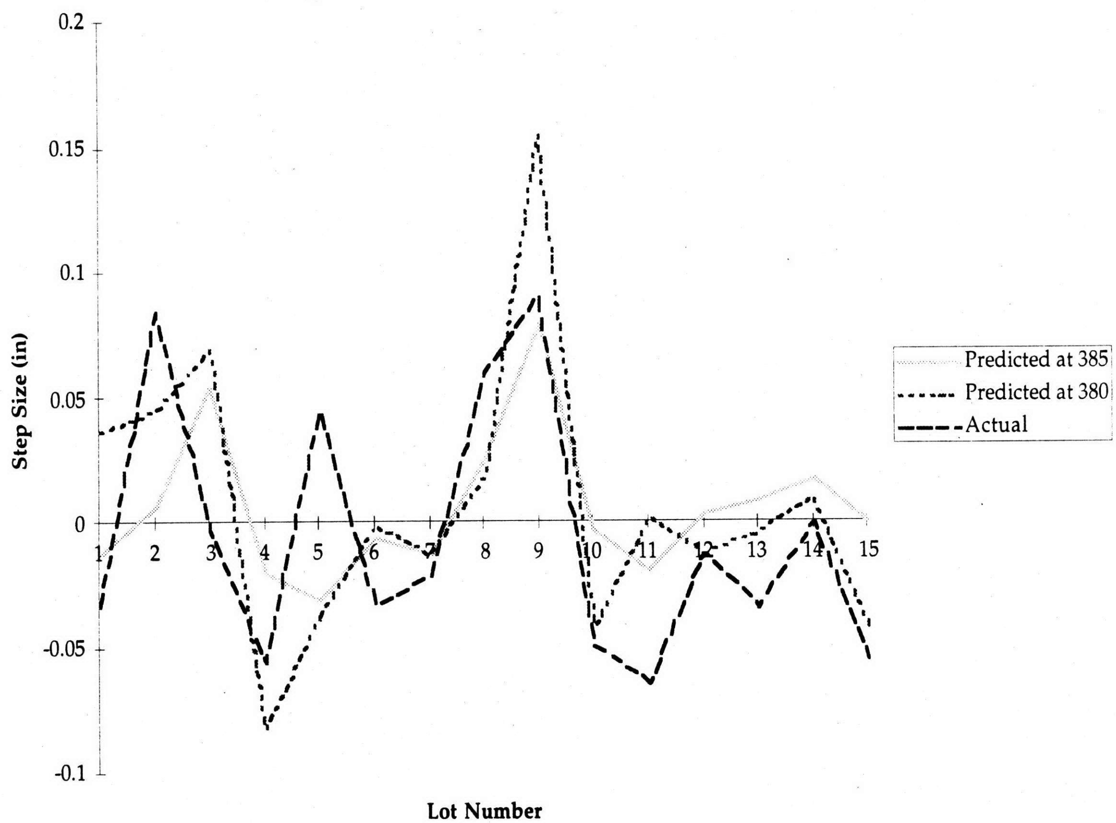

Figure 5.8: Predicted vs. Measured Steps, Joint 6 (Fwd Measurement Point)

The step data shown is calculated as the difference between the location of the right and left fairings. As shown in the Table 5.2, predictions made at both the 385 and 380 subassembly stages are poor indicators of the final step. In the best case, only 33% of the final assembly trends are explained by variation at 385, and about

41% are explained by 380. This indicates either that the measurement systems at the three stations are not consistent, or that there are significant problems due to factors at other stages in the chain. Regardless, the measurements taken at 385 and 380 are not very useful in controlling the step at final assembly. They are both about equally poor indicators. While they predict the outcome in some cases, there must be other factors affecting the system.

Further insights into the problem can be gained by looking at each of the subassemblies individually, i.e., by examining the right fairing and left fairing separately. This is done in Table 5.3.

Assembly	Right Fairing (Fwd) Correlation Factor (R^2)	Left Fairing (Fwd) Correlation Factor (R^2)
380 - 385 (fwd)	0.32	0.73
385 - 300B (fwd)	0.16	0.23
380 - 300B (fwd)	0.39	0.39
380 - 385 (aft)	0.01	0.49
385 - 300B (aft)	0.05	0.23
380 - 300B (aft)	0.21	0.08

Table 5.3: Correlation Factors (R^2) for Fairing Step Measurements, Joint 6.

For both the forward and aft measurement points on the right fairing, the data taken at the 385 subassembly is a poor indicator of the final assembly. In addition, 380 and 385 do not closely follow each other, particularly in the aft case. However, the 380 subassembly does tend to be a better predictor, although even in the best case, for only 39% of the time. On the left fairing, the story is much the same. The 380 and 385 measurements are more consistent than on the right side. However, again, in the best case, final assembly trends are predicted only 39% of the time. In the majority of cases, the story is much worse.

The implications of this analysis for resource allocation are profound. The low correlations associated with both the 385-300B/D and 380-300B/D links indicate that the problems at 300B/D may originate in other steps (perhaps 370, for example). Resources that are allocated to process improvement at 385 and 380 are, therefore, probably not well spent at present. While there may be some local improvements, there is virtually no impact on the KC. Resources should therefore be dedicated to links where the correlation with final assembly is highest. These links have a greater effect on the KC, and resources dedicated to solving problems in these links will have a greater impact. Note that, because of the incomplete perceived chain, identification of these links is not possible at present.

If a quick thought experiment is used, a second insight can be obtained from the correlation analysis. Imagine for an instant that there was a high correlation between 380 and 300B/D. This would indicate that the problems with the KC stem in part from something happening that is also happening at 380. However, imagine also that the correlation between 380 and 385 remained low. This fact would tell us that the problem originated at 380! If the opposite were true and the 385-380 correlation high, 385 would have to be examined as the origination of the problem.

This thought experiment illustrates the fundamental principle behind the technique of structured correlations. Correlations are tracked along the links of the perceived chain. The perceived chain is laid out to match the physical chain. The advantages of this technique are that cause and effect can be clearly identified using the chain, and that it can be automated quite easily, by simply specifying a perceived chain and collecting the appropriate information. By automatically sorting through the links in a complex chain and identifying those that are important at any given time, organizational complexity seen by the workers will be greatly reduced, freeing up time and resources for increased process improvement and learning. When the importance of links change, it is automatically picked up by the system and appropriate persons notified.

5.9 Changes at ZipAir, and Future Possibilities

The realization that the 385 and 380 data was not contributing to the problem at Joint 6 resulted in the halting of the collection and transmission of this data.[4] No noticeable effect (positive or negative) on the step resulted from this. However, resources which had been spent on the data collection and transmission is being saved.

The fact that data collection and transmission was stopped is not entirely positive. While resources are being saved, the lack of data is an obstacle to problem solving as the strength of the 385-300B/D or 380-300B/D loops could change.

