# A SYSTEM COMPLEXITY APPROACH FOR THE INTEGRATION OF PRODUCT DEVELOPMENT AND PRODUCTION SYSTEM DESIGN

by

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## ABSTRACT

Complexity is generally believed to be one of the main causes of present difficulties in plant design and control. The complexity of a manufacturing system cannot be viewed without considering the products produced in the system. Lack of understanding in this relationship may lead to difficulties in product portfolio design and manufacturing system design. In this thesis, it is shown that by designing a manufacturing system properly, we can manage increased product variety while simultaneously eliminating system complexity. In addition, this thesis explains how 'lean' concepts eliminate system complexity.

To see and compare complexity of manufacturing systems, complexity metrics are developed based on a complexity model provided by system theory. These metrics focus on sources of complexity to facilitate system improvements in terms of system complexity. With these metrics, a case study was carried out to apply these complexity metrics to a real industry case. In this case study, a lean manufacturing system that substitutes the existing mass-type manufacturing system is proposed and the impacts of this conversion on manufacturing system complexity are studied. According to this case study, the complexity of the proposed lean production system is much less than the complexity of the existing system in terms of proposed complexity metrics.

Once the complexity of a manufacturing system is well understood, the manufacturing system can be designed to decrease complexity. In addition, product families can be designed for manufacturing systems and detailed product designs for manufacturing systems are possible.

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# CHAPTER 1. INTRODUCTION

In today's highly competitive market environment, it is essential to approach the market with a strategic product portfolio that will satisfy various customer requirements while considering a company's capabilities and long-term goals, with an understanding of future market opportunities. Therefore, choice of a product portfolio is a central factor in influencing a company's chances for success [1]. In this context, Clausing [2] developed a model to explain the relationship between the characteristics of product portfolio and total cost, including cost and revenue loss due to non-ideal product variety. In his model, he focused on complexity and product variety impact to explain how feasible optimum point can be achieved. This model can be summarized into a three dimensional graph as follows:

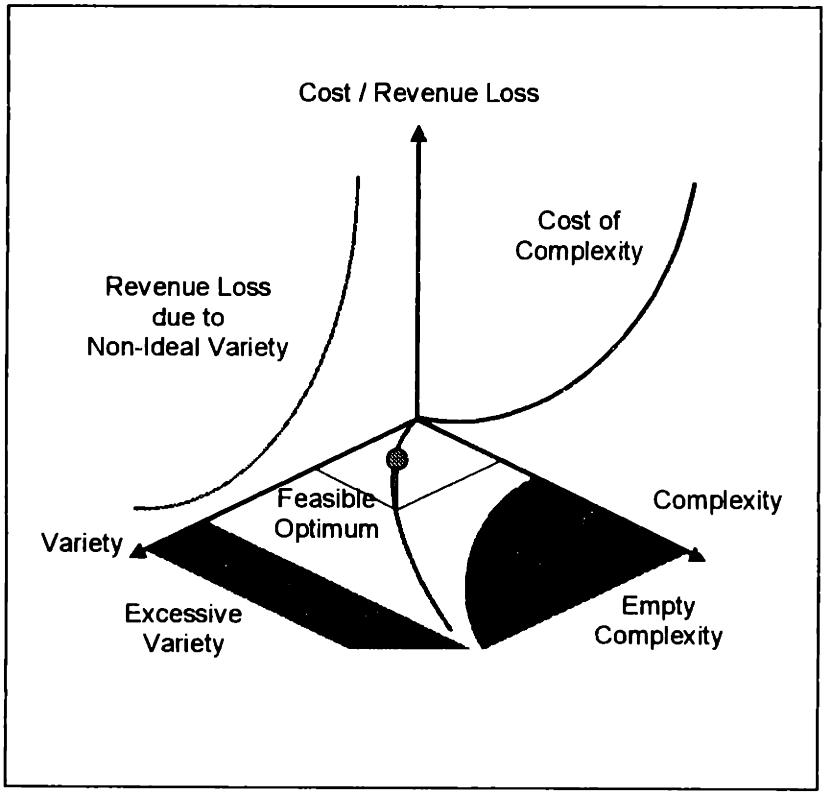

Figure 1-1. Variety – Complexity – Total Cost Model [2]

In this model, product variety and complexity relations are on focus of this thesis. Figure 1-1 shows Clausing's claim that if variety increases, complexity increases exponentially, which eventually increases costs exponentially. Here, complexity is the product complexity that is linked to difficulties in product design processes and manufacturing. Focusing on difficulties in manufacturing, this model may be restated as increased product variety adds more complexity to a manufacturing system and will be followed by increased cost. However, it is doubtful that the relationship between product variety and manufacturing complexity is really exponential. Research in production system design shows that with proper manufacturing system design, such as a lean manufacturing system design, a system's complexity does not necessarily increase exponentially as product variety escalates. Consequently, cost itself does not increase exponentially.

In fact, the advantage of having the right manufacturing system design has been cited by many researchers such as Ulrich [3], Fisher et al. [4], Ishii[5], and MacDuffie et al. [6] qualitatively and intuitively as an advantage of lean manufacturing systems. However, there has not been any supportive proof in a quantitative way.

This thesis shows that, in terms of 'quantifiable' metrics, by designing a manufacturing system properly, we can manage increased product variety and simultaneously eliminate system complexity. In addition to this, it is shown and explained how 'lean' concepts reduce system complexity.

## 1.1. Why Complexity?

There have been several approaches to evaluating the impact of product variety on the manufacturing system. For example, MacDuffie et al. [6] show, in their analysis of the productivity of 62 auto assembly plants worldwide, that there is no correlation between measures of product variety and plant productivity. Fisher et al. [4] discuss ways various manufacturing systems handle product variety. This research was performed from the managerial perspective. On the other hand, from the engineering point of view, vast research related to FMS (Flexible Manufacturing System) has dealt with increased product variety in terms of flexible automation. Recently, Ishii [5], and Martin and Ishii [7], [8] developed metrics to measure the cost impact of product variety in his design for variety research (DFV). DFV is unique from the perspective that it provides quantifiable indices to measure and compare the costs of product variety. In their research, Martin and Ishii claim that the manufacturing cost of dealing with a variety of products consists of direct and indirect costs [7]. The direct costs are easy to calculate and include increased capital equipment, more training of personnel, the engineering time required to make new drawings and analyze the new design, run certification or qualification tests, and to find new suppliers. However, indirect costs are more difficult to consider and include raw material inventory, work in process inventory, finished goods inventory, post-sales service inventory, reduction in capacity due to set-up, and the increased logistics of managing the product variety.

With these concepts, Martin and Ishii developed three indices that measure: the commonality of the parts, the differentiation point in manufacturing processes, and setup costs. The costs related to the increased product variety can be decreased by increasing the commonality of parts, postponing the differentiation point, and decreasing setup costs.

However, in his approach, Ishii does not seem to have considered the fact that through proper design, a production system with a high degree of product variety can achieve exceptional performance characteristics. He assumes that the impact of product variety is confined to increases in inventory, production capacity loss by frequent setups, and problems in logistics. More importantly, he assumes that the production system is a fixed entity, which may not be true under the continuous improvement environment. In other words, if we have a different production system design, we may be able to decrease the cost due to product variety without increasing the commonality of parts, postponing the differentiation point, or decreasing the setup costs. Therefore, the Martin – Ishii indices should be reexamined from the system point of view while considering the relationship with other system elements and system performance[1].

For these reasons, this thesis proposes a system complexity approach to deal with increased product variety more efficiently. We believe that by studying the change in system complexity under increased product variety conditions, we can see the impact of product variety on system performance and gain insight into what a manufacturing system should look like. This insight will eventually lead us to proper product design to help the manufacturing system to manage increased product variety, since product design and production system design are reciprocal relations.

---

[1] In fact, Fisher et al. [4] point out that many attempts to increase the commonality of parts eventually failed due to the lack of providing the literal meaning of 'variety'. In the same context, postponing the differentiation point may not work. In other words, reducing complexity of manufacturing systems by these strategies may be possible, but if they eliminate the real variety of products, they are not the right approaches to reduce complexity.

## 1.2. Assumptions and Hypothesis

Underlying assumptions in this research are:

- Cost is proportional to manufacturing system complexity.
- A manufacturing system's complexity can be seen by measuring some attributes of the system.

The first assumption is based on the growing consensus that complexity is the major source of difficulties in designing and operating a system. To maintain a complex system to be in a desirable state, efforts should be taken to solve many problems that drive a system into unwanted states. These efforts may be seen as a certain type of cost. In addition, possible revenue loss caused by poor performance of a system due to its complexity may be considered as cost.

The second assumption is about the way to perceive complexity itself. In fact, it is not so clear what the essence of complexity is, so as to make it difficult to see or measure complexity itself. For example, if there exist a large number of relations between system components, this system may be said to be complex because it is difficult to control, or predict behaviors of this system. However, a number of relations does not necessarily show complexity itself. Rather, it is a kind of possible source of complexity. On the other hand, probability of this system to fall into an undesirable state, for instance, may be seen as describing complexity itself. Since research interests lie in reducing system complexity by modifying some system attributes, knowledge on sources of complexity will be more helpful than that on complexity itself. In this context, sources of complexity are focused rather than complexity itself in this thesis and it is assumed that system complexity can be seen from its resources.

The hypothesis to be proved by this thesis is:

"In a lean manufacturing system, system complexity as affected by increased product variety is much less than that in an equivalent mass production system."

As mentioned before, many studies have discussed and claimed that lean manufacturing systems can manage increased product variety more efficiently than conventional mass production systems. The unique part of this thesis lies in the notion of system complexity and adopting it to show that this is true in terms of suggested complexity metrics.

The hypothesis can be summarized by the following graphs.

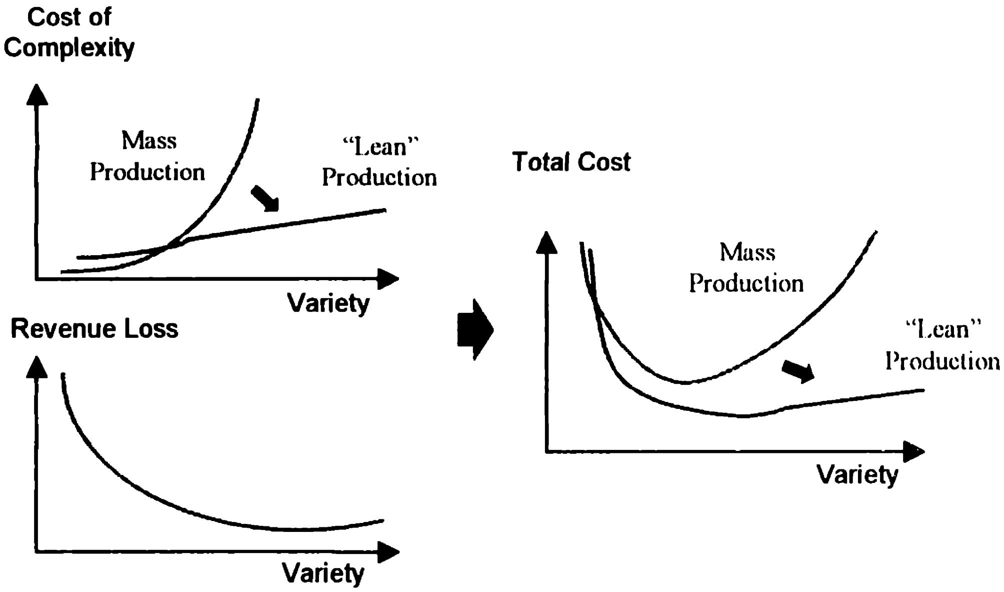

Figure 1-2. Hypothesis

## 1.3. Research Approach

First, the complexity of a manufacturing system is defined. To develop the right definition of complexity that fits for the purpose of this thesis without losing the fundamental ideas on complexity, two approaches are taken. One is to consult various literature, especially in the area of system theory, to capture fundamental ideas on complexity. The other is to investigate insights and ideas for the complexity of systems in various fields to see different definitions and meanings of complexity according to different interests. Based on knowledge and understanding of complexity from these two approaches, a definition of complexity of a manufacturing system in our context is then provided.

The second phase is the development of complexity metrics based on the definition of complexity of a manufacturing system that is defined in the first phase. For background research, existing methods for measuring the complexity of a system are presented and their advantages and disadvantages are discussed. Then new metrics to measure the complexity of a manufacturing system are proposed considering advantages and disadvantages of these existing methods.

Third, by using of these new metrics, the change in complexity of a manufacturing system as the product variety in the system increases is investigated. Here, it is shown that the complexity of a manufacturing system that adopts lean strategies is much less than that of an equivalent manufacturing system that adopts mass production strategies. Based on the relationships between product variety and complexity of manufacturing systems, strategies for product variety and manufacturing system design are discussed from the product portfolio decision point of view.

Finally, we provide a case study showing the application of these metrics to a real system. The comparison of an existing system with a suggested system in terms of system complexity metrics is done and provided. In this case study, it is shown that the lean manufacturing system suggested has much less complexity than the existing mass production system, which results in lower costs while keeping higher controllability and predictability.

# CHAPTER 2. COMPLEXITY

## 2.1. Definition of Complexity

The word complexity itself is not an easy word to define. Each of the researchers has used a different definition of complexity using general and implicit terms. The Webster's English dictionary defines the word 'complex' as 'difficult to understand, or explain'. Starting from this intuitive definition of the 'complex', there are many definitions and explanations of complexity or a complex system that are somewhat different according to the area of interests. Some of them are listed in Table 2-1.

From the fact that there are many definitions and explanations of complexity according to different areas of interest, we may infer that complexity does not have a unique, universally applicable definition. In fact, this is the problem with defining complexity since, indeed, complexity is characterized by the absence of one single dominating task that can be considered as most important. In other words, we can say that it is a characteristic of complexity that it has many facets or dimensions. In this context, Klir [11] stated that "it is not operationally meaningful to view complexity as an intrinsic property of objects".