The exploration of other approaches suggested by the contact chain has been limited due to the lack of a consistent measurement system, and the expense and resources involved with developing one. While a preliminary use of the structured correlations methodology applied to the available data (with the inconsistent scheme) indicated that a higher correlation exists in the 370-300B/D link, these results are not considered by the author to be meaningful. The errors introduced by the measurement system have likely skewed the results too much.

4. Only data needed for record keeping was recorded.

This raises an interesting point. One of the dangers of the correlations analysis is that a high correlation will be misinterpreted. Even with a computerized system, the correlation analysis is no substitute for a in-depth understanding of the chains and the system as a whole. Correlations should be used as a guide, not as a solution. As any good statistics book will stress, a high correlation does not mean that a cause and effect relationship necessarily exists.

5.10 Implementing or Improving Processes

This chapter has illustrated several techniques that can be used to aid in the improvement or implementation of manufacturing processes. The key lessons and corollaries are:

1. A systems-oriented approach to process improvement (using the contact chain) has advantages over the part-oriented approach used by many manufacturing companies.[5] This is particularly true when the contact chains are complex.

2. At least two types of contact chains exist in a manufacturing operation – physical chains and perceived chains. The former can be determined with some certainty while a process is still in the design phase. The latter should be designed so as to match the physical chain.

3. In many existing manufacturing operations, the physical and perceived chains do not match. This limits the possible improvements that can be made in a system, and the first step in process improvement should be to eliminate the discrepancies.

4. The physical chain represents the explicit learning loops in a system. There-

5. See Cunningham [6] for a discussion of this, and for examples.

fore, all of the techniques for strengthening explicit loops, described in Chapter 2, can be used to improve the manufacturing system.

5. As the complexity of a physical chain is an indicator of the integral nature of a process architecture, a good rule of thumb is that the more integral a process architecture, the more important are explicit loops.

6. The usefulness of the chain approach to process improvement is limited by the system knowledge and macro-skills of the workers. Often the perceived chain seen by a particular work team is greatly skewed from the actual perceived chain, and from the physical chain.

7. Tracking correlations along contact chains (here called structured correlations) can provide critical information on the strength of particular loops, and can help direct process improvement resources. Organizational complexity can be reduced using this technique.

8. Chains are dynamic, and the strength of different loops constantly changes. An equally dynamic and adaptive approach to process improvement and learning is necessary.

9. Chains have implications for the entire organization, not just for work teams. For example, managers must allow the work teams to adapt to constantly changing environments. IPTs must act less as a managing board, and more as a conduit through which system information can be passed.

10. Lastly, all of the above points have implications for supply chain management and outsourcing policy. In a system with integral process regions, the customer and supplier companies must work closely. Agile organizations, in which

organizational boundaries are unstable, are unsuitable when the process architecture.

Chapter 6

Case Study: Precision Assembly

6.1 The Need for Precision Assembly

The aircraft industry is a low volume, high fixed cost industry. Typical production rates for commercial aircraft range from about 3-6 per month. Parts for these aircraft are produced in various places around the world. They are assembled into subassemblies at still other locations, and are shipped to a final assembly plant where the aircraft is assembled.

Much of the assembly work is still a largely manual process. This is true in both military and commercial production. Large, inflexible fixtures are used to locate and assemble parts. Teams work around these fixtures, using them as guides and locators. Much of the work, however, is done directly by the workers in the team.

These fixtures are both large and costly. They take up valuable floor space, resulting in larger facilities, overhead and often inventory costs.[1] In addition, they cost several hundred thousand dollars, depending on their size and complexity, and are very inflexible. Only one assembly design can be produced on these fixtures, often only in a particular assembly sequence. If demand for one type of aircraft is low but that for another is high, the fixture for the former might become underutilized at the same time as there is a shortage of fixtures to meet demand for the latter.

1. Although large facilities are not always accompanied by large inventories, the discipline imposed by the lack of space in a small facility ensures that inventory levels are maintained at a lower level. Based on a lecture at MIT (11/96) by Mr. David Fitzpatrick, Senior Manager for Strategic Planning, The Boeing Company.

Eliminating fixtures would solve many of these problems. A flexible assembly process that did not rely on fixtures would result in lower capital costs and greater product and capacity flexibility. It would also allow the assembly work to be conducted in smaller facilities.

Precision Assembly is the name given to a set of fixtureless assembly processes being developed by several aircraft manufacturers. For this case study, a fixtureless assembly process for the horizontal stabilizer of a large aircraft was studied. Although the case was studied in detail during extended on-site plant visits, the details on the Precision Assembly process presented in this section are based upon a process developed by members of the MIT Fast and Flexible Manufacturing Program. This work is described in [7] .

6.2 Implementation Issues

Precision Assembly represents a radical change from current assembly practices in the aerospace industry. From a technical perspective, the way in which assembly occurs will be fundamentally different. Instead of locating parts using fixtures and techniques such as match drilling (where two parts are lined up and a hole drilled through them), parts will be located using features established during the fabrication stage. Issues surrounding tolerance propagation and temperature control are more important as the process is less forgiving of errors and variation.

The absence of fixtures and the reliance on part features in the assembly process also has large implications for the organization. Workers will need a different set of skills and roles to operate the new system. Supplier roles will also change, as must the importance of timely information flows. Learning rates will be affected, as will the ways in which learning is accomplished.

All of these organizational and technical issues must be addressed in order for Precision Assembly to work. Failure to address these issues will result in poor overall performance, long start-up times and high error rates. In order for Precision Assembly to be a success, it is vital that efforts be made to change both the technology and the organization. Much work is happening on the former front; very little on the latter.

In this chapter, some of the organizational issues involved in Precision Assembly are examined to discover exactly what should change when implementation occurs.

6.3 Horizontal Stabilizer Skin Panel Assembly

Before any of the issues surrounding the existing (as-is) or the Precision Assembly processes are discussed, the parts and assemblies must first be described.

The horizontal stabilizer is the wing-like structure found on the rear of most aircraft. The skin panel assemblies make up the top and bottom of the box-like stabilizer structures. Rib structure are used between the panels to help form the shape and to provide some stiffness.

The skin panel assemblies are made from thin sheets of aluminum. There are two parts to each skin panel: the aft skin and the forward skin. The stiffness of these sheets is increased by attaching long slender beams, called stringers, to the skin so that each stringer runs along the length of the skin, from the inboard to the outboard end, as shown in Figure 6.2. The forward and aft skins are joined together by Stringer 3. Finally, at the inboard end of the assembly is a structure known as a plus chord. This structure bears much of the load that is seen by the cantilevered stabilizer.