Due to this ambiguity, in this paper we loosely define complexity as 'difficulty in understanding or explaining a system to achieve some 'goals' of a system'. The reason we add the phrase about achieving some goals is that the focus is on a manufacturing system and a manufacturing system design exists to achieve its goals. In other words, complexity in pursuing the goals of a manufacturing system is within our interest throughout this thesis.

| Fields of studies | Definition or Explanation of Complexity or a Complex system |
|---|---|
| Computer Science [9, p3] | The complexity of an object (pattern, string, machine, algorithm, ...) is the difficulty of the most important task associated with this object. |
| Biology [10, p193] | A complex system has a multitude of partial simple descriptions but we cannot construct from them a single "largest" description that is also simple. In this sense, the reductionistic paradigm fails for complex systems |
| Manufacturing Science [11, p7] | A manufacturing system may make thousands of part types (not just parts) during a year. There may be hundreds of machines. At each moment, the managers are faced with hundreds of decisions, such as: which part should be loaded onto each machine next? The consequences of each decision are hard to predict. |
| Physics [9, p22] | A complex system is a complicated system, composed of many parts, whose properties cannot be understood. |
| Information theory | The complexity of a system is closely related to the content of the information that the system contains. |
| International system theory [12, p9] | In objective terms: Complex systems are those that have many components, many feedback loops among those components, and multiple Interconnections among subsystems.<br>In subjective terms: Complex systems involve unfamiliar sequences, or unplanned and unexpected sequences, either not visible or not immediately comprehensible, because of their complex interconnections and multiple feedback channels. |
| Large technological system [9, p94] | A system is complex when it is built up of a plurality of interacting elements, of a variety of kinds, in such a way that in the holistic result no evidence an be traced of the characteristics of the single elements. |
| ... | |

Table 2-1. Various Views to Complexity or a Complex system

## 2.2. Characteristics of Complex Systems

According to Rosen, R. [10], characteristics of complex systems are as follows:

1) There can be no such thing as a "state space" in a mathematical image of a complex system, which can be fixed once and for all. More generally, the causal categories (which become much subtler in this context) cannot be segregated into disjoint classes; at least some elements of our image play several causal roles simultaneously. Moreover. These causal roles can shift in the course of time as a consequence of a system dynamics.

2) A complex system will have a multitude of partial images of the Newtonian type, which can in some sense "approximate" to the behavior of the system. But this approximation of complexity by simplicity is only local and temporary. This means that, as the complexity system develops in time, any such simple approximation ceases to describe the system. The discrepancy between what the complex system is actually doing and the behavior of the simple approximation grows in time. When the discrepancy becomes intolerable, we must replace our initial simple approximation by another. The discrepancy between the behavior of a complex system and any such simple approximation is depending on the context, called error or emergence.

3) Even though a complex system has a multitude of partial simple descriptions, we cannot construct from them a single "largest" description that is also simple. In this sense, the reductionistic paradigm fails for complex systems.

4) The great richness of causal structure in complex systems makes the problem of interpretation or explanation of experimental observation very different from what we are used to.

5) In complex systems, an ideal of final causation or anticipation can be introduced in a perfectly rigorous, nonmystical way. Briefly, a complex system may contain

predictive models of itself and/ or its environment, which it can utilize to modify its own present activities.

6) Because complex systems ultimately depart from the behavior predicted on the basis of any simple approximation, their behavior appears to us to be surprising and counterintuitive.

In this context, trials to capture unique images of complexity may not be promising. We should keep in mind that the complexity of a manufacturing system can be seen from many perspectives and has many dimensions.

## 2.3. Complexity Issues in Manufacturing System

### 2.3.1. Definition of a Manufacturing System

There are several definitions of a manufacturing system, most of which are similar. Cochran and Lima [12] define a manufacturing system, "as a subset of the production system and the arrangement and operation of elements (machines, tools, material, people, and information) to produce a value-added physical, informational or service product whose success and cost is characterized by the measurable parameters of the system design." From this statement we understand that a manufacturing system has 'elements' and by assembling and managing of these elements, the relationships between them are defined.

### 2.3.2. Complexity Issues in Manufacturing Systems

Today complexity is generally believed to be one of the main causes of present difficulties in plant design and control. According to Toni and Tonchia [13], system complexity is linked to two dimensions: uncertainty and time. Uncertainty may come from a lack of information or a lack of knowledge caused by the limits of those who take decisions. On the other hand, time intervenes in terms of sequentiality and cumulativeness. Sequentiality directs the irreversibility of incidents and decisions, cumulativeness is linked to the accumulation of knowledge which will improve decision-making performance.

For example, a manufacturing system may make thousands of part types (not just parts) during a year while the demand for these products arrives and varies almost randomly. There may be hundreds of machines in a plant that might fail at any time. At each moment, the managers are faced with hundreds of decisions, such as which part should be loaded onto each machine next and must make decisions in spite of insufficient information. The consequences of each decision are hard to predict. Table 2-2 shows some of the activities and events that happen in a manufacturing system [14].

|  | Controllable | Uncontrollable |  |
|---|---|---|---|
| Activities | • Operations<br>• Maintenance<br>• Setup changes<br>• Calibration | Unpredictable | • Failures<br>• Repair times<br>• Worker absence<br>• Vendor non-delivery<br>• Starvation<br>• Blockage |
|  |  | Predictable | • Holidays, lunch, and other breaks<br>• Training sessions |
| Non-Activity events | • Acquisition of new equipment | Demand changes<br>Engineering changes<br>Rejection<br>Rework |  |

Table 2-2. Examples of Events and Activities in a Manufacturing System [14]

# CHAPTER 3. COMPLEXITY METRICS

## 3.1. Existing Approaches to Measuring Complexity

In this chapter, existing approaches to measure complexity are studied. Most of literature consults on the concept of information that is originally developed by Shannon [72]. Advantages and disadvantages of this information approach are provided and discussed. Among these information approaches, Axiomatic Design is thought to be unique, therefore it is explained in a separate chapter (III-1.2). The remaining approaches can be classified as heuristic approaches and explained in the last chapter.

### 3.1.1. Entropy / Information Approach

Since Hartley [71] introduced a logarithmic measure of information in the context of communication theory, entropy or information concept has been used to measure complexity by many researchers. For example, Hoult and Meador [56] used position information metrics to estimate the manufacturing cost of a part. Suh [70] et al. suggests to use information contents as a means of selecting a design option as part of Axiomatic Design.

In this section, underlying assumptions in the entropy/information approach are discussed and several formulas for measuring entropy or information content are provided. In addition, advantages and problems with this approach are studied.

#### 3.1.1.1. Measures of Entropy – Information

*Hartley's Information Measure*

Hartley's information measure [71] can be used to explore the concepts of information and uncertainty in a mathematical framework [52]. Let X be a finite set with a cardinality $|X| = K$. A sequence can be generated from set X by successive selection of its components. Once a selection is made, all possible elements that might have been chosen are eliminated except for one. Before a selection is made, ambiguity is experienced and the level of ambiguity is proportional to the number of alternatives available. Once a selection is made, no ambiguity remains. Thus, the amount of information obtained can be equated to the amount of ambiguity eliminated. In this context, Hartley's information measure I is given by;

$$I = \log_2 |X|^s \text{ (bits)} \qquad \text{(Equation 3-1)}$$

where /*s*/ is the sequence of selection. In this approach, the amount of uncertainty needed to resolve a situation or the amount of complexity to be reduced in a design problem is equivalent to the potential information involved.

Hartley's measure is different from Shannon's measure because it is essentially the logarithm of the cardinality, while Shannon formulated his measure, the entropy, in terms of probability theory.

***Shannon's Measure***

Shannon [72] derived his entropy in order to express uncertainty about an information source in terms of probability. For example, consider a language like English. In this example, a source of information is a pair Q = (X, P) where $X = \{\chi_k\}$ is a finite set representing the alphabet, and P is a probability distribution on X. Here, probability of $\chi_k$ is given by $p_k$. An element of X provides specific representation in a given context. Suppose we randomly pick up $\chi_k$ with probability $p_k$. Before selection, there is a certain amount of uncertainty involved with the outcome. However, an equivalent amount of information is gained after selection. If no intersymbol influence had been present, the information associated would have been given by;

$$H_b(p_1, p_2, \ldots, p_k) = -\sum_{k=1}^{K} p_k \log_b p_k \qquad \text{(if b = 2, then the unit will be bit.)}$$

(Equation 3-2)

Shannon's entropy is a weighted sum of log $p_k$ or the expected value of function log $1/p_k$. The interpretation of Shannon entropy is as follows: When the probabilities are small, we are surprised by the event happening; we are uncertain if rare events will happen, and thus their occurrences carry considerable amounts of information [52].

***Boltzmann Entropy Concept [73]***

In case of continuous $\chi$ and p that characterize a continuous information source, h(f) can be defined as:

$$h_b(f) = -\int_S f(x)\log_b f(x)dx \quad \text{if integral exists} \qquad \text{(Equation 3-3)}$$

where $S = \{x / f(x) \geq 0\}$

Boltzmann entropy metric may be considered as a continuous analogy of Shannon's entropy when /p$_k$/ is replaced with the probability distribution function, $f$. However, there are two major issues in adopting Boltzmann entropy as a complexity measure: For some probability distribution functions, Shannon entropy does not converge to Boltzmann measure and there is no closed form integral [52].

### 3.1.1.2. Assumptions with Entropy Approach

A common assumption in entropy approaches for measuring system complexity is that complexity is a universal quality that exists, to some degree in all objects, and there is a uniform metric for measuring the complexity of a system.

This assumption is somewhat controversial to opinions discussed in section 2.1. In that section, it is mentioned that Klir [11] stated that "it is not operationally meaningful to view complexity as an intrinsic property of objects." Some other authors in system theory [9] also claim that complexity is always subjective and relative. Therefore, its evaluation depends on the purpose of the observer – that can be any outer, or inner system – and on the degree of description or analysis required.

In addition to this basic assumption, to make the equation simple, independence between components is usually assumed. For example, Hoult and Meador [56] assume that the dimensioning is proper so that each dimension is independent of the others. If this assumption is not true, equations like equation 3-2 can not be used since information can not be expressed as a simple summation of the logarithm of inverse probability. In this case, the conditional probability should be considered and accordingly conditional entropy measure should be used instead of the Shannon's measure.

Consider the language example again and assume a sequence of letters in which intersymbol influence extends only over pairs of adjacent letters. For two such letters i and j, the information obtained when j is received is – log p(j / i); that is minus the logarithm of the probability of receiving j, given that I has been received. In order to find the average information over all letters we simply have to average over all possible pairs of letters i, j. The result is the conditional entropy H(i/j) of the sequence and represents the information per letter in such a sequence:

$$H_b(j/i) = -\sum_i \sum_j p(i,j) \log_b p(j/i) \qquad \text{(Equation 3-4)}$$

Accordingly, Boltzmann entropy measure that is the integral form of the Shannon's measure should also be changed to a conditional format.

### 3.1.1.3. Examples of Application

Many examples that develop new complexity metrics are based on a certain research that is famous and well-known in system theory area. For example, some authors develop their own complexity metrics based on the study by Catsi [50].

Catsi [50] pointed out that there are two types of complexity; static complexity and dynamic complexity. Static complexity comes from the hierarchical structure, the connective pattern, the variety of components and strength of interactions. On the other hand, dynamic complexity consists of randomness versus determinism and complexity, and time scales.

Based on this notion of static complexity and dynamic complexity, some researchers such as Deshmukh et al. [54] and Calinescu et al. [53] developed complexity metrics. Deshmukh et al., developed a measure of static complexity in [54]. Their metric for static complexity is as equation 3-5.

$$H_p = -C\sum_{i=1}^{m}\sum_{j=1}^{m}\sum_{k=1}^{r}\sum_{l=1}^{n}\bar{\pi}_{ijkl}\log\bar{\pi}_{ijkl} \qquad \text{(Equation 3-5)}$$

In this metric, three components of Catsi's original attributes of static complexity are considered: the structure of a system, the variety of sub-systems, and strength of interactions. In a manufacturing system, the structure is reflected by the part flow and the variety of sub-systems is determined by the different types of resources and part types in the system. Processing time is used to reflect strength of interactions. (For details in the development of this metric, refer to [54].)

On the other hand, Calinescu et al. [53] use concepts of structural complexity (static complexity) and operational complexity (dynamic complexity) that were originally developed by Frizelle and Wookcock [75]. Here, the structural complexity is measured by the following equation.

$$H_{static}(s) = -\sum_{i=1}^{M}\sum_{j=1}^{N_j} p_{ij}\log_2 p_{ij} \qquad \text{(Equation 3-6)}$$

In the above equation, M represents the number of resources, $N_j$ indicates the number of possible states at resource j, and $p_{ij}$ is the probability of resource j being in state i. The outer summation represents the AND relationship between resources, and the inner summation represents the OR relationship between the states at each resource. This metric can be interpreted as indicating intrinsic difficulty of the process to produce the required number and type of products within the required period of time.

Operational complexity can be measured by equation 3-7.

$$H_{dynamic}(s) = -P\log_2 P - (1-P)P\log_2(1-P) \\ -(1-P)\left(\sum_{i=1}^{M^q}\sum_{j=1}^{N^q} p_{ij}{}^q \log_2 p_{ij}{}^q + \sum_{i=1}^{M^m}\sum_{j=1}^{N^m} p_{ij}{}^m \log_2 p_{ij}{}^m + \sum_{i=1}^{M^b}\sum_{j=1}^{N^b} p_{ij}{}^b \log_2 p_{ij}{}^b\right)$$

(Equation 3-7)

In this equation, P represents the probability of the system being controlled, $P_q$ is the probability of having queues of varying length greater than 1, $p_m$ is the probability of having queues of length 1 or 0, $p_b$ is the probability of having non-programmable states, M represents the number of resources, $N_j$ represents the number of states at resource j, and $N_j = N_{jq} + N_{jm} + N_{jb}$. The main idea with this metric is that operational complexity is reflected by queues. (For details, refer to [53])

There are some more examples in which entropy or information is used to measure complexity while adopting only the information (or entropy) concept without counting on Catsi's notion of complexity. One example is as follows.