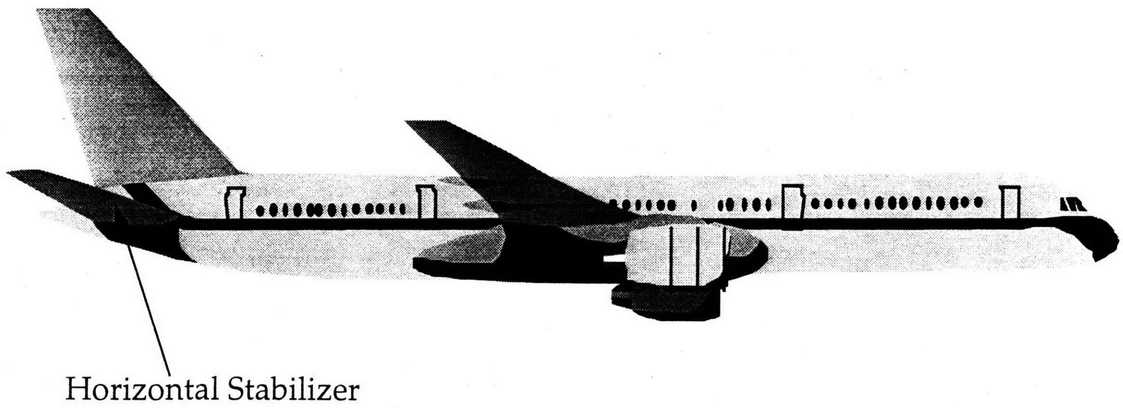

Figure 6.1: Horizontal Stabilizer.

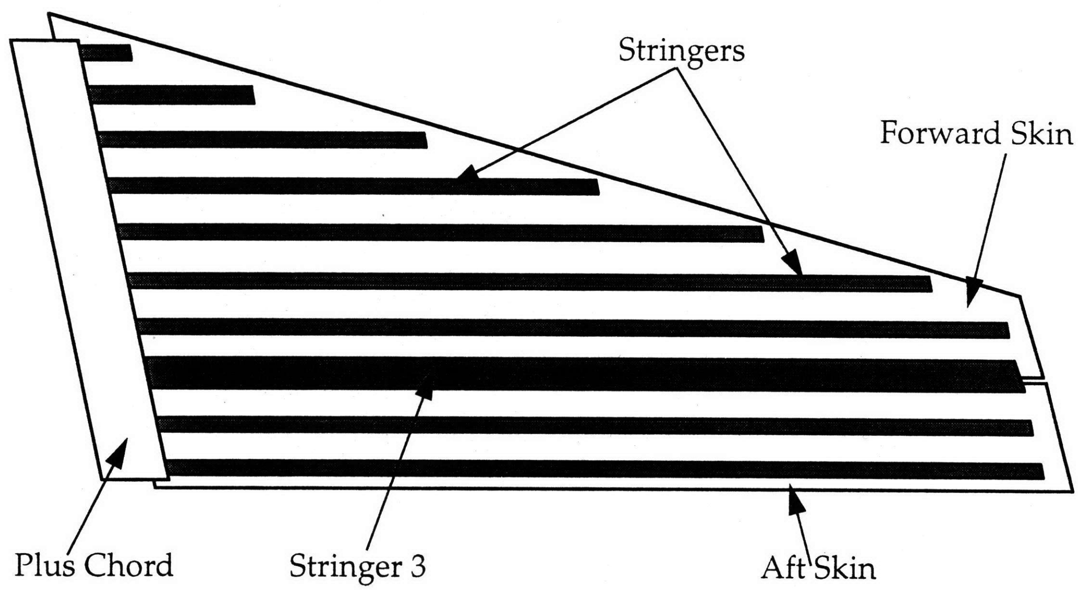

Figure 6.2: Schematic of a horizontal stabilizer skin panel assembly.

At present, the horizontal stabilizer skin panel is assembled by a team of three people. Several hand tools, as well as a fixture, are used. In the proposed Precision Assembly Process, a flexible contour fixture is used to hold the skins in the proper shape. Holes and slots are the primary features used for part location. These features are established at the fabrication stage. The assembly sequences for the as-is and proposed processes are found on the Process Interactions Matrices, Figure 6.3 and Figure 6.4.[2]

6.4 Key Characteristics

The first step in analyzing the two processes is to understand their goal. That is, the Key Characteristics for the system must be understood. As both processes produce the same product, the KC's for both processes are the same. As identified by Cunningham et. al. [7] , there are five KC's:

- PKC: Gap between the forward and aft skins of the skin assembly.
- AKC #1: Plus chord angle relative to aft skin edge.
- AKC #2: Plus Chord fore/aft position relative to aft skin.
- AKC #3: Spacing and contour of the splice plate, skin, plus chord sandwich structure.
- AKC #4: Blade seal hole locations.

Once the KC's for the processes have been identified, detailed analysis and comparisons can be completed.

6.5 As-Is Process

As in the nacelle example in Chapter 5 , the first step in analyzing any process is to understand the general assembly map. Several groups contribute to the as-is assembly process. There are basically four separate parts suppliers (all of them different organizations within the in-house fabrication department) and an assembly organization. Each of the four suppliers is responsible for making their

2. The proposed Precision Assembly process was developed by Messrs. Timothy Cunningham and Krish Mantripragada, and Dr. Daniel Whitney, of the MIT Fast and Flexible Manufacturing Process. Details of the development process and of the assembly steps can be found in [7] .

parts (the skins, plus chord, splice plate and stringers) and shipping them to the assembly station. At the assembly station, the skin panel is assembled using one fixture and several hand tools. Once the assembly is completed, it is sent to another group for riveting. It is then incorporated into the overall stabilizer structure.

Communication between each of these five groups tends to be limited to structured channels, such as IPTs and vertical management structures. Improvement efforts have a local, team-oriented focus. Information does not flow between teams on a regular basis. Instead, information is passed on to another group only if a problem is seen with the parts that group is producing.

Once the general assembly map is understood, a detailed examination of the interactions within the system can be undertaken. For the as-is process, this can be done in two ways. First, interviews of the personnel currently working on the process can be performed. Second, walking through the operations and understanding all of the factors that can cause variation in a KC can illuminate several of the interactions.

The reader will note that what these two steps are similar to those used to document the physical chain in the previous case study. In essence, that is precisely what we are doing here. However, because the nature of this study is different, additional techniques are needed. In particular, because one of the objectives of this case is to understand the total organizational impact of the new process, greater effort must be spent on understanding these organizational issues.

The next step is therefore to break down the interactions into different categories. As noted in Chapter 4 , there are four types of possible interactions. In order to differentiate the interactions into these four groups, each interaction must be examined closely. For example, when a stringer is first introduced into the assembly station, there is an interaction. This interaction exists because the stringer must be transported from the machine shop to the assembly area. It is therefore a worker-worker interaction.

As a further example, consider the process of locating the plus chord on the fixture. In this case, two interactions were noted. First, there was an interaction with the bump-forming process, where the plus chord obtains the shape with which it enters the assembly area. This is a part-part interaction, as the plus chord locating process depends upon the part features formed at the bump form stage. Second, there is worker-worker interaction associated with transporting the plus chord from fabrication to assembly.

Finally, consider the step at which the aft skin is clamped to the stringers on the fixture. Here there is one interaction, with the step at which the stringers are themselves loaded and clamped to contour. This interaction is different from those previously discussed, however, in that two types of interaction are happening at once. There is a part-tooling interaction, as the skin is being clamped into position using features on the fixture. In addition, there is a part-worker interaction, because the worker has a considerable role in deciding how to clamp the skin. Some judgement and experience is required in order for the step to be performed correctly.

Using this detailed knowledge of the interactions, a PIM for the as-is process can be drawn. The PIM is shown in Figure 6.3. Figure 6.5 shows the key for the interactions. The numbers in the first row and column in the matrix refer to process steps. A brief description of these steps can be found in Table 6.1. Note that the thick line that runs across to the diagonal represents an organizational boundary (Fabrication and Assembly organizations).[3]

It is worth noting that the PIM is used here because it conveys information that cannot be conveyed using a contact chain. In Figure 6.3, worker-worker interactions ('service elements') and part-worker interactions are shown. Displaying these interactions on a contact chain would be extremely difficult. Only part-part, part-tooling, and some worker-worker interactions ('physical elements') can easily be shown on a contact chain.

A quick examination of this PIM gives considerable insight into the nature of the as-is process. First, note that the PIM is broken down into several sections, each representing a different type of coupling.[4] Most of the interactions are located in the Assembly coupling and Fabrication-Assembly coupling regions. When only the physical elements are considered (i.e,. the worker-worker interactions, which mostly represent transportation, are ignored), the Assembly region is by far the most integral of the three regions.

Second, virtually all of the interactions are contained within a single team. The only exception are the part-part interactions associated with the plus chord and splice plate assembly steps. In addition, the majority of the interactions contain a combination of part-tooling and part-worker interactions.

Using this quick analysis, one can make several conclusions about the nature of the as-is process. First, the power to solve problems associated with the five KCs lies almost entirely with the assembly team. This is seen by the fact that the majority of the interactions in the system occur within the boundaries of the

3. Please refer to Figure 4.6 for further discussion of this point.
4. Please refer to Figure 4.6 on page 72 for a discussion of the difference between coupling regions and interactions.

assembly team. Fabrication and assembly are, for the most part, modular processes.

A follow-on from this is that the majority of learning in the as-is system happens primarily through either implicit loops or team-based explicit loops. Therefore, micro-skills are particularly important in the as-is process. In addition, the roles of the work teams, which enable them to effectively encompass all of the learning loops, are well designed from a learning perspective.

However, that said, the other point that should be made about the as-is process is that the limited number of learning loops does not allow for many learning opportunities. While the low-level of complexity in both the organization and technology is beneficial from a learning perspective, some complexity can easily be managed and incorporated into the system. For a small amount of added complexity, large amounts of learning can likely be achieved.

6.6 Precision Assembly Process

Much about the operating environment remains the same in the proposed, Precision Assembly process and in the as-is process. The assembly map is likely to remain constant, with four suppliers and one assembly team. What will change, however, is the roles of each of these organizations.

To understand exactly how their roles will change, the PIM analysis that was carried out for the as-is process must be repeated for the proposed process. One critical difference between the two processes must be kept in mind when constructing the PIM. Unlike the as-is process, the proposed process has not yet been implemented. This means that the techniques used to construct the PIM in the as-is case must be modified.

Instead of using interviews and observations, imagination and detailed analysis of the proposed assembly steps must be used. One must imagine the process in action, and walk through it in one's mind, asking the same questions as in the as-is case. How can variation enter the system and affect the KC? What parts and tools interact with each other? How exactly does this process work? How can it fail?

The implications of using this technique is that it is extremely likely that the PIM will be wrong. However, the challenge is in being close enough at an early stage to get a general idea of the preparation needed for implementation. The actual details can be understood as the process gets closer to implementation, or even after implementation has occurred. It will take some time before the PIM becomes fairly static.

Many of the interactions in the proposed process come from the fact that features created in one organization determine the performance of the system in another organization. Consider, for example, the step where Stringer 3 is located and attached to the aft skin. In the as-is process, this was accomplished using tool features and some worker judgement. The stringer was match drilled to ensure that the parts fit together. The match drilling process absorbed much of the variation.

In the proposed process, however, this is not possible. Holes and slots are created in both the aft skin and in Stringer 3 during their fabrication. This creates part-part interactions between the step when the assembly occurs and the steps where the holes are created. In addition, the step where the aft skin is located is itself important. Variation in any of these steps can prevent the assembly step from being successful. For example, if the holes are fabricated in the wrong places, they will not line up, and the fastener cannot be inserted.

Because of the widespread use of fabricated features, many of the interactions in the system are similar to that described above. The end result is shown in Figure 6.4. The description of the process steps in the PIM can be found in Table 6.2.

Again, several conclusions can be drawn from an examination of the PIM. The process is, in general, more integral than the as-is process. There is a great deal of both Assembly and Fabrication-Assembly coupling. Furthermore, most of the interactions are part-part interactions with only small amounts of part-worker interactions.

The presence of Fabrication-Assembly coupling indicates that there are explicit loops which transcend organizational boundaries. The fact that Assembly coupling also exists means that some of the loops are contained within the team. This combination represents a much more complex situation than that which existed in the as-is case.

Because of the increased organizational complexity associated with the explicit loops, techniques for reducing the effective complexity must be put into place. At least three different techniques can be used. First, the interactions map represented in the PIM shows the communications channels that need to exist. Effort should be made ensuring that these channels are in fact created – the perceived chain should match the physical chain. One way to do this would be to use computerized information management systems to make information transfer more efficient. Second, some of the organizational boundaries can be made more transparent. For example, teams could visit each other on a regular basis to learn about other processes in the system that affect their process. This would allow workers to gain a greater overall understanding of the workings of different elements of the system. Lastly, worker roles and skills can be designed so that workers are comfortable and able to work in the integral environment. They need to be given a mix of macro and micro-skills, and roles that allow both team-based system-wide improvement activities.

An important point to notice at this point is that these conclusions would remain the same even if a few of the interactions on the PIM are incorrect, or if some are left out. While the PIM should be updated as more accurate information becomes available, useful information can still be obtained from the PIM even at early stages in the process development, when all the details are not yet known.

6.7 Comparing the As-is and Proposed Processes

There are clearly some striking differences between the as-is and proposed processes. First, consider process architecture. The proposed process is has a much more integral architecture than the existing process. This makes sense intuitively. In the as-is case, a great deal of the part location was handled by tools and fixtures. Part locations were not a function of any previous steps. However, in the fixtureless case, part features, which were created during earlier fabrication stages, are much more important to the overall outcome. Thus, the amount of Assembly-Fabrication interaction is much greater in the proposed case.