Hoult and Meador [56] claim that there is a uniform metric for measuring the complexity of mechanical parts. The metric proposed for measuring design information is the logarithm of dimension divided by tolerance. They provide a couple of theorems developed based on this notion of complexity. As mentioned in section III – 1.1.2, it is assumed that the dimensioning is proper, i.e. each dimension is independent of the others. According to the theory of dimensioning, this is true for a correctly dimensioned engineering drawing. The part is assumed to have proper and consistent dimensions, congruent with good engineering practice.

In this case, the total component or design information is simply the sum of all the dimension information contents of the N total dimensions on the part drawing, as shown in equation 3-8.

$$I = \sum_{i=1}^{N} Log_2\left(\frac{\text{dimension}_i}{\text{tolerance}_i}\right)$$

(Equation 3-8)

They conclude their paper by asserting that the theorems prove that, on the average, for a given manufacturing process, the time to fabricate is simply proportional to this metric.

#### 3.1.1.4. Advantages

The most impressive advantage of the entropy / information approach may be that one can come up with one number indicating the complexity of a system. This is possible since the information is measured by the logarithm of probability function that has the same dimension while representing many different characteristics of a system. This characteristic of the information approach to system complexity facilitates the comparison between several system options in terms of their complexity, which helps designers to choose the best option available. In other words, it is clear which design has less complexity since the level of complexity is given by one number.

In their research comparing entropic method [75] to MFC (Meyer and Foley Curley) method [76], Calinescu et al. [53] point out that the strengths of entropic methods lie in the use of objective data and valuable formal tools in mathematical language for assessing the complexity.

#### 3.1.1.5. Problems with Entropy / Information Approach

There are two major problems with applying entropic approach to measure system complexity. One is related to the practical difficulties to gather information to know the probability of a certain task and the other is linked to fundamental deficiency lying under the assumptions made in entropic approach.

***Practical Difficulties to Apply Entropic Measure of Complexity to a Real System***

Practical difficulties in applying an entropic measure to a real system is well studied in [53]. In their case study to apply entropic method to a real system, Calinescu et al., [53] report practical difficulties associated with applying the entropic method that was originally developed by Frizelle and Woodcock [75]. In this section, examples of [53] are modified and used to explain these difficulties.

The first difficulty in applying an entropic measure to a real system lies in choosing the variables of which probabilities are to be calculated. For example, consider a simple manufacturing system composed of two machines and 2 operations as shown in Figure 3-1.

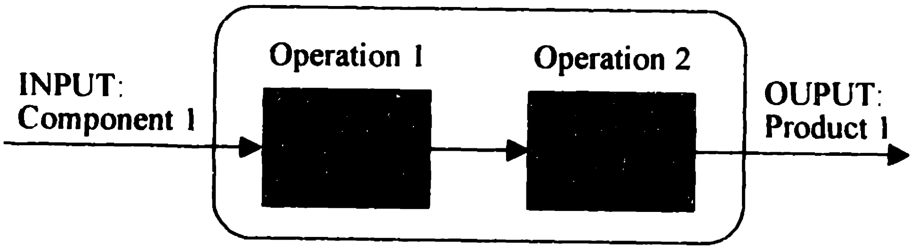

Figure 3-1. A Simple Manufacturing System Model

In this example, information related to production may come from components and operations required. A question arises: What aspects of components and operations should be considered to calculate probabilities that are used to quantify system complexity? The answer is not so clear - the probability of producing a good part in a given time range may be considered, or the probability of a machine to run a part may be chosen. For example, in [53], authors consider three states of a machine and calculate the probability for each state: Make, Set-up, and Idle. In this context, this approach can be said to focus on machines in the system. They claim that the entropic sum of the probabilities of a machine to be in one of these states is the structural complexity. However, it is not quite evident whether there are more aspects that should be checked, for example, availability of an operator, machine capability, quality or something else. In addition, if the number of machines were increased to 20, for instance, there would be 320 combinations of states, which are too large to be calculated. As for operational complexity, it is clearer since it can be expressed as a size of a queue in front of a machine, but it is still somewhat confusing to decide which queue should be considered. For this kind of problem, Axiomatic Design approach helps a lot since it defines functional requirements and design parameters first, which define what probability should be measured and how they can be calculated.

Another problem is that simply it is quite difficult to get data in order to calculate probability. Consider the previous example in Figure 3-1. As discussed by Calinescu et al., [53], to decide the probability of the state of a machine, data is needed for machine utilization such as available time, setup time, processing time, etc. This data should be collected from the long-term information on machines, which might require great attention and efforts from operators and engineers. However, if those kinds of data are not available, they should be estimated by using simulation technology or should be collected by simply watching machines. As for the simulation technology, it takes a long time and high cost to develop a model to reflect only a partial image of the real system. In addition, since there is not any exact analytical model to explain a complex manufacturing system, a simulation model is based on some assumptions that may degrade the accuracy of a model (e.g., infinite size of buffer, no defects, etc.). Due to this deficiency and the difficulty to develop a simulation model, Calinescu et al. [53] calculate the probability based on their observation of the system. But even with this approach, the static complexity for all the parts can not have been calculated, due to several interdependent reasons. One of the reasons is the high number of parts produced in the analyzed shop, and the lack of long-term information on part demand and routing. Another reason is the practical impossibility of calculating the operational complexity for all the parts produced in the shop, which makes its corresponding static complexity unusable. This practical impossibility lies in the resource requirements (people, time, and costs) associated with observing the process for a continuous and long enough period so as to capture the processing of all the products.

This difficulty may be more critical in the design stage of a system. In entropic approach, probability is usually expressed as a ratio of design range vs. system capability range. Even for exceptional cases, at least some data on the system are needed (e.g., state of machine, etc.). However, it is very difficult to estimate the system capability range without having a real system or prototype. Simulation may be an alternative way to calculate the system capability, but considering its high cost and limited applicability due to accuracy in question, it is not practically applicable for a complex system like a manufacturing system. In addition, since there is no implemented system, data can not be directly collected. From this point of view, it may be almost impractical to apply entropic methods during the design stage of a system to compare complexities of several design options.

Even though entropy or information is calculated, there still remains a problem regarding to interpretation – measured complexity is very difficult to interpret. This can be critical for the purpose of design or system improvement. For example, the meaning of 5 bits of information (or entropy) measured is not so clear for the purpose of system improvement. What does 5 bits of information really mean and how is it different from 3 bits of information? This kind of question is not easy to be answered. Entropy itself doesn't tell how one can decrease the complexity of a system. In addition, it doesn't reveal new problems that are not noticed by system observers since it is calculated with the probabilities of system components and their characteristics. In this context, Calinescu et al. [53] report that main benefits from entropic approach may be associated with the thinking process carried out and understanding gained in order to be able to apply the method.

### *Fundamental Problems with Entropic Method*

In above section, practical difficulties that arise when applying entropic methods to measure system complexity were discussed. In this section, more fundamental problems underlying entropic methods are considered. These fundamental problems mainly come from the assumptions made in entropic methods.

First, as already mentioned in section III – 1.1.2, many entropic approaches assume independence between system components. This makes an equation simpler and calculation easier. However, in many real systems, system components usually have interdependencies with each other, so that many equations provided by entropic methods become inapplicable. To consider interdependency between system components, conditional probability should be used instead of the probability of one independent component. However, if a system were complex and had many system components, the resulting equation to measure the information content (or entropy) would be very complex. This will eventually worsen the practical difficulties discussed above and make it impractical to use entropic methods.

A more fundamental argument may lie in the very first assumption of entropic methods: complexity can be expressed as an information content or entropy. In fact, Rosen [21] points out that information itself is not a scientific word and may show our lack of knowledge or understanding of a system. For example, information is never mentioned in a mature science such as physics. In other words, physical phenomena dealt by physics can be explained well without using the information concept. However, it is easy to define information in human terms; it is anything that is or can be the answer to a question. In this context, complexity may be a concept beyond our existing science such as physics or mathematics. See [21] for detailed arguments on this subject.

### 3.1.2. Axiomatic Design Approach

Basically, the method used in Axiomatic Design is pretty much the same as entropic methods that are studied in the above section. However, from the perspective that Axiomatic Design explains explicitly which probability should be calculated and how it can be calculated, it is different from other entropic approaches. For more information on the Axiomatic Design, please refer to [77], [78].

#### 3.1.2.1. Definition of Complexity in Axiomatic Design

In Axiomatic Design, the design process is described as the mapping between domains (see Figure 3-2). The design goals for a product are described in the functional domain in terms of functional requirements (FRs). The design task is to achieve the set of specified FRs by mapping FRs in the functional domain to design parameters (DPs) in the physical domain. Thus, the selection of DPs determines the uncertainty related to satisfying FRs.

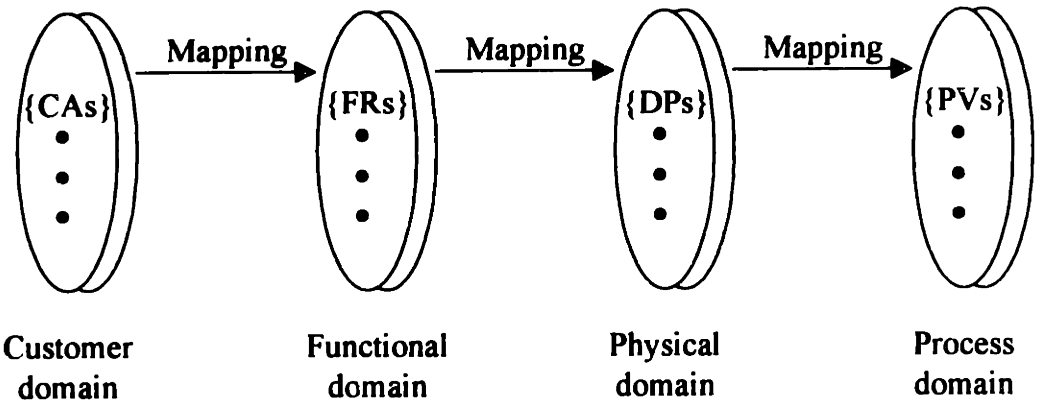

Figure 3-2. Four Design Domains in the Axiomatic Design

In this context, complexity is defined as a measure of uncertainty in achieving the specified FRs [78]. In other words, complexity is defined only relative to what we are trying to achieve (FRs). This complexity is related to the information content that is defined as a logarithmic function of the probability of success of DPs to meet the specified FRs. The probability of success is determined by computing the area of the common range as a fraction of the area of the system range.

The information content is inversely proportional to the probability via the logarithm function. In other words, a design that is achieved with minimum information content (complexity) is a design that has a maximum probability of success. Therefore, the simpler design is better because its chance to succeed is higher and this idea is reflected in the second axiom:

Axiom 2 (The Information Axiom):
Minimize the information content of the design.

### 3.1.2.2. Types of Complexity in Axiomatic Design

In his recent edition [78], Suh classifies complexity into two categories: time-independent complexity and time-dependent complexity. Time-independent complexity can further be divided into time-independent real complexity and time-independent imaginary complexity. Time-dependent complexity may be divided into two kinds: time-dependent combinatorial complexity and time-dependent periodic complexity.

### *Time-independent Complexity*

Time-independent complexity is related to the real uncertainty coming from variation and imaginary uncertainty coming from lack of design knowledge. Real uncertainty is the one that is covered by the second axiom in axiomatic design. It is the result of the difference between the desired probability distribution of the FRs and the actual probability distribution of DPs. Details to measure this complexity are discussed in III – 1.2.3. On the other hand, imaginary complexity comes from the lack of knowledge or understanding in a specific design itself. For example, if the design matrix that defines the relationships between FRs and DPs is not made, the sequence of design deployment can not be made. In this case, designers may try to change their design specification ad-hoc to meet a certain FR, which makes the design seem to be complex. This kind of complexity is called imaginary complexity.

### *Time-dependent Complexity*

Time dependent complexity is linked to time dependent uncertainty that exists because the future events occur in unpredictable ways and thus, cannot be predicted. Combinatorial complexity is related to the uncertainty of combinatorial problems that grows more complicated indefinitely as time goes by because the future events are unpredictably affected by the decisions made in the past. A good example of a combinatorial problem may be the scheduling of a manufacturing system. In this case, the future scheduling that defines which parts are produced from which machines is affected by the decisions made earlier. On the other hands, periodic complexity is related to the uncertainties existing only for a given period. If new period starts again, uncertainties created during the prior period would be eliminated. Airplane scheduling may be the good example of this periodic complexity.

Time-dependent complexity can be reduced by changing combinatorial complexity into periodic complexity.

### 3.1.2.3. Measure of Real Complexity in Axiomatic Design

Among four types of complexity suggested in Axiomatic Design, only time-independent real complexity has a metric to quantify it. According to [78], real complexity can be measured by the sum of information content of leaf DPs. Information is defined as a logarithmic function of the probability of success of DPs to meet the specified FRs. Specifically Suh defines the probability of success as the probability of meeting specifications in the concerned mapping domains. In other words, information content is determined by computing the area of the common range as a fraction of the area of the system range. Considering the desired probability distribution function of the FR, the probability of success of satisfying the FR can be calculated by (see Figure 3-3):

$$p(FR) = K \int_{dr^l}^{dr^u} f[p_d(FR)]\, g[p_s(FR)]\, d(FR) \qquad \text{(Equation 3-9)}$$

where $K = \dfrac{1}{\int_{dr^l}^{dr^u} f[p_d(FR)]^2\, d(FR)}$.