Second, the nature of the interactions is different in the two cases. Because of the use of fabricated locating features, much more part-part interaction exists in the proposed case. This part-part interaction naturally has a great deal of part-worker content, because it is the worker who must line up the features and connect the two parts. (Note that in some cases, part-part may be accompanied instead by part-tooling interactions, as in a robotic assembly station.) The as-is process, on the other hand, has a great deal of part-tooling interaction. (Again, part-tooling interaction can either be accompanied by part-worker interactions, as in this case, or be completely part-tooling, as in robotic assembly.)

6.8 Learning and Worker Management in Precision Assembly

The two insights gained through use of the PIM provide valuable information about the changing nature of the assembly process, and have great implications for organizational design and operation. In particular, the two areas in which the implications are the largest are in learning and workforce management.

In the as-is process, the ratio of interactions to distinct assembly steps is quite low when compared to the proposed process. This means that the majority of learning that occurs in the as-is process will be implicit learning. There is some limited opportunity for explicit learning within the assembly team. However, because of the nature of the interactions, this explicit learning will not greatly improve the learning rate. Part-tooling interactions, even when accompanied by part-worker interactions, provide limited feedback to the worker. Much of the feedback is instead absorbed by the tool. In this case, the fixtures absorb much of the variation and interactions, often leaving the worker with simple pick and place tasks.

Opportunities for implicit learning also exist within the proposed process. Because the amount of human content involved in the tasks in both processes remains about constant, the amount of implicit learning should remain about the same. However, the high number of powerful explicit loops makes this type of learning a much greater factor. The part-part interactions provide much more feedback directly to the worker. In this case, the parts are somewhat flexible, meaning that some variation could possibly be absorbed by worker 'fixes'. However, the majority of the problems will come to light much more quickly than in the as-is case, meaning faster feedback and higher learning.

None of the learning improvements will occur unless the explicit loops are nurtured. In the simple case in which they are ignored, no explicit learning will happen. In fact, one of the risks of explicit loops is that neglect will lead to an overall worsening of the learning rate, with subsequent cost and quality problems. So, the risks are much higher with the integral architecture. However, if properly designed and implemented, the explicit loops can be a source of great gain.

One of the factors involved in creating the explicit loops is training the workforce to operate in this new environment. Workforce management techniques and philosophies must not remain as they are in the as-is process. Without innovation in the management of the workforce, the feedback channels necessary for information to flow up and down the chain will collapse.

The fundamental change that will occur when Precision Assembly is implemented is that **direct workers will become a much more critical part of the overall process.** Their responsibilities will increase, as will their contribution to the system. This is a direct result of the integral nature of the Precision Assembly Process. Workers will have to manage, understand and use the interactions in the process.

Consider just one of the integral regions – where the plus chord is attached to the system (Steps 26 and 27) – as an example. The PIM in Figure 6.4 indicates that there are several interactions that are important at Step 26, where the plus chord is located to the skins and stringer 3. These interactions fall within both the Fabrication-Assembly coupling and Assembly coupling regions, and are a combination of part-part and worker-worker interactions. In addition, note that the parts being used in Step 26 are a combination of fairly rigid (plus chord) and flexible (skins and stringer). First, consider the interactions in the Assembly coupling region. These are the interactions which the worker has direct control over. The explicit loop is contained within the team, and organizational complexity is relatively small. However, because of the flexible nature of some of the parts, the part-part interactions in this region rely on the workers' actions and judgements. It is possible that part could be forced to fit, perhaps inadvertently. The direct workers are the only ones who can manage or plan the interactions and ensure that problems are noticed and corrected. In contrast, in the as-is process, the tools and fixtures largely take care of these 'management' and planning tasks. Much of the variation is absorbed by the fixtures, and many of the problems are, in fact, hidden by the fixtures. In the as-is process, the fixture was the glue that held the process together; in the Precision Assembly process, the people are the glue.

Second, consider the part-part interactions that lie in the Fabrication-Assembly coupling region. Here, the interactions exist because of features that were made in parts at the fabrication stage. There are at least two possible ways to manage these interactions. On the one hand, the direct workers could be responsible for their management, meaning that they would be the ones who would communicate with the fabrication teams. In this scenario, the direct workers obviously need a great deal of system knowledge to ensure that their perceived chain is accurate, and to aid in troubleshooting. On the other hand, indirect workers could be made responsible for all inter-organizational communication. However, as pointed out in the nacelle example, this leads to several problems. Foremost among these is the delay in the feedback loop that results from the addition of the extra element (indirect workers) into the loop. A related problem is that the group responsible for the problem recognition (direct workers) is not the same as the group with problem solving responsibilities (indirect workers). Explicit-loop learning is therefore much less efficient. The ideal scenario is, therefore, the former. Indeed, this scenario is much more in line with the conclusions reached by examining the Assembly coupling region interactions. As a result, it can be concluded that not only is it more efficient for direct workers to assume a much larger role in the new process, it is, in fact, necessary for the system to operate smoothly.

The above example focused on only two steps in the Precision Assembly process. Yet, those steps are typical of many of the steps in the process. Given this situation, the issues identified in the above example are greatly magnified. However, the example should not lead anyone to think that indirect workers will no longer have a place in the assembly process. On the contrary, they should be involved, but working as a resource and aid for the direct work teams, instead of as an independent entity. They can become a source of new ideas, technical expertise, and systems knowledge, while leaving much of the actual analysis and the main tasks (such as communication) associated with both local and systems level problem solving to the direct teams.

To prepare for this change, the direct and indirect workers must be involved in the actual design of the process, and in the creation and operation of the organizational structure. A situation in which a group of engineers design a process and then try to implement it will lead to reduced buy-in and motivation for the new process by the direct workers. If this lack of buy-in occurs, it will foster a positive feedback loop where the effectiveness of the new process is continually reduced; the process will enter a death spiral from which it will be very difficult to recover.

Among the changes needed in the workforce are improved systems thinking and communications skills. Team structures should be created to encompass as much of the explicit loops as possible. This could be accomplished by, for example, creating a liaison team in areas in which there are large clusters of interactions. These teams would be made up of direct and indirect workers from the teams responsible for and affected by the interactions. It is critical to have both the direct and indirect workers (maintenance, transportation, engineering support as well as mechanics) involved in the process because each of these people does some of the learning and possesses some of the knowledge the others need.

With all of the changes needed in the areas of workforce management and organizational design/supplier management, it should be clear that these issues must be addressed before implementation occurs. This is particularly important because of the increased complexity in the proposed process. While explicit loops provide greater opportunities for learning, operating the system without actively taking steps to reduce the complexity will yield a chaotic and worsening situation. Only by taking proactive complexity management steps can a disastrous situation be avoided.

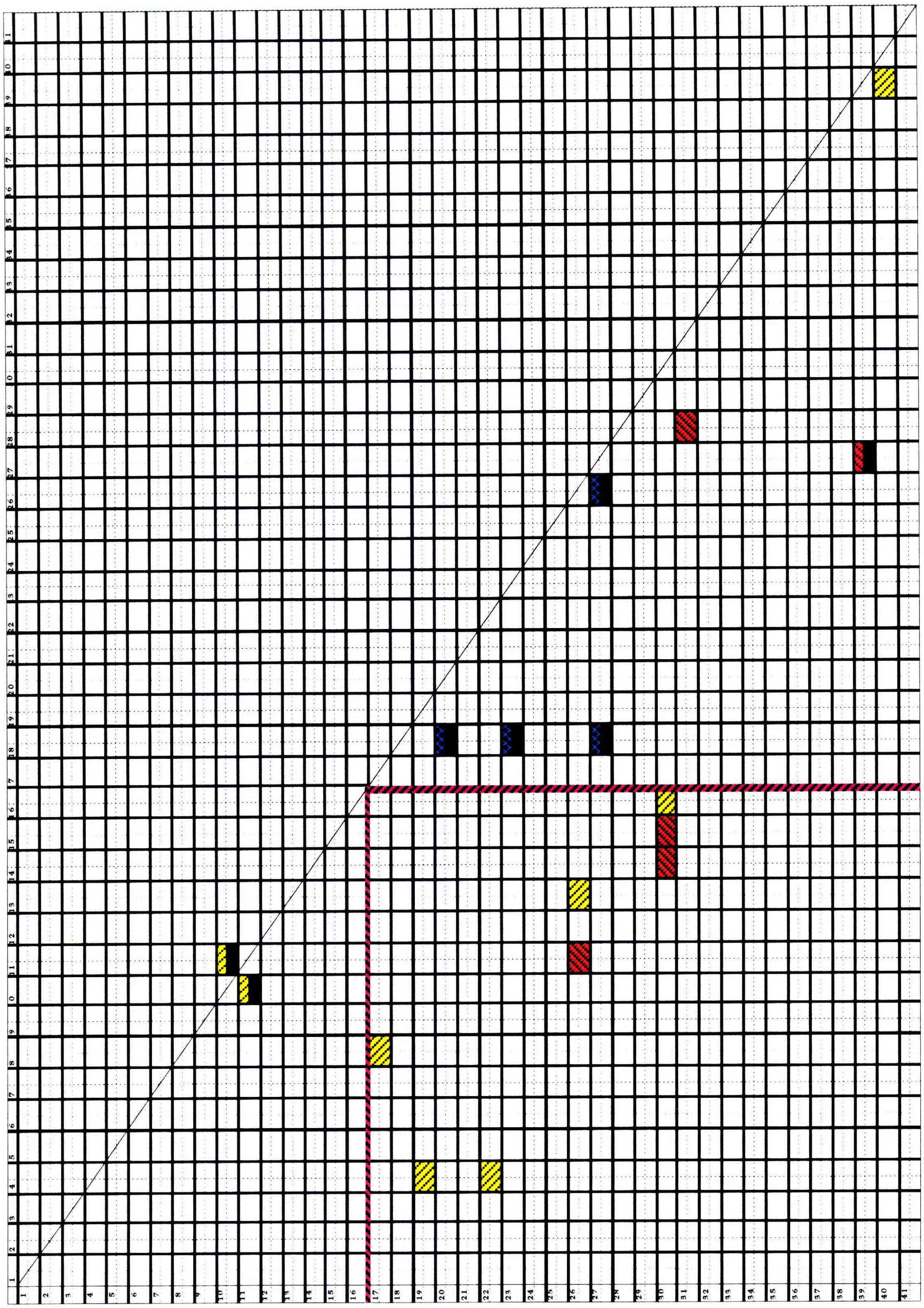

Figure 6.3: Process Interactions Matrix for the As-Is Assembly Process.

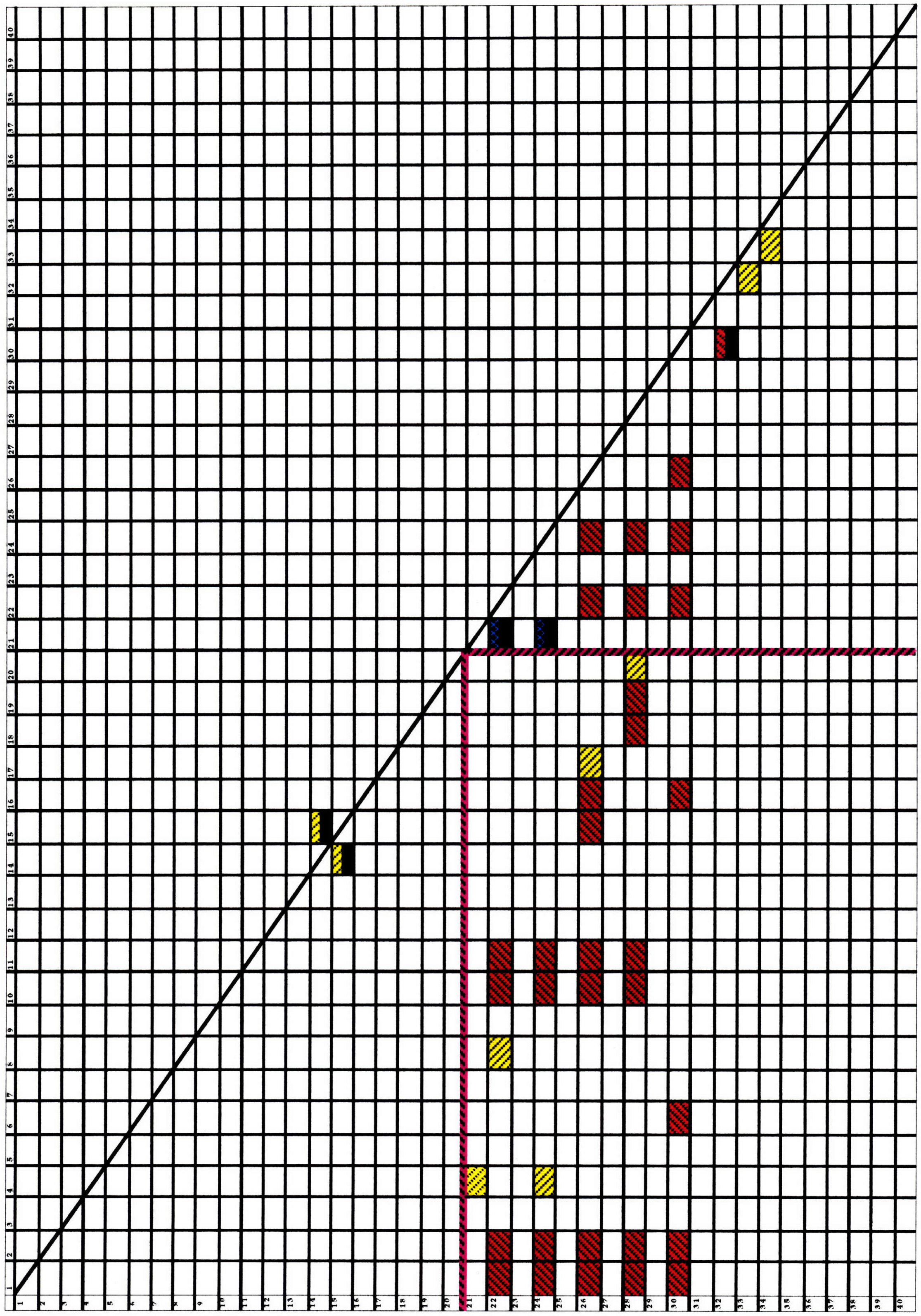

Figure 6.4: Process Interactions Matrix for Proposed Precision Assembly Process.