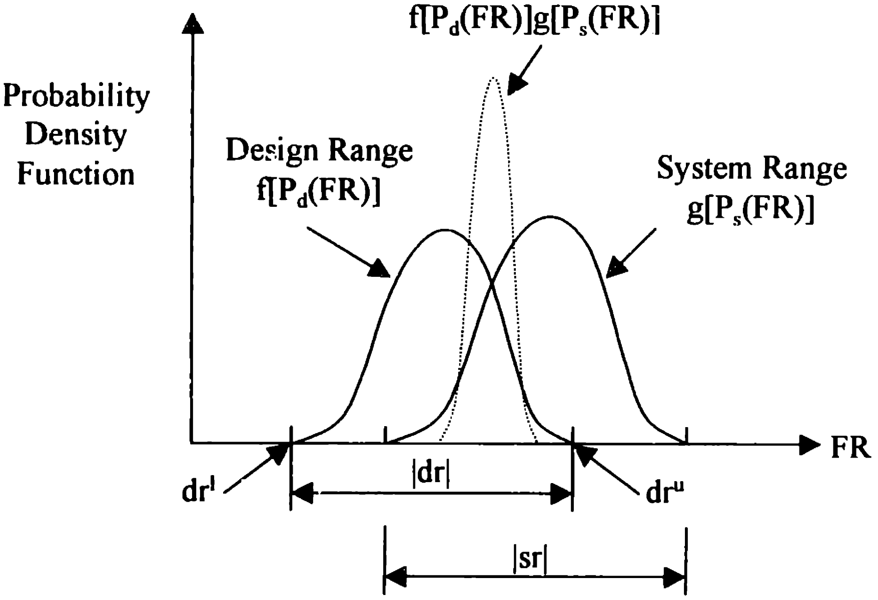

Figure 3-3. Desired Probability Distribution of the Design Range, the Probability Distribution in the System Range, and the Product of the Two Functions

As can be seen from the equation 3-9 and the Figure 3-3, the real complexity is defined as a measure of uncertainty when the probability of achieving the FR is less than one due to the fact that the common range is not equal to the system range. Information content is calculated as the sum of logarithms of inverse probabilities.

One problem with this approach is that sometimes it is difficult to estimate system range because system range is decided by several DPs when decoupled designs[2]. To know what DPs affect the system range for a certain FR, the interdependency of a FR and DPs should be checked first. However, since a certain FR's dependency on DPs propagates through the design hierarchy, this work becomes very difficult and the full design matrix should be checked to confirm the interdependency of a FR and DPs. In addition, even with known interdependency relationship, it is very hard to estimate the system range that is the result of combined effects of several DPs without measuring it from the real physical system. In this context, modification of the 'probability of success' concept into other metrics that are easy to measure is necessary while maintaining the idea that complexity is closely related to what we want to achieve.

#### 3.1.2.4. The advantages and disadvantages of the Axiomatic Design approach

The Axiomatic Design approach has similar advantages and disadvantages with entropic approaches since it is based on the information theory. However, it is different from other entropic approaches from following perspectives:

- Axiomatic Design provides FRs and DPs, which indicate the kind of probability that should be measured and how they can be calculated. In an Axiomatic Design context, complexity is defined by the information content that is the logarithms of probability of success. Probability of success is defined as the probability of DPs to

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[2] In Axiomatic Design, there are two design axioms. One is the independence axiom, which tells to maintain the independence of the functional requirements (FRs). The other is the information axiom and it tells to minimize the information content of the design. To satisfy the independence axiom, the design should be a uncoupled design or a decoupled design. Uncoupled design is characterized by the diagonal design matrix and decoupled design is characterized by the triangular design matrix. Please refer [77], [78] for more details.

meet FRs. As discussed in section 3.1.2.3, however, it is still difficult to find the system range because it is decided by several DPs in case of decoupled designs.

- Axiomatic Design suggests that time-dependent combinatorial complexity should be changed to time-dependent periodic complexity to reduce system complexity. This can be seen as a heuristic approach to decrease complexity and in fact, periodicity is mentioned frequently as a problem solving technique in TRIZ [79], [80], [81] and systems architecting texts [82].

In summary, the Axiomatic Design approach adopts both heuristic approaches and entropic methods.

### 3.1.3. Heuristic Approaches

In this section, examples of different types of metrics used to measure system complexity are presented. Considering most of examples come from the intuition of system complexity based on personal experiences, these examples may be classified as a heuristic approach. Due to this intuitive starting point, heuristic methods have an advantage that they are very easy to be applied to real systems – easy to collect data, interpret, and eventually improve systems. However, for the same reason, it has a deficiency of being subjective to an argument whether metrics really reflect the system complexity. In addition, they can not be applied to different types of systems (e.g., a manufacturing system and a product). Some examples of heuristic approaches are provided in the rest of this section.

Sarkis [51] describes the relationship between productivity and system complexity in Flexible Manufacturing Systems. Complexity is measured by the number of numerically controlled machine tools and industrial robots within a system. This metric seems to be reasonable considering the definition of Flexible Manufacturing Systems.

Flexible Manufacturing Systems (FMS) are defined as production systems consisting of more than one numerically controlled machine and/or industrial robot, interconnected by a transportation system which enables computerized control of the whole production cycle. According to this definition, larger number of numerically controlled machine tools and industrial robots will bring out more control efforts including scheduling and transportation, which may indicate higher complexity. However, as mentioned before, a question is whether it is enough to capture the system complexity with this one metric. In addition, it may not be generally applicable to other systems other than FMS.

The result of this study shows that overall there is a continuous drop in productivity measures as the system becomes more complex, supporting the argument that the less complex systems seem to be more efficient and productive.

Another heuristic metric is suggested by Calinescu et al. [53], which was originally developed by Meyer and Foley Curley [76]. This approach is called as the Meyer and Foley Curley (MFC) method. In this method, there are two complexity metrics: knowledge complexity and technology complexity. Knowledge complexity is defined as the domain-specific knowledge and decision-making complexity supported by an application. To assess knowledge complexity, decision-making is considered to involve three different levels:

1. The knowledge of the decision-maker
2. The information used by the decision-maker
3. The interpretation and synthesis of the above information, by applying domain-specific logic, to resolve uncertainty and make partial or complete decisions

In the MFC method, the following set of variables are defined so as to assess the above levels [53], [76]:

| **Variables** | **Reflected attributes of decision-making processes** |
|---|---|
| Breadth of decision-making domain(s) | Reflects the number of specific distinct fields of expertise employed by the decision-makers |
| Depth of decision-making domain(s) | Considers the combination of educational training and work experience required by decision-makers |
| Rate of change of decision-making domain(s) | Quantifies the frequency with which decision-makers have to renew their knowledge |
| Decision-making domain penetration | Synthesizes the level of computerization of each specific domain in the computer system |
| Comprehensiveness of decision outputs | Reflects the category of the output, which could be of the following types: problem diagnosis, recommended actions, actual solutions, hypothesis testing |
| Breadth of information inputs | Regard the information inputs used by the decision-maker |
| Required interpretation of information inputs | Reflects the level of interpretation the decision-maker needs to make regarding the information inputs |

Scores are assigned to each variable in order to quantify these variables within each organization. Next, all variables are considered equally important and then a weight factor is assigned to each variable so that all the variables have a common denominator. Finally the knowledge complexity is calculated by equation 3-10.

$$Knowledge\ \ complexity = \frac{\left( \sum_{i=1}^{no.\,of\ variables} score_i \times weight_i \right)}{norm} \qquad \text{(Equation 3-10)}$$

Technology complexity is defined as the complexity of the underlying computer technology used to develop, integrate, and diffuse an application throughout an organization. This complexity is also assessed by a similar method with eight characteristic variables (See [76] for details). With these metrics, MFC concluded that effective management of application development depends on embodied complexity.

In addition to these works, there are more examples of research that provide complexity metrics. These are summarized in Table 3-1.

| Researcher | Complexity Metrics Suggested |
|---|---|
| Fernandez [60] | dimension counting |
| Busch [61] | a mold complexity factor as the ratio of total mold surface area to the projected area of the mold in the direction of mold parting. |
| Busch [62] | a parametric model for injection molding costs, in which he rejected his complexity factor of [61] as inadequate in capturing cavity detail |
| Wilson [63] | component symmetry: the use of information theory to measure complexity using symmetry for rotationally symmetric parts |
| Boothroyd et al [64] | specific complexity factors |
| Pearce [65] | number of dimensions on the print |
| Pugh [66] | number of part features and setups |

Table 3-1. Heuristic Approaches to Measure System Complexity

### 3.1.4. Summary of Existing Approaches to Measuring Complexity

The summary of existing approaches to measuring complexity is shown in Table 3-2.

| Approach | Type | Metric(s) to measure Complexity |
|---|---|---|
| Entropic Approach [52], [53], [54] | Hartley's Information Measure [71] | $I = \log_2 \lvert X \rvert^S$ |
| | Shannon's Measure [72] | $H_b(p_1, p_2, \ldots, p_k) = -\sum_{k=1}^{K} p_k \log_b p_k$ |
| | Blotzmann Entropy Concept [73] | $h_b(f) = -\int_S f(x) \log_b f(x) dx$ |
| Axiomatic Design [70], [77], [78] | Time-independent Real Complexity | $H_b = -\sum_{k=1}^{K} \log_2 p_k$ |
| | Time-independent Imaginary Complexity | Should be changed to real complexity |
| | Time-dependent Combinatorial Complexity | Should be changed to periodic complexity |
| | Time-dependent Periodic Complexity | N/A |
| Heuristic Approach | Sarkis [51] | Number of numerically controlled machine tools and industrial robots within a flexible manufacturing system |
| | Meyer and Foley Curley [76] | Knowledge Complexity (seven variables and weight factors) |
| | | Technology Complexity (eight variables and weight factors) |
| | Fernandez [60] | Dimension counting |
| | Busch [61] | A mold complexity factor as the ratio of total mold surface area to the projected area of the mold in the direction of mold parting. |
| | Busch [62] | A parametric model for injection molding costs, in which he rejected his complexity factor of [61] as inadequate in capturing cavity detail |
| | Wilson [63] | Component symmetry: the use of information theory to measure complexity using symmetry for rotationally symmetric parts |
| | Boothroyd et al [64] | Specific complexity factors |
| | Pearce [65] | Number of dimensions on the print |
| | Pugh [66] | Number of part features and setups |

Table 3-2. Summary of Existing Approaches to Measuring Complexity

## 3.2. Proposed Complexity Metrics

As mentioned earlier, complexity is generally recognized as a chief cause of present difficulties in plant design and control. Therefore, the search for a measurement tool is an urgent necessity since the search for simplicity cannot be performed unless a comparative evaluation is made [9].

To this end, variables related to system complexity are sought and studied. The relationship of these metrics to system complexity are provided based on the disassembly of a complexity model proposed by Flood [15]. Flood suggests that complexity can be disassembled up to the 4th level as shown in Figure 3-4. This approach is focusing on "sources" or "elements" of complexity rather than trying to capture partial images of complexity by probabilistic approach.

Interestingly, this model considers 'people' as one of two major elements contributing to complexity. This explains why people are important when lean manufacturing principles are applied.

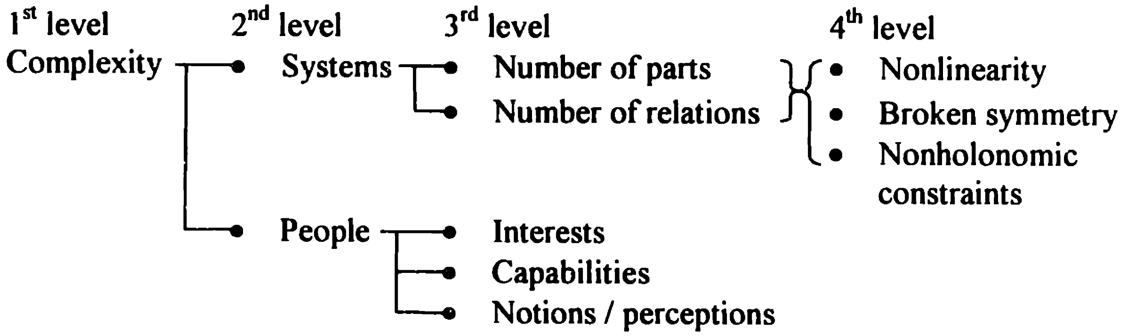


Figure 3-4. Disassembly of complexity [17]

One thing that should be mentioned before proceeding to complexity metrics is that complexity is always subjective and relative. Therefore, its evaluation depends on the purpose of the observer – that can be any outer, or inner, system – and on the degree of description or analysis required [9]. For this reason, the following metrics have applicability limited to manufacturing systems only and may not show all aspects of complexity in a manufacturing system, but at least they provide some meaningful insights when used in system comparison.

## 3.2.1. Relationships between System Components

### 3.2.1.1. Number of Flow Paths

The number of flow paths is closely related to the interconnection effects of a complex system. Since flow path can be said to be a sequence of operations of a set of system components to produce a particular type of products, naturally it involves a relationship between system components, such as machines and operators. In other words, system components along with a flow path should be able to work together to produce a product. In this sense, the number of flow paths indicates the number of relations between components in a system and the number of relations in a system is strongly linked to system complexity. Pippenger [16] discussed a demonstration of the diversity of phenomena that can arise through the interaction of simple components, in interconnected constructs of a large number of simple components, such as computers or a telephone exchange.

In this context, a large number of flow paths will bring a high level of complexity in a manufacturing system. For example, a large number of flow paths may worsen the traceability of defects or production problems, making it hard to solve problems before they spread to the entire system. An even worse aspect is that people inside the system cannot see the upstream or downstream processes clearly. Operators do not know how their small mistakes can affect the whole system. They cannot see quality or time problems, which easily propagate throughout the system. Even engineers may not understand complex systems with a large number of flow paths so that when problems occur, they may not be able to eliminate the root causes and prevent them from happening again. Under this environment, improvements simply concentrate on eliminating the symptoms.

Typically, to prevent these chains of problems from occurring, increased level of inventory has been used to dampen the interconnection effects. A large inventory buffer, however, is definitely undesirable for many reasons, such as increased cost and poor response to customer demands. Therefore, system complexity should be reduced by decreasing the number of flow paths, rendering the manufacturing system more understandable and consequently more controllable.