Figure 6.5: Key for Process Interactions Matrices Interactions

Step Number in PIM	Description
1	Machine on Gantry Mill
2	Shot Peen
3	Paint
4	Anodize
5	Machine undersize on spar mill
6	Shot Peen
7	Drill undersized holes
8	Paint
9	Machine
10	Inspect on Check Fixture
11	Bump form on arbor press
12	Shot Peen
13	Paint
14	Machine and drill on Gantry Mill
15	Shot Peen
16	Paint
17	Locate stringers

Table 6.1: As-is Process Fabrication and Assembly Steps for PIM in Figure 6.3:

Step Number in PIM	Description
18	Clamp to contour
19	Locate aft skin
20	Clamp to stringers
21	Match drill and tack
22	Locate forward skin
23	Clamp to stringers
24	Match drill and tack
25	Spray dots on skin
26	Locate plus chord
27	Match stringers to plus chord
28	Drill holes through skin and plus chord
29	Trim forward skin
30	Locate splice plate using coord holes
31	Drill holes
32	Locate splice plate in main fixture
33	Drill holes
34	Disassemble plus chord and splice plate
35	Deburr
36	Reassemble
37	Fasten
38	Remove assembly from fixture
39	Shim stringer and plus chord
40	Fasten stringers 3-11to plus chord
41	Rivet skins to stringer (not Aft skin to S3)

Table 6.1: As-is Process Fabrication and Assembly Steps for PIM in Figure 6.3:

Step Number in PIM	Description
1	Machine Skins on Gantry Mill, including features
2	Shot Peen
3	Paint
4	Anodize
5	Machine Stringer 3 undersize on spar mill
6	Drill holes
7	Shot Peen
8	Paint
9	Machine remaining stringers undersize on spar mill
10	Create features on mill
11	Shot Peen
12	Paint
13	Machine plus chord and create features
14	Inspect on Check Fixtures
15	Bump on Arbor Press
16	Shot Peen
17	Paint
18	Machine splice plate and create features on gantry mill
19	Shot Peen
20	Paint
21	Load Aft Skin on Flexible Contour Fixture
22	Locate Stringer 3 to aft skin holes and slots
23	Tack Stringer 3 to aft skin
24	Locate forward skin to Stringer 3 holes and slots
25	Tack Forward Skin to Stringer 3

Table 6.2: Proposed Process Fabrication and Assembly Steps

26	Locate Plus Chord to aft and forward skin and S3
27	Tack Plus Chord to parts
28	Locate Splice Plate to aft and forward skin and S3
29	Tack Splice Plate to parts
30	Locate stringers to plus-chord and skins
31	Tack stringer to +-chord and skin
32	Shim stringers to +-chord
33	Autorivet
34	Drill through splice plate, +-chord and skin
35	Drill blade seal holes
36	Drill stringer to +-chord holes
37	Disassemble
38	Deburr
39	Reassemble
40	Fasten

Table 6.2: Proposed Process Fabrication and Assembly Steps

Chapter 7

Conclusions

7.1 Aligning Technical and Organizational Strategies

Learning rates are typically considered to be intrinsic properties of systems. Because of this, little thought goes into "design for learning". Yet, in industries in which learning is extremely important (those with short product life cycles or low production volumes), the success of a new product or process can be greatly improved when learning is considered as a process is being designed.

Only recently have studies begun to examine the mechanisms behind learning in product development and manufacturing systems. Several authors spell out the role of organizational factors in the success of new product and process implementation. Few of these authors provide tools for understanding exactly how to analyze and make decisions on the necessary organizational adaptation.

This thesis represents an initial attempt at developing a framework for understanding the organizational adaptation necessary when a new process is introduced. This chapter contains a summary of the conclusions reached in the thesis, as well as a discussion of some of the implications of these conclusions.

7.2 Two Categories of Learning

All learning occurs through feedback. One of the central hypotheses of this thesis is that there are two fundamental feedback mechanisms behind the 'learning by doing' phenomenon that is the basis of the learning curve. Implicit loop learning is that which happens at the individual worker level as a 'natural' part of their tasks. Explicit loop learning is that which happens through deliberate actions and effort. Both of these loops operate in both the single-loop and double-loop learning environments defined by Argyris. [2]

The concepts of implicit and explicit loop learning help form a link between two areas that have, until now, been quite separate: process improvement and learning. Process improvement efforts such as those developed by Dr. Deming involve the creation of explicit learning loops. The learning-through-experience phenomenon, on the other hand, acts primarily through implicit learning loops.

Furthermore, implicit and explicit learning loops provide the link between organizational and technical aspects of manufacturing systems. Combined with tools such as contact chains and the Process Interactions Matrix, a reliable map of the organizational infrastructure needed for successful process implementation can be generated. Communications flows, skill levels and worker roles can all be designed before a process is implemented.

Lastly, the concepts of implicit and explicit learning loops helps to explain one of the misconceptions behind the learning curve discussions – that labor-intensive processes must learn faster than capital-intensive processes. This holds for the most part when only implicit learning loops exists. As implicit learning loops are contained completely within a single person, the more people contribute to a process, the more learning will happen. However, explicit loops are not subject to this constraint. Their only requirement is that there be a person at at least one link in the loop. The rest of the links could involve machines. Neither implicit loops nor explicit loops are stronger than the other. In some cases, labor-intensive processes might have higher learning rates than similar, capital intensive machines. The important point is that <u>this need not always be the case.</u>

The main contribution of this thesis lies in the links made between process improvement and learning on the one hand, and between learning and technical systems on the other.

7.3 Design for Learning

Whether one is dealing with a new process that has yet to be implemented, or with an existing process that is not operating at its peak level, certain techniques developed in this thesis can help to improve a system's operations.

The primary method for improving systems is to identify discrepancies between the desired state of the system, and the actual state. This is done using physical and perceived chains, illustrated using either the contact chain or the process interactions matrix. The physical chain represents the communication that needs to exist for a system to perform successfully. As such, it also represents the explicit learning loops that need to be created. Matching this desired state to the actual state, as shown by the perceived chain, allows resources to be allocated correctly and feedback to be efficiently processed and utilized.

Once learning loops have been identified and created, they should be strengthened so that the maximum benefit can be realized. Depending on the type of loop, loop strength depends on a variety of factors including worker roles and skills, the efficiency of feedback channels and the complexity of the organizational and technical systems compared to the worker skills and roles. Techniques for decreasing the complexity of systems (thereby improving learning rates) include the use of IT systems to facilitate information flows, and the design of worker roles to encompass all of the explicit loops. To this end, a general rule of thumb is that processes contained within a team should be as integral as possible, whereas the processes between teams should be as modular as possible. There should be as few interactions between teams as possible. The limiting factor in either case is the manageable level of complexity.

7.4 Continuous Process Improvement

Continuous process improvement methodologies have been extremely successful in increasing the quality and reducing the cost of products. The traditional techniques – risk analysis, SPC, cause and effect diagrams – have their limitations, particularly in integral process environments.

One of Deming's 14 Points for Top Management [8] states the importance of requiring statistical evidence of part quality from critical part suppliers. This is certainly critical. However, a negative result has been the promotion of a part-focus, often at the exclusion of all else. In many products today, it is not so much any particular part that is important as much as it is the way in which these parts come together. The critical interfaces and process flows are as important as the critical parts.

In systems with many interconnections in either the product or process, these interfaces and flows are often the most significant sources of variation. Using traditional improvement techniques, however, these sources are often passed over. The contact chain is a tool for refocusing process improvement efforts. Parts and interfaces that form part of a particular contact chain are the sources of variation for a system.

The advantage of the contact chain approach is that the biases developed through experience and ingrained philosophies do not play a role. Techniques such as risk analysis, by contrast, are often tainted by the lack of systems knowledge of the workers, or by internal biases. Using the physical contact chain as a focus for SPC, root cause analysis and other improvement techniques allows the part and process focus to be combined into an overall systems view.

7.5 Agility, Virtual Organizations and Supply Chain Management

Using the systems view provided by the contact chain results in more complete process improvement efforts. However, the implications of this approach are far-reaching.

Consider the discussions of agile production and virtual organizations. In such environments, suppliers are changed as needed, partnerships are made one day and dissolved the next. In an increasingly 'agile' environment, in which suppliers and products both change rapidly, there is even less opportunity to understand other processes, not to mention your own processes.

How much process improvement and learning can occur in this environment is questionable. This seems to be a major limitation of the agile model, and one which could significantly degrade its effectiveness, particularly in environments with integral process architectures. As the process architecture becomes more modular, the possibility of successfully manufacturing in an agile environment improves.

7.6 Make-Buy Decisions

Fine and Whitney [12] have discussed the link between product architecture and make-buy decisions. Much of this discussion relies on the level of product and process knowledge possessed by the product company. The more critical the part to the overall function of the product, and the more reliant you are on the supplier for knowledge and expertise, the riskier is outsourcing.

Process Architecture as another indication of outsourcing risk. The risk here is not that the supplier could supplant you; instead, it is that outsourcing will significantly affect productivity and quality in your process. Integral processes rely heavily upon other stages being completed successfully. When a supplier has control of critical stages in the KC realization chain, the control you have over the process outcome is greatly diminished.

More importantly, however, as links in the chain are outsourced, the less systems knowledge is held by the prime. This affects the ability of the prime to improve their processes and products, and their capability for developing new processes that overcome the limitations of the existing ones.

The issue here is one of knowledge management. If two companies have equally integral processes, dispersed to the same types of supplier organizations, the one that can manage the system knowledge will have the competitive edge. Knowledge management should be a core competency of any company making a product in a complex product realization web.

7.7 Reengineering

The fundamental shift in outlook from parts to processes and systems is, of course, not new. One of the places where it can be seen is in the business process reengineering efforts that are taking place in corporations throughout the world.

The initial idea behind reengineering was that, by reorganizing businesses to focus upon the processes that produced their products rather than upon functional organizations, productivity and quality could be improved.

Much of this is similar to the idea behind the contact chain. In a manufacturing system, most of the emphasis is on the functional organizations or individual assembly stations and parts. Changing this to a focus on the processes through which the outcomes (KCs) are achieved will yield gains in productivity, time and quality.

Both approaches emphasize the power of designing the process specifically to achieve the desired outcome. Instead of accepting the chains that have built up over a long period of time, one should proactively create the chains that are best for the system.

A few differences do exist. First, most manufacturing systems cannot be reorganized very easily. The change to a process focus happens more on an organizational level than on a fundamental structural level. Second, reengineering is process focused, but not systems focused. Similar to the initial 'tree' view of the supply chain, reengineeding efforts typically do not account for interconnections and feedback between elements. Contact chains can add to reengineering by incorporating the systems view into standard reengineering efforts.

Another difference between reengineering and the work presented in this thesis is that the standard reengineering approach is to make processes as simple as possible. While this sounds appealing, it may not always yield the best results. From the perspective of learning, higher levels of learning should be possible if one is willing to live with some complexity. The challenge is not in simplifying processes as much as possible, but in recognizing the level of complexity that can be effectively managed.

7.8 Beyond Manufacturing Processes

In this thesis, chains have been used to understand manufacturing systems. However, the fundamental principles behind chains – focusing on process, not distinct elements, and an emphasis on the system semantics (the interfaces between elements and how they are achieved) – can be applied to a variety of systems.

The requirements for the use of the chains are that there be some definable outcome, and that the interfaces between elements be understood well enough to provide insights into the process through which the outcome is achieved. This criteria can be applied to many different areas, particularly in service industries such financial transactions.

7.9 Future Research Areas

The concepts of explicit loop and implicit loop learning presented in this thesis deserves more attention. The working hypothesis for this thesis was that all learning could be explained by these two types of feedback loops. While implicit loop and explicit loop learning certainly exist, it is worthwhile to investigate whether any other forms of learning also exist. In addition, each type of loop can be broken down into more detailed categories. If this is done, detailed prescriptions for improving learning in particular situations could be more easily generated. Another area of investigation lies in determining the strength and benefit of particular learning loops. The blanket statement made in this thesis that "the more loops the better" is certainly an oversimplification. A system for refining this idea is needed.

There are several areas in which additional research would be beneficial. First, large scale comparisons could be made between 'learning' companies and other organizations to identify various techniques for implementing explicit loop learning infrastructure. Secondly, in order to be better able to quantitatively understand the benefits of different processes, the different types of interactions and their relative strengths should be studied further. A third area, tying into this, would be an investigation of the link between learning rate, quality improvement rate, the number of feedback loops and the strength of the various interactions. The end result would be a model through which various processes could be quickly compared quantitatively.

Lastly, the issue of complexity is interesting and needs to be observed further. Can tools be developed to help managers determine what level of complexity they can live with? Can a more rigorous approach to the trade-offs between learning loops and complexity be developed? Studies to answer these questions would be enormously beneficial to managers.

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