The number of flow paths can be measured by literally counting the possible product flow paths. The formula is:

$$Nf = \prod_{i=1}^{n_p} m_i \qquad \text{(Equation 3-11)}$$

$N_f$ = number of flow paths

$n_p$ = number of different types of processes

$m_i$ = number of machines that $i$th process has

There are optimization issues between keeping a system flexible and decreasing the complexity of a system. One advantage of having multiple flow paths may be that when one system element (e.g., machine) is down, products can be passed through other routes, which makes the system more 'flexible' to unexpected accidents.

#### 3.2.1.2. Number of Crossings in the Flow Paths

Crossings occur in the flow path when parts share a machine that is usually high speed, or just by the share of the physical space during the transportation. In either case, it contributes to the system complexity by adding nonlinearity to the system. In other words, the number of crossings alters the relationship between flow paths and their elements.

When sharing a machine, as shown in Figure 3-5a, production must be scheduled to sequence products and make setup changeover where different setup configurations are required. Crossings occurring during transportation, as shown in Figure 3-5b, may cause the interruption of transportation and may increase the ambiguity of the product flow path.

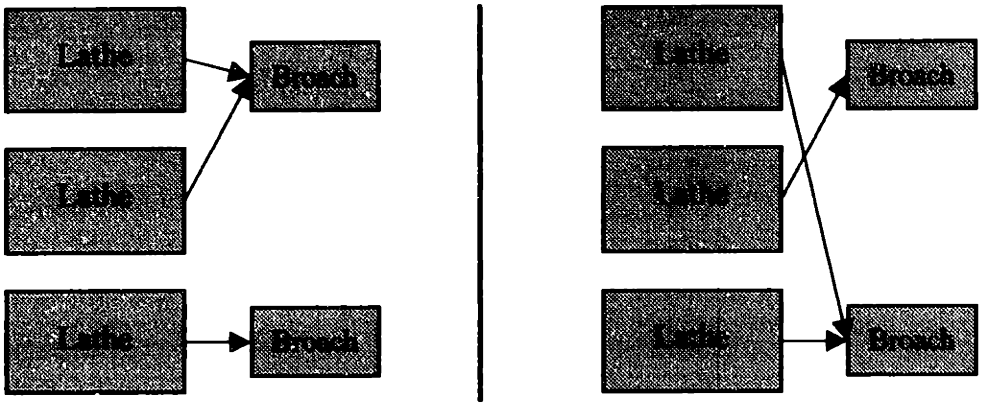


Figure 3-5. Crossings of flow paths (a: Left, Crossings Caused by Machine Sharing, b: Right, Crossings Caused by Sharing Physical Space during Transportation)

Number of crossings in flow path can be calculated by following formula:

$$Nc = \sum_{i=1}^{np-1} {}_{m_i}C_2 \times m_{i+1} + \sum_{i=1}^{np-1} Nct_i \qquad \text{(Equation 3-12)}$$

$N_c$ = number of crossings in the flow path

$N_{ct,i}$ = number of crossings during transportation between *i*th process to *i*+1th process

### 3.2.1.3. Total Travel Distance of a Part

Travelling distance of a part is closely correlated to the variation of a manufacturing system. Variation itself contributes to system complexity by increasing uncertainty in system behaviors. It affects the throughput time variances since the longer the travelling distance is, the more probable the part flow will be disrupted by disturbance sources such as forklifts, passing people or a material handler's operational mistakes. It also affects the quality of the product since longer travel distance may allow more chances for part damage.

This metric can be calculated by measuring physical distance of a part flow. Several ways may be possible such as calculating the average travel distance, maximum travel distance or the sum of travel distances of parts to compose a finished product. Among them, the average travel distance may be calculated by following formula:

$$Dt = \frac{\sum_{j=1}^{Nf} \sum_{i=1}^{n_p - 1} d_{ji}}{Nf} \qquad \text{(Equation 3-13)}$$

$D_t$ = Average travel distance of a part

$d_{ji}$ = Travel distance between *i*th process to *i*+1th process along the *j*th flow path

### 3.2.1.4. Number of Combinations of Product and Machine Match

This metric indicates the relationship between product types and system components, which is closely linked to scheduling and logistics difficulties. From this metric point of view, if there is only one type of product produced, there may not be any scheduling difficulty. In a modern plant, however, due to thousands of parts that should be produced by hundreds of machines, enormous scheduling efforts are required.

This metric can be calculated by the following formula:

$$Nm = \prod_{k=1}^{ns} \prod_{j=1}^{np_k} \prod_{i=1}^{m_j} V_i \qquad \text{(Equation 3-14)}$$

$N_m$ = Number of product-machine matches

$n_s$ = Number of sub-systems (e.g., number of cells)

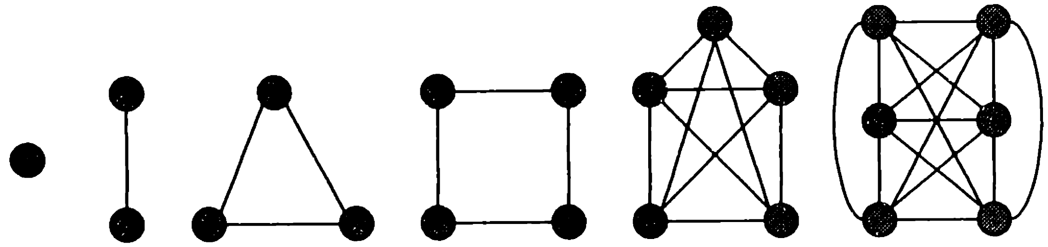
$V_i$ = Number of product types operated at ith machine

## 3.2.2. Elementary System Components

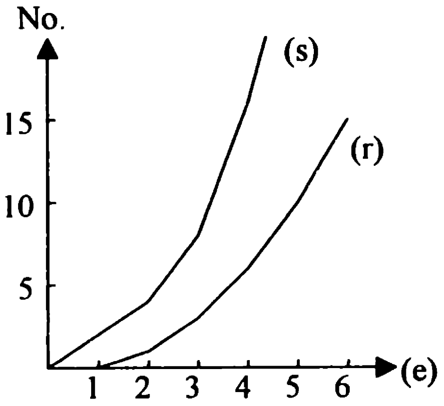
Here elementary system components include machines, operating stations, people, etc.

### 3.2.2.1. Number of Elementary System Components

The number of elementary system components contributes to the system complexity in two ways. It increases the number of possible relationships and states. Flood [15] illustrates these aspects by simple example shown in Figure 3-6.



| | | | | | | |
|---|---|---|---|---|---|---|
| (e) | 1 | 2 | 3 | 4 | 5 | 6 |
| (r) | 0 | 1 | 3 | 6 | 10 | 15 |
| (s) | 2 | 4 | 8 | 16 | 32 | 64 |



| KEY | | |
|---|---|---|
| | --- | a relationship |
| | ● | an element / node |
| | (e) | number of elements |
| | (r) | number of relationships |
| | (s) | number of states |

Figure 3-6. Elements, possible relationships, and states as a measure of complexity; where (e) are elements, (r) are relationships and (s) are states (Flood, [15])

Consider each node as an element (e), each connection as a relationship (r) between two of the elements and the number of possible states (s) where each element may be in one of two states (e.g., working or down, on or off, etc.). The graph in Figure 3-6 shows that the rise in the number of potential relationships grows at a faster rate than that in the number of elements. The number of possible states rises even faster than the number of potential relationships. This also means an increase in the amount of information that should be sent to system components.

In this context, a large number of elementary system components may indicate a high level of system complexity. For example, in a typical manufacturing system, there may be hundreds of machines, stations and buffers, which have relationships between each other and have several states – down, used, temporarily starved, etc. Due to the exponentially increasing trend in the number of states or relationships, even with the fastest computer available, to consider all combinations of states or relationships of these system components would be impossible, which indicates the high level of complexity in a manufacturing system.

This metric can be calculated by the following formula:

$$Ne = \sum_{i=1}^{n_p} m_i + s_i + p_i \qquad \text{(Equation 3-15)}$$

$N_e$ = Number of elementary system components

$s_i$ = Number of stations at *i*th operation

$p_i$ = Number of people at *i*th operation

### 3.2.2.2. Complexity of Each Elementary Component

In this section, we seek to identify the complexity of each elementary component. Reasons that each element fails to meet system requirements are presented while considering financial constraints on system design.

#### 3.2.2.2.1. Reliability of Elementary System Components

Reliability is linked to the state of elementary components in a manufacturing system. Elementary components, such as machines, stations or operators, should not be out of order or unavailable during a certain planned time period. When deciding possible flow paths, uncertainty is increased where system components fail randomly and frequently, adding critical difficulties to the design of the control activities of a manufacturing system. In this case, in terms of time, a balance between manufacturing system components will be broken and, as a consequence, the system capacity becomes different from the designed value. To decrease these uncertainties, machines are managed by total preventive maintenance, which changes the unpredictable event of machine down time to a predictable event of scheduled maintenance. Absenteeism of operators has to be eliminated, while on time attendance should be encouraged and even required.

Reliability of elementary system components may be calculated by the following formula:

$$R = \frac{Tt - Tr - To}{Tt - Tr} \qquad \text{(Equation 3-16)}$$

$R$ = Reliability of elementary system component

$T_t$ = Total scheduled time

$T_r$ = Required downtime (lunch or breaks and other planned downtimes e.g., meetings, preventive maintenance, setups if scheduled and done periodically, etc)

$T_o$ = All other downtime (unplanned downtime, e.g., breakdowns, absenteeism, adjustments, minor stoppages, lateness, etc.)

#### 3.2.2.2.2. Quality Outputs

If seen from the system point of view, defects are not just a matter of cost caused by rework or scrapped materials, but play an important role in whether the whole system performs on time and at the right rate. Defects disable system predictability, which results in problems with manufacturing activities that are designed to function in an integrated way. This situation can be interpreted as adding non-linearity to a system, which consequently increases system complexity.

In a manufacturing system, defects are usually dealt with two ways: rework or scrap. Rework is pursued to decrease production cost, but it brings many other problems. For example, rework loops may increase the number of product flow paths, which adds complexity. In using the normal production line as a rework line, rework may decrease system capability through lost production time or increased changeover time. In a similar way, removing defects from the production flow by treating them as scraps may affect the time predictability of a system and the inventory level, since now more products should be produced. In this contest, both scrap and rework affect the predictability of system output.

In this case, system predictability may be reacquired by a time buffer or inventory which are not desirable. Quality output can be measured by the system yield, which can be calculated by following formula:

$$Sy(\%) = \frac{nt - nd}{nt} \times 100 \qquad \text{(Equation 3-17)}$$

$S_y$ = System yield (%)

$n_t$ = The number of total parts run

$n_d$ = The number of total defects (scrapped or reworked)

The lower the system yield is, the worse the predictability of output. This metric is same as First Time Through Capability (FTTC), a metric widely used in industry.

#### 3.2.2.2.3. Time Outputs

*Cycle time*

Here, the term 'cycle time' is used to indicate the time taken for a part to be processed by any category of operation [17] – processing, transportation, storage, or inspection. It is postulated that the length and the variation of cycle time affect system complexity.

A long cycle time contributes to system complexity. This factor decreases the ability to trace defects by increasing the time to detect a problem and fix it. Variation in cycle time may affect the whole system negatively since delivery and output are not predictable. In other words, variation in cycle time increases the nonlinearity of the relationship between system elements. Additionally, achieving the desired results of a schedule is difficult, due to the unpredictable time output of each system component.

Time outputs regarding the cycle time can be calculated by mean cycle time of a system component. Variation in cycle time may be shown by the variance of cycle time.

***Setup time (when setups are pre-scheduled.)***

Setup time plays a very important role in system complexity when different manufacturing setups are required for various product types at the same machine. Both long setup time and highly variable setup time increase the system complexity since it blocks the whole changeover in machines along the flow path. Large run sizes are used to allocate the setup-time delay to as many parts as possible in the same run. Partial changeover increases nonlinearity of part flow and consequently causes logistics problems. Time outputs regarding setup time can be calculated by mean setup time of a system component. Variation in setup time may be shown by the variance of setup time.

### 3.2.3. People

People are the most important factor in managing and controlling system complexity. People observe a system, perceive a system and perform activities within a system.

According to Flood's model [15], there are three attributes in the third level of his model that pertain to people and complexity: interests, capabilities, and perceptions / notions. Originally, these attributes are used to explain the complexity of a given system but here we modify them to focus on system improvement. The effects of point-of-view (or interests) may be shown by the following example:

> To the microprocessor designer, pentium chips, as the combination of millions of transistors and networks connecting them, are certainly highly complex. However, to the normal computer user, pentium chips are simple, for they have to distinguish them only in terms of their speeds or capability [18].

Researchers have shown that people have limited ability to process and keep information. Perception can be explained as the way we build up models in our mind for a certain system and the concept of notions may be considered as our understanding or opinion of the model construction in our minds.

To decrease system complexity, we may claim that the proper level of interest should be shown from the people in the system according to their role. To overcome the limitation of man's capability, strategies such as standardization may be pursued. Teamwork is important to share common perception of a system.

This metric might be the toughest one since it is about people and it is generally very difficult to measure something inside of people. An interview may be the most effective method to gather information and probably we can use popular 5 point system. Questions in this interview should reflect people's perceptions of the whole system, their interests on the system and their operations, and their capabilities enabling feedback from operators.

Here, we suggests to measure:

1. Process improvements performed by team members
2. Accessibility to the information about the system / knowledge of employees about the system
3. Employee feedback system

Following measures can be investigated:

- Number of suggestions each employee makes for a year
- Number of suggestions implemented for a year
- Budgets to improve employee feedback system

### 3.2.4. Inventory

In case of increased complexity caused by increased uncertainty, one may counterbalance it with increased inventory buffers. However, it is not desirable to manage high level of system complexity with increased buffers due to cost reasons, so it is generally pursued to cut down the inventory level. In this context, inventory level can be seen as the metric that shows the system complexity that couldn't be properly handled.

The level of inventory can be determined by calculating the days for which the existing inventory can cover the production – e.g., 1 month, 3 weeks, etc.

### 3.2.5. Scheduling

Scheduling is the activity that defines the relationship between machines and products through time for the goal of product manufacture. Scheduling itself may not contribute to the complexity of a system, but system complexity can be seen indirectly from scheduling difficulties, since the need for scheduling is the result of numerous variables that affect system complexity.

According to Gershwin [14], a schedule is a sequence of times when specified events will take place. This meaning is useful if these times can be specified precisely, and if the events will probably take place as scheduled. This meaning does not disclose the limitations of scheduling in a production environment for two reasons [14]:

1. "The environment is stochastic. Disruptive events occur frequently and prevent the planned events from taking place, or make the times that had been calculated less desirable than they were before the disruptions.

2. There are too many events. Even the fastest supercomputer with enormous memory cannot calculate optimal, even satisfactory, times if there are too many events. In addition, human managers can usefully comprehend a schedule only of limited size."

Scheduling difficulties indicate the controllability of the manufacturing system against the stochastic environment. However, no metric is proposed since scheduling is the result of other complexity factors. For scheduling, we may have to consider four dimensions – start time, volume or rate, run size (number of consecutive parts before changeover) and sequence.

### 3.2.6. Summary of Proposed Complexity Metrics

Proposed complexity metrics can be summarized into Table 3-3.

<table>
<tr><th colspan="3">Metrics</th><th>How to measure</th></tr>
<tr><td colspan="4"><b>Relationships between system components</b></td></tr>
<tr><td colspan="3">Number of flow paths</td><td>$N_f = \prod_{i=1}^{np} m_i$</td></tr>
<tr><td colspan="3">Number of crossings in flow paths</td><td>$N_c = \sum_{i=1}^{np-1} {}_{m_i}C_2 \times m_{i+1} + \sum_{i=1}^{np-1} N_{ct,i}$</td></tr>
<tr><td colspan="3">Total travel distance of a part</td><td>$D_t = \frac{\sum_{j=1}^{N_f} \sum_{i=1}^{n_p - 1} d_{ji}}{N_f}$</td></tr>
<tr><td colspan="3">Number of combinations of product and machine match</td><td>$N_m = \prod_{k=1}^{n_s} \prod_{j=1}^{n_{p_k}} \prod_{i=1}^{m_j} V_i$</td></tr>
<tr><td colspan="4"><b>Elementary system components</b></td></tr>
<tr><td colspan="3">Number of elementary system components</td><td>$N_e = \sum_{i=1}^{np} m_i + s_i + p_i$</td></tr>
<tr><td rowspan="4">Complexity of each elementary component</td><td colspan="2">• Reliability of elementary system components</td><td>$R = \frac{T_t - T_r - T_o}{T_t - T_r}$</td></tr>
<tr><td colspan="2">• Quality outputs</td><td>$S_y(\%) = \frac{n_t - n_d}{n_t} \times 100$ (or FTTC)</td></tr>
<tr><td rowspan="2">• Time outputs</td><td>Cycle time</td><td>(Length) Mean cycle time of a system component<br>(Variation) Variance of cycle time</td></tr>
<tr><td>Setup time</td><td>Same as Time outputs</td></tr>
<tr><td colspan="4"><b>People</b></td></tr>
<tr><td colspan="3">Process improvements</td><td>5 point survey questions</td></tr>
<tr><td colspan="3">Information accessibility</td><td>5 point survey questions</td></tr>
<tr><td colspan="3">Number of suggestions</td><td>• Suggestions per employee<br>• Suggestions implemented<br>• Budgets to improve employee feedback system</td></tr>
<tr><td colspan="3">Inventory</td><td>Production days that existing inventory can cover.</td></tr>
<tr><td colspan="3">Scheduling</td><td>It is the result of other metrics.</td></tr>
</table>

Table 3-3. Summary of System Complexity Metrics

## 3.3. Impact of Product Variety on the Complexity Metrics

In this section, changes in the complexity metrics according to product variety are studied. By looking through changes of each metric, we may have insights on how product variety affects the system. Based on these insights, those changes of metrics in two types of manufacturing systems are compared (mass production vs. lean production) and the way a lean manufacturing system deals with increased complexity is discussed. The schematic layouts of two systems are as Figure 3-7.

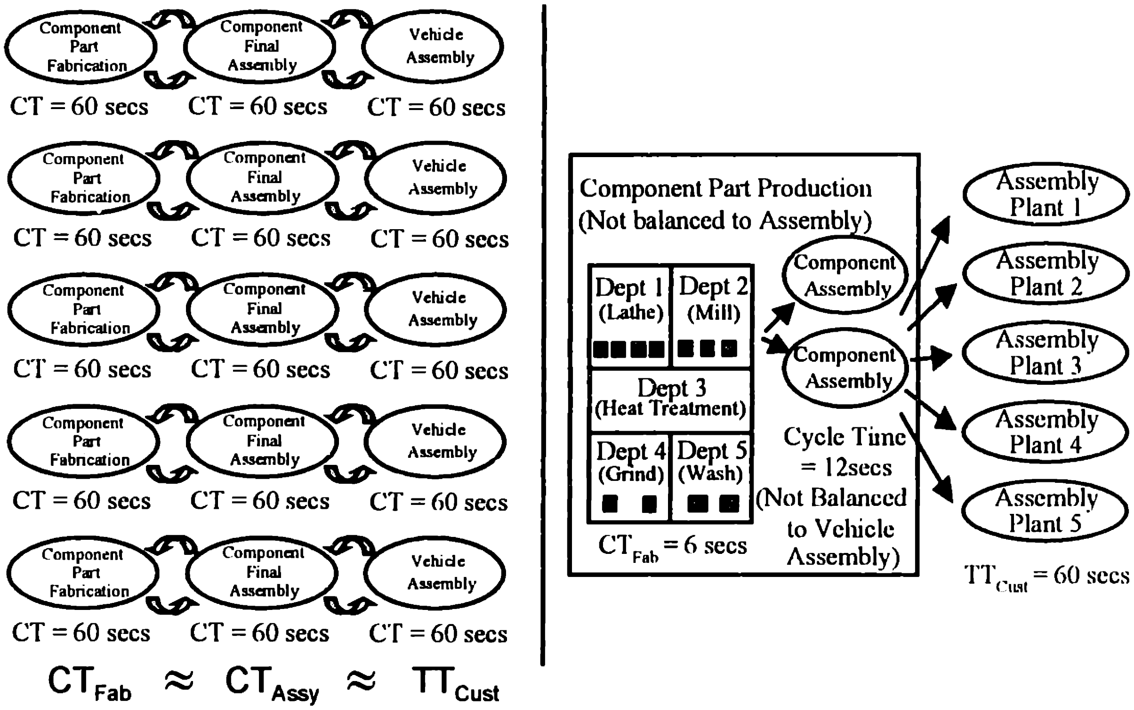


Figure 3-7. Linked Cell System (left) vs. Mass System (right)

As seen in Figure 3-7, mass production equipment is not designed based on the single customer's demand cycle time. Linked-cell manufacturing systems, however, group product families, manufacturing facilities and customers of a supply chain focused on producing at the customer demand cycle time. Consequently, the cells within a linked cell system are designed to run at the same pace as the customer. This supply chain approach based on the demand cycle time is the linked-cell manufacturing strategy that is pervasive in lean manufacturing.

If the reader is not accustomed to the principles of lean production, please refer Appendix 1. In Appendix 1, a list of references for lean production system design is provided.

## 3.3.1. Relationships between System Components

### 3.3.1.1. Number of Flow Paths

Number of flow paths is the metric that shows the number of relationships between different types of processes such as milling, grinding, heat treatment, assembly, etc. For example, in the functional layout-based manufacturing in Figure 3-8a, the number of unique flow paths is:

$$Nf = \prod_{i=1}^{np} m_i = \prod_{i=1}^{5} m_i = 5 \times 4 \times 5 \times 4 \times 5 = 2000$$

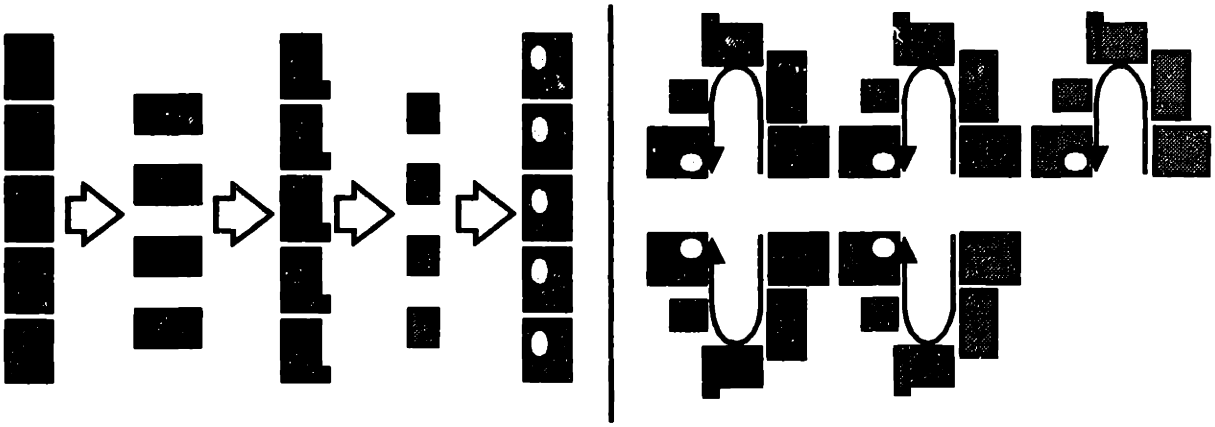


Figure 3-8. Functional Layout (a: left) vs. Cellular Layout (b: right)

Considering the product variety, this result indicates that there are 2000 flow paths for each product type that should be traced in case of defects or other problems. More importantly, considering machine utilization rates, determining the flow path for each product type is very difficult since the flow paths cannot be decided without considering other flow paths. This means that someone could choose a flow path out of 2000 combinations across 5 different product types. In addition to these difficulties, machine capability will be another issue due to the limited investment. Unless all machines have 100% capability for all types of products, machine capability should be considered during the flow path decision process.

This large number of flow paths increases the difficulty to trace defects. It takes a lot of time to find the sources of defects and to get rid of them. This condition results in the quality traceability problem that is another source of system complexity.

To decrease this large number of flow paths, one single large machine may be used. In that case, however, other metrics on the complexity of elementary components will be worsened. Therefore, in a lean manufacturing system, 5 cells are used with simpler, more cost-effective machines (see Figure 3-8b). If we arrange the machines into cells, the number of flow paths can be decreased to 5 rather than 2000. Further improvements may be possible by assigning certain product types to a cell or decreasing the number of cells, which can be done by redistributing the processes (work contents) to each machine.

This effect is illustrated by the model in Figure 3-9 [19] – reorganizing the entities of a system into a network of self-organizing groups can reduce the integrated complexity of work assignment and load balancing.

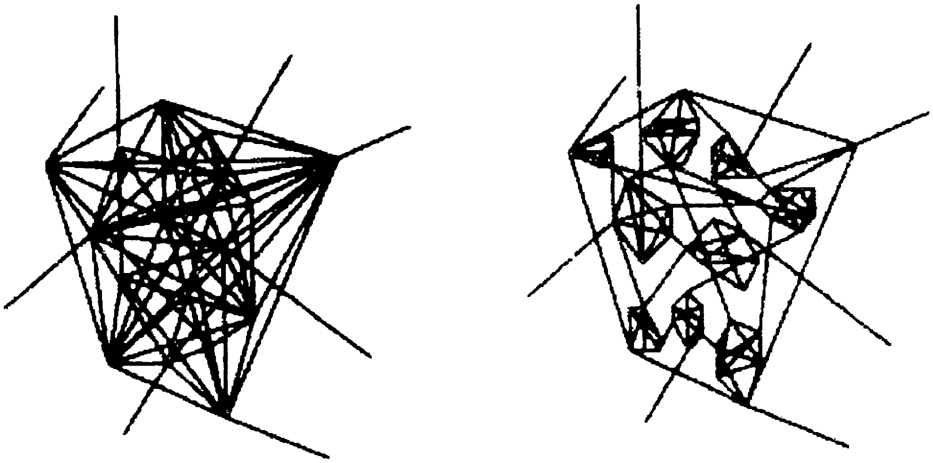


Figure 3-9. Reducing System Complexity [19]

### 3.3.1.2. Number of Crossings in Flow Paths

Continuing using the system in Figure 3-8a as an example, the number of crossings caused by the sharing of machines and sharing of physical space during transportation is:

$$
\begin{aligned}
Nc &= \sum_{i=1}^{np-1} {}_{m_i}C_2 \times m_{i+1} + \sum_{i=1}^{np-1} Nct_i = \sum_{i=1}^{5-1=4} {}_{m_i}C_2 + \sum_{i=1}^{4}(40+30+20+10) \\
&= \{{}_{m_1}C_2 \times m_2 + {}_{m_2}C_2 \times m_3 + {}_{m_3}C_2 \times m_4 + {}_{m_4}C_2 \times m_5\} + 4 \times 100 \\
&= {}_5C_2 \times 4 + {}_4C_2 \times 5 + {}_5C_2 \times 4 + {}_4C_2 \times 5 + 400 = 40+30+40+30+400 = 540
\end{aligned}
$$

Considering the product variety, 540 crossing in flow paths should be checked for each type of product in case of problems such as variations in quality or production disruptions, etc. In addition, crossings in flow paths caused by machine sharing means that machines have to be changed over according to different product types.

To decrease the number of changeovers, several ways may be adopted such as decreasing the number of flow paths itself or eliminating the machine sharing that is the source of the crossings. In a lean manufacturing system, cells eliminate this machine crossing. In the system shown in Figure 3-8b, the number of crossings in flow paths is zero.

### 3.3.1.3. Total Travel Distance of a Part

There doesn't seem to be any explicit relation between the total travel distance of a part and the product variety. Implicitly, however, since product variety increases inventory level in many cases and increased inventory may lengthen the travel distance of a part, we may say that there is proportional relationship.

In fact, the arrangement of equipment in the departmental (or functional) layout versus the cellular layout most greatly affects travel distance. In lean, linked-cell manufacturing, since all machines are moved to right next to each other, the total travel distance is decreased to very low level. See this drastic change in Figure 3-10.

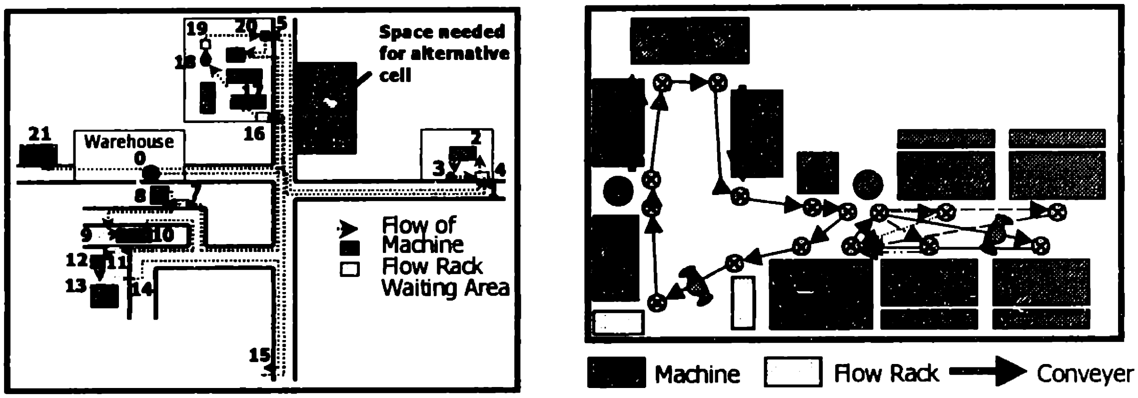


Figure 3-10. Pump Cover Production System Design Change [20]

### 3.3.1.4. Number of Combinations of Product and Machine Match

Increased product variety has a huge impact on the number of combinations of matching a machine to a product. For example, in a system like Figure 3-8a, when there is only one type of product, the number of combinations of matching a machine to a product is only one. However, if we assume that there are 5 types of products, and each machine can pick up any type randomly with perfect capability, the number of combinations will increase to:

$$N_m = \prod_{k=1}^{n_l} \prod_{j=1}^{np_k} \prod_{i=1}^{m_j} V_i = \prod_{k=1}^{1} \prod_{j=1}^{5} \prod_{i=1}^{m_j} 5 = 5^5 \times 5^4 \times 5^5 \times 5^4 \times 5^5 = 5^{23} = 1.19209285\, e+16$$

which is beyond our ability to deal with. Even worse is that someone must decide which product-machine combination to use out of 1.192092895508e+16, everyday. This choice may become simpler in case of considering only one process, $5^5 = 3125$ combinations and having inventory buffers between processes, which is common case. However, in this case, we may lose control over the whole system and should endure problems caused by high level of inventory This large combination inhibits understanding the system behavior and the development of solutions for disruptions caused by time variation or quality variation.

In a cellular manufacturing system like Figure 3-8b, however, this product machine combination is steeply decreased. If 2 product types are assigned to each cell, this is decreased to $2^5 = 32$ combinations. Further, since each cell is operated pretty much independently, this number may be considered to be lower than 32.

## 3.3.2. Elementary System Components

### 3.3.2.1. Number of Elementary System Components

Going back to the example of Figure 3-8a, there are total 23 machines. One worker is likely to be tied to one machine. Thus, it is likely that there will be 23 operators. If the product variety is increased, each machine should have the capability to process multiple types of products, which increases the number of sub-level components such as fixtures and tools. Accordingly, the number of elementary system components is increased. The combination of people and these sub-level components of fixtures and tools add to system complexity.

In the cellular design of Figure 3-8b, the number of machines is slightly increased to 25 but the number of operators is flexible from 5 to 25 according to the production rate. In fact, there might be further advantage in terms of the number of system components, since a cell may be seen as one element. From this perspective, the number of system components is 5, which further reduces complexity. Furthermore, the interaction of an operator to tools and fixtures (i.e., sub-level components) is reduced since a cell is focused to a family of parts rather than to all parts as in the departmental system.

### 3.3.2.2. Complexity of Elementary Components

#### 3.3.2.2.1. Reliability of Elementary Components

Reliability of elementary components is the ratio of (net available time – unplanned downtime) to net available time. In this equation, unplanned downtime includes breakdowns, minor stoppages, adjustments and setups.

Increased product variety can decrease the reliability of elementary components in two ways. At first, since increased product variety may require more frequent setup changes, it can do harm to the reliability of system components by increasing the time for setups and adjustments. Second, since machines are required to have capability for more types of products, they are likely to be more complex and consequently vulnerable to break down.

In a lean manufacturing system, however, setup activities are done by standardized tools and steps within a short time period. Thanks to that, setup changes are pre-scheduled and done within the scheduled time, so that they don't affect the reliability of elementary components. As for machine breakdown, cells are composed of simple general machines that have high reliabilities. This is possible because in a cell, operations are grouped to small segments and these are assigned to a machine, so that a machine is not required to have high level of capability.

#### 3.3.2.2.2. Quality Output

Increased product variety affects the quality output by increasing the complexity of operation contents. Machines or operators should distinguish each product type and match it to corresponding sequences of processes. For example, right sub-parts should be supplied and right fixtures, tools, and programs should be prepared, which is not an issue when there is only one type of product. If there is any mistake in these activities, it may result in poor quality product. In this context, we can say that increased product variety does harm to the quality output.

In a lean manufacturing system, assigning focused levels of variety to each cell and performing intensive kaizen activities solve this problem. Focusing the variety to each cell decreases the system complexity by cutting down the number of different resources needed at each cell. On the other hand, kaizen activities including applying pokayoke (mistake-proofing) techniques decreases the chance of making mistakes.

#### 3.3.2.2.3. Time Outputs

***Cycle time***

With increased product variety, the variation in the processing time of each product type can be an issue when balancing upstream processes with downstream ones. This factor is critical in assembly lines that are usually transfer line designs. Stations that are not fully balanced to the line cycle time cause workers to be idle and results in poor labor productivity.

In lean, cellular manufacturing the worker is separated from the machines. Each station is designed to operate and less than or equal to the takt time. Labor productivity is achieved since workers are not tied to a given station. In addition, variation itself is small since a cell is focused to a family of parts rather than all parts.

***Setup time***

Increased product variety requires more changeovers and consequently more setups. The length of setup time plays a significant role in this case, since the loss of production time due to frequent setup becomes an important issue. On the other hand, possibly product variety affects both the length and variation of setup time since it requires setup operators with more capability.

### 3.3.3. People

Various product types generally do harm to people's perception of the system by generally increasing the number of events that should be dealt with. People's ability to perceive the system is limited but the product variety increases the number of possible incidents, which may bring poor perception.

In lean manufacturing, the system itself is simpler to understand and enormous effort is made in visual system design to help people to know what is going on In addition to that, people are encouraged to work together as a team. By working as a team member, individual operators can get ideas for the system (at least the subsystem he/she is working on) from other operators. Team members are cross-trained for several types of machines, which will help an operator to understand other types of works and the way system works. In addition to that, operators are supposed to deal with many problems caused by product variety by themselves, so that they have more understanding on the effect of product variety. In these ways, people in a lean manufacturing system are able to deal with product variety more effectively because the system design reduces complexity. In other words, the increase in number of products is independent of system complexity.

### 3.3.4. Inventory

We can expect higher levels of inventory to be observed with increased product variety. This deduction is reasonable since at least a certain level of safety stock should be kept for all types of products.

### 3.3.5. Schedule

For the same reason as inventory, a higher level of scheduling difficulties are expected with increased product variety. As mentioned before, scheduling difficulty is the result of other complexity factors. However, as studied before, there are factors in the lean, linked-cell manufacturing system design that enable large product variety without increased system complexity.

## 3.4. Summary of Impact of Product Variety on the Complexity Metrics

The impact of product variety on the complexity metrics can be summarized as Table 3-4.

| Metrics | Impact of Product Variety | | How can Lean Manufacturing be less complex than Mass Production |
|---|---|---|---|
| | Mass Production System | Lean Manufacturing System | |
| Number of Flow Paths | Large increase because it is large even when not considering product variety | Small increase because it is small when not considering product variety | By reorganizing the entities of a system into a network of self-organizing groups (cells) |
| Number of Crossings in the Flow Paths | Large increase because it is large from the first | 0 | By eliminating the crossings caused by machine sharing |
| Total Travel Distance of a Part | No explicit impact – it is long | No explicit impact – it is short | By product oriented layout |
| Number of Combinations of Product and Machine Match | Critical increase | Small increase | By decreasing the number of flow paths and making it easy to restrict product types to each cell |
| Number of Elementary System Components | No impact | No impact – it can be larger or smaller than Mass production | It is larger when counting the components literally, but if considering a cell as one component, it is smaller. |
| Reliability of Elementary System Components | Worsened | Minor impact | By quick setup change over, making setup activities be predictable (scheduled), and using simpler machines |
| Quality Outputs | Worsened | Minor impact | By extensive use of poka-yoke devices, kaizen activities, and less product variety to each cell |

| | | | |
|---|---|---|---|
| Cycle Time (L: Length, V: Variation) | (L) No explicit impact | (L) No explicit impact | (L) By eagerly pursuing to have cycle time shorter than takt time |
| | (V) Huge increase | (V) Minor impact | (V) Each cell is designed to accommodate pre-assigned product variety. Machine cycle time variation is absorbed by operators work-loop cycle time |
| Setup Time (L: Length, V: Variation) | (L) Minor impact | (L) Minor impact | (L) By applying SMED techniques extensively |
| | (V) Huge increase | (V) Minor impact | (V) By applying SMED techniques extensively and standardizing every setup changeovers |
| People | No explicit impact | No explicit impact | By seeing people as the most valuable resources and encouraging continuous improvements by 'people' |
| Inventory | Huge impact | Slight increase | By shortening the replenishment time and just-in-time delivery from suppliers |
| Scheduling | Huge impact | Minor impact | All above methods will help to reduce scheduling difficulties |

Table 3-4. Summary of Impact of Product Variety on the Complexity Metrics and How Lean Manufacturing Reduce Complexity

## 3.5. Interpretation of Results and Product Design Issues

As shown in the preceding section, most complexity metrics increase as product variety increases. However, it is also shown that with lean manufacturing system designs, the values of these metrics can be greatly decreased, compared to those with conventional mass production system designs. This result supports the hypothesis: "In a lean manufacturing system, system complexity as affected by increased product variety is much less than that in an equivalent mass production system."

From the perspective that product design should reflect manufacturing system designs, several product design strategies for lean manufacturing systems may be considered. For example, if a lean, linked-cell system is used to decrease the system complexity, products are designed according to families that are tied to the linked-cell capability. In this case, families may be based on product geometry, customer, series type, etc. Other strategies such as using common fixtures and avoiding designs preventing certain process technology used for short cycle time should be also considered. These strategies are to take full advantage of decreased system complexity by lean production system design while providing 100% product variety required by customers.

While the role of product design described above is passive, there is an active way for product design to decrease system complexity. Three strategies are explained in following sections considering their effects on system complexity.

*System Complexity approach and Design for Variety approach*

Interestingly, complexity approach developed in this thesis can explain how the indexes of DFV (Design for Variety) – commonality, differentiation point, and setup cost – work for a system. For instance, commonality decreases the system complexity by eliminating the product variety that each system component should manage. Having differentiation point in downstream process is another way to decrease product variety for early operations by implementing the variety toward the end of the manufacturing process. Consequently, complexity metrics such as the number of product and machine matches or time outputs are decreased by these strategies, which shows decreased complexity of a manufacturing system. They, specially help a lot to decrease the number of product and machine matches by decreasing Vi in each processes in Equation 3-14. Setup cost, which is another index suggested in DFV, is reflected by the setup time metric, length and variation.

### *System Complexity approach and Design for Manufacturing approach*

There seem to be two other approaches to reduce system complexity from the design standpoint. One is design for manufacturing approach and the other is product architecture. From the system complexity perspective, design for manufacturing approach can be interpreted to reduce complexity of elementary system components by following ways:

- Prevents quality problems caused by operations
- Reduce cycle time and its variation in operations by avoiding designs difficult to be manufactured

On the other hand, product architecture is closely related to the system level complexity. For example, it decides the relations between subsystems (or cells). Along with the product architecture concept, modularity, standardization and integration are generally discussed as major issues and among these issues, modularity is discussed in the next section.

### *System Complexity approach and Modularity*

Recently modularity has gained its popularity as a core competitive advantage of high performance benchmarked companies. For example, Spear [84] claims that modularity of organization plays a very important role to make the Toyota Production System work. In addition, modularity of products is discussed by Carliss and Clark [85] as a solution to growing complexity of products. In fact, modular design has been recognized as an efficient way to provide customer-required product variety without increasing the cost critically. For instance, Ulrich [3] claims qualitatively that two ways are possible to achieve high product variety without causing high cost; one is having lean manufacturing systems and the other is having modular product design.

From the system complexity perspective, modularity can be seen as a driver to eliminate the interrelationships between system components, which consequently reduces system complexity. The notion of independence of a system component[3] with other components simplifies the material and information flow. Further, if the extreme case is assumed, modularity eliminates the need to have in-house manufacturing systems since it enables outsourcing of components. In this way, modularity decreases system complexity.

Due to this benefit of modularity to decrease system complexity, it may be applied to the extended enterprise concept [45] to facilitate strategically aligning companies to achieve a common goal – success in a market. Computer industry may be considered as a good example of this case. However, still further research is needed to clarify the relationships between modular design and system complexity as well as its extension of applications.

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[3] Modularity is defined as 'building a complex product or process from smaller subsystems that can be designed independently yet function together as a whole.

# CHAPTER 4. CASE STUDY: BOSCH CHARLESTON PLANT

## 4.1. Introduction to the Company and Products

The Bosch Charleston plant is located in Charleston, South Carolina. They produce ABS (Anti-lock Break System) units and fuel injectors for automotive companies such as Ford, Toyota, GM, etc.

This case study was carried out from 07 July to 01 Sep 1998, focussed on the ABS production especially in machining area for housings of ABS 5.3 family. The current ABS production system has a machining area with a departmental layout and several half-automated assembly lines. Some attributes of lean manufacturing philosophy are adopted in both assembly lines and machining areas, but not dominant considering the whole system. Automation is extensively pursued for high quality and flexibility.

As for product variety, within the ABS product, currently two generations are produced: ABS 5.0 and ABS 5.3. The ABS 5.3 is reduced in size, weight and cost compared to ABS 5.0. Within the ABS 5.3 generation, there are many versions, driven by customer needs. However, the basic modular system is the same within the ABS 5.3 family. The features that vary are a selection of variable components that tune the modulator for the specific automobile, customer specific items for fit in the vehicle, customer specific visual criteria, customer specific integrated electronic functions and the base system definition of either having only anti-lock breaking or ABS with traction control (ASR) or ABS/ASR with vehicle dynamic control (VDC). This kind of variation in product types requires flexibility; the cost due to this required flexibility is recognized as a problem.

Due to the internal confidentiality, some of numbers and drawings may be modified.

## 4.2. Current ABS Housing Production

The current production system design can be characterized by its departmental layout to maximize the machine utilization rate while attempting to follow some techniques of lean manufacturing to take advantages of its benefits in terms of throughput time and reduced inventory level. Highly efficient machining centers are adopted and automated guided vehicles (AGV) are moving parts between departments. One operator operates 4 machining centers and does the inspection of parts while the machine is running. Obviously, the problem with this system design is not the well-optimized sub-system but the lack of view to the whole system.

Following is more detailed description of the machining area according to the material flow.

### 4.2.1. Receiving

Raw materials (aluminum-extruded blocks) are supplied from a supplier using big containers that each holds 385 or 462 units of these blocks. The supplier receives the confirmed order two months before the parts are actually needed in production and ships an average of 12,500 parts twice a week to the separately located warehouse. It takes two days for travelling and two trucks are needed to make these shipments.

In the separately located warehouse, approximately 150,000 blocks are stored using same containers. After having been stored for an average of 2 weeks in this warehouse, parts are moved to the receiving area of the plant. This work is done by a truck twice a day and it takes about 6 minutes from this warehouse to the plant. Moved containers are stored again in the main storage area of the plant. A total of 16 containers are always stored in the main storage area and withdrawn containers are replenished based on the pull replenishment system. In other words, whenever the containers are withdrawn by production, the plant orders new containers from the warehouse to replace them.

After being stored for approximately 12 hours in the main storage area, containers are pulled from the machining area for production. This happens 6 times a day by using of a forklift and moved containers are stored again in the sub-storage area inside the machining area.

The parts needed are determined by an MRP system and the demand information is fed by assembly lines by requesting parts. MRP then schedules the production but since assembly lines pull their parts out of a buffer between machining and assembly, production does not necessarily replenish these parts immediately.

The pallets that are not used directly for the production are moved to the storage area inside the machining area, where they are stored for a few hours until they are used.

### 4.2.2. Machining

After being stored for a few hours in the sub-storage area, parts are moved to the repackaging area where these aluminum blocks are repackaged to smaller containers that hold 18 parts per container. This operation is done manually. After that, two of these small containers at a time are sent to one of 26 machining centers by AGVs (Automated Guided Vehicle).

Four of these machining centers are grouped into a cell that is operated by one operator. Machining centers used are five axle CNC machines equipped with three spindles, which can process three parts parallel (See Figure 4-1).

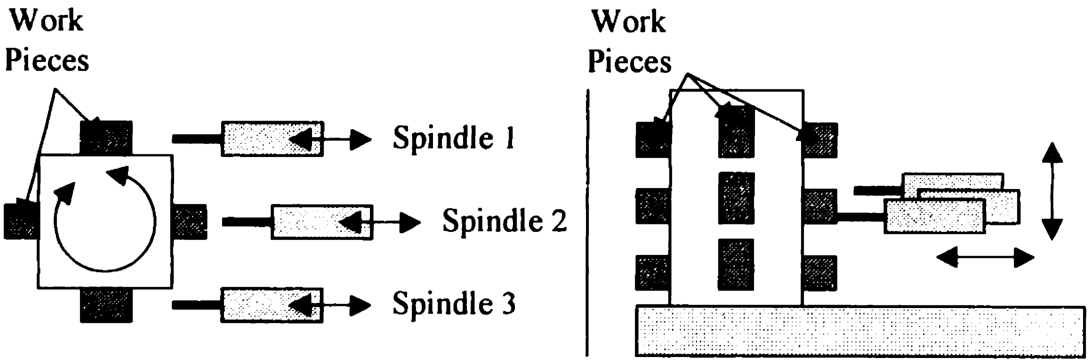


Figure 4-1. Schematic View of a Fixture (Top View: Left, Side View: Right)

Even though these machining centers have been purchased to perform as many operations as possible in one load, finishing a part cannot be done in one load because all faces must be processed. Due to this, the parts have to be manually unloaded from one position in a fixture and then loaded to another position, so that a total of 4 times of load and unload are required to finish a part. Tombstone fixtures are applied to hold 12 parts at a time to justify the large investment to this machine. The fixtures used here are shown in Figure 4-2.

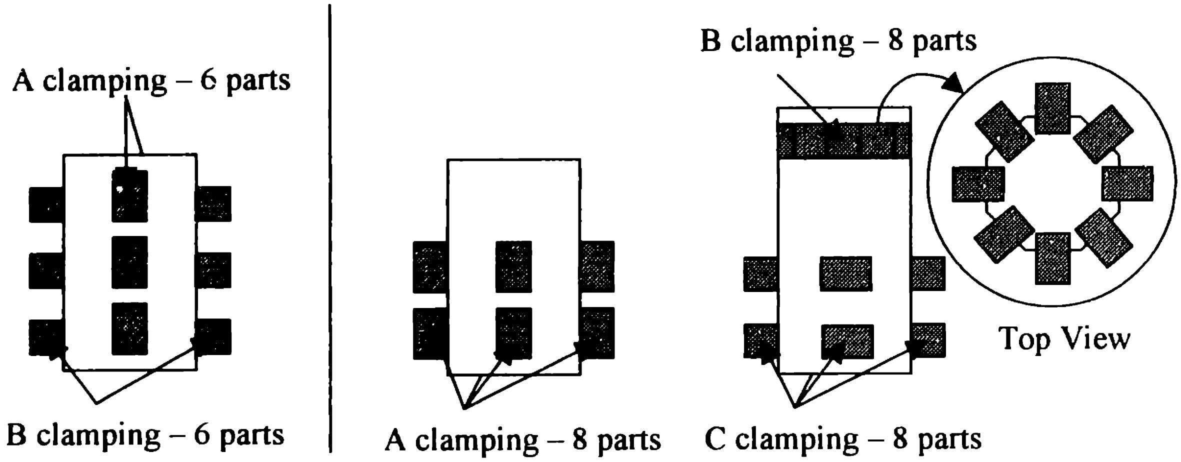


Figure 4-2. Schematic View of Fixtures for ABS (Roehm, Left) and ASR (Hohenstein, Right)

At the beginning of each cycle, 12 blocks of housings are set to the fixture, half of which are new blocks to position A and another half are moved blocks from position A to B.

The cycle time for each load is about 25 minutes, but only 6 parts come out as finished housings. The other 6 parts need a position change in the fixture to get machined again for another cycle time. Therefore, the whole cycle time to finish one housing is about 8 minutes and the production rate is 6 parts / 25 minutes = 1 part / 4 minutes.

Machining itself is relatively simple – make tens of holes with different diameters in a block, which consist of the circuits for the break fluid. However, since there are some holes with big diameters that require large horsepower and precision, high precision and horsepower machining centers are currently used.

### 4.2.3. Inspection

After getting machined, 1 part out of 6 parts is inspected by the operator with 18-22 tools and the results are recorded for SPC purpose. Some of the tools are pneumatically operated gauges and some are go/no-go type tools. Since one out of 6 parts coming out of one load to the fixture is inspected, if any defect is detected, at least the whole load of 12 parts is scrapped. An even worse case is a "chip in spindle" that is the most common problem, since the machine already starts running when the parts are inspected, the next load is also most likely to be defects.

### 4.2.4. Deburr and Washing

After getting inspections, 18 of these parts are located in a container and moved to one of 8 deburring machines by AGVs. At the deburring machines the parts are manually loaded by one piece at a time. The deburring operation that removes burrs from the hydraulic circuits is done automatically by using a high pressure water jet.

After being manually unloaded from deburring machines, these deburred parts are put on the conveyor belt. While moving through the washing and drying machines on the conveyor belt, parts get washed and dried. Coming out of the washer, washed and dried parts are manually inspected again and repacked into containers holding 18 parts. These bins are moved to a buffer area by AGVs and bins are retrieved by assembly lines.

### 4.2.5. Buffer

The buffer can hold 1000 containers and usually 36 containers of each part type should be in the buffer (There are 17 types of housings currently produced). The space, however, provided by this buffer area is not often enough for produced parts so that it is common to have extra areas assigned as a temporary storage area near machining area.

### 4.2.6. Assembly

Three containers of parts in the buffer area are moved to the assembly area by AGVs at a time. At the starting point of each assembly line, these containers are manually unpacked and each part is placed on a single piece flow conveyor. Assembly tasks are performed in a kind of U-shaped cell that has incorporated some ideas of lean production, which is not the focus in this paper.

### 4.2.7. Shipping

After assembly, finished parts are manually taken off the conveyor and packed into containers of 200 units. These containers are first stored in the shipping area before they are shipped out to the customer or another separately located warehouse. These shipments take place once a day.

Existing plant layout is as in Figure 4-3.

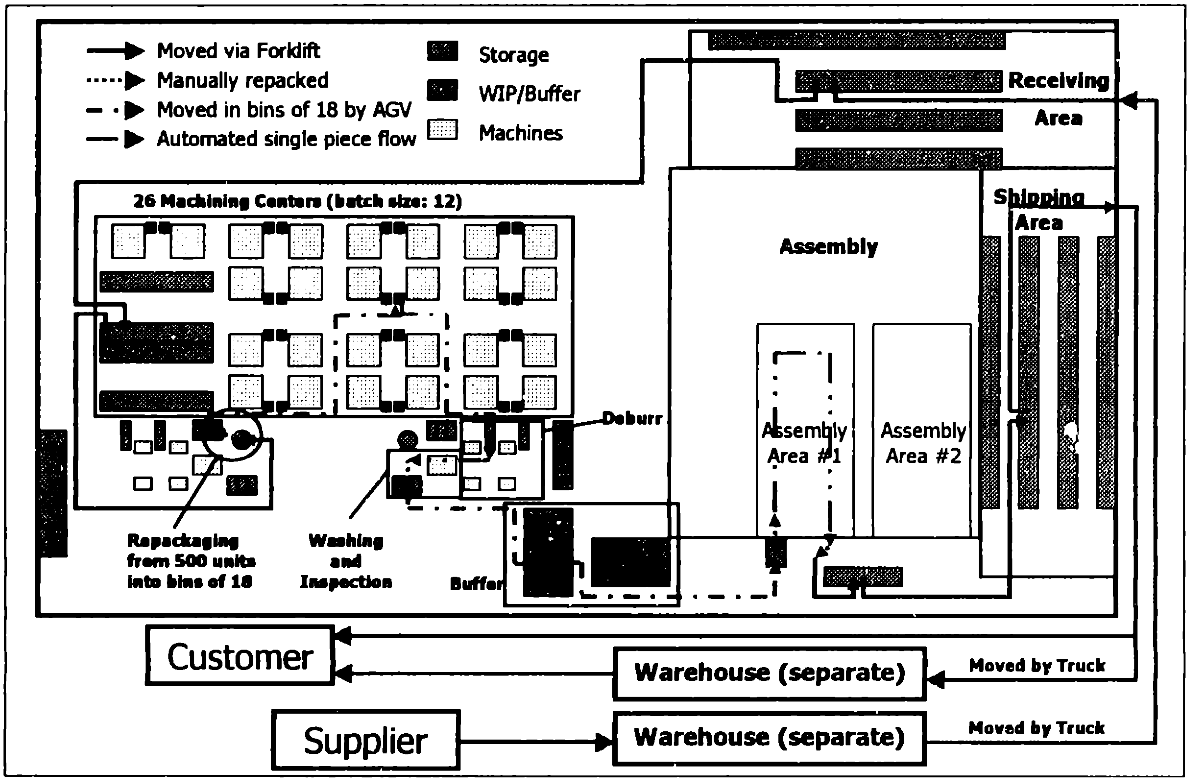


Figure 4-3. Current Plant Layout and Material Flow

## 4.3. Designed Linked Cell System

In this section, the steps followed to design the linked cell system that substitutes the current machining area are explained. The steps in [83] are adopted to pursue the ideal lean manufacturing system and the design is based on a "green field situation". The simplified cell design process is as follows:

1. Group Products.
2. Determine the output rate of the cell, or takt time. Based on that takt time, determine the number of cells and assign product types to each cell.
3. Standardize process and operators routine.
4. Check if the takt time is met. If not, operations of both machine and operators should be rechecked and modified to meet the takt time.
5. Link cells to assembly or other cells with a pull system.

Following the above steps, the new system has 4 cells: 3 of these cells are for ABS housings only and one cell is designed for both ABS and ASR housings. Each cell has 100 percent flexibility for all types of housings within its assigned product family. Single piece flow is adopted and setup changeover requires only program exchanges, which can be done in less than a minute. The receiving and storage area is moved near the machining area, but current assembly lines are used. The designed lean plant layout is shown in Figure 4-4.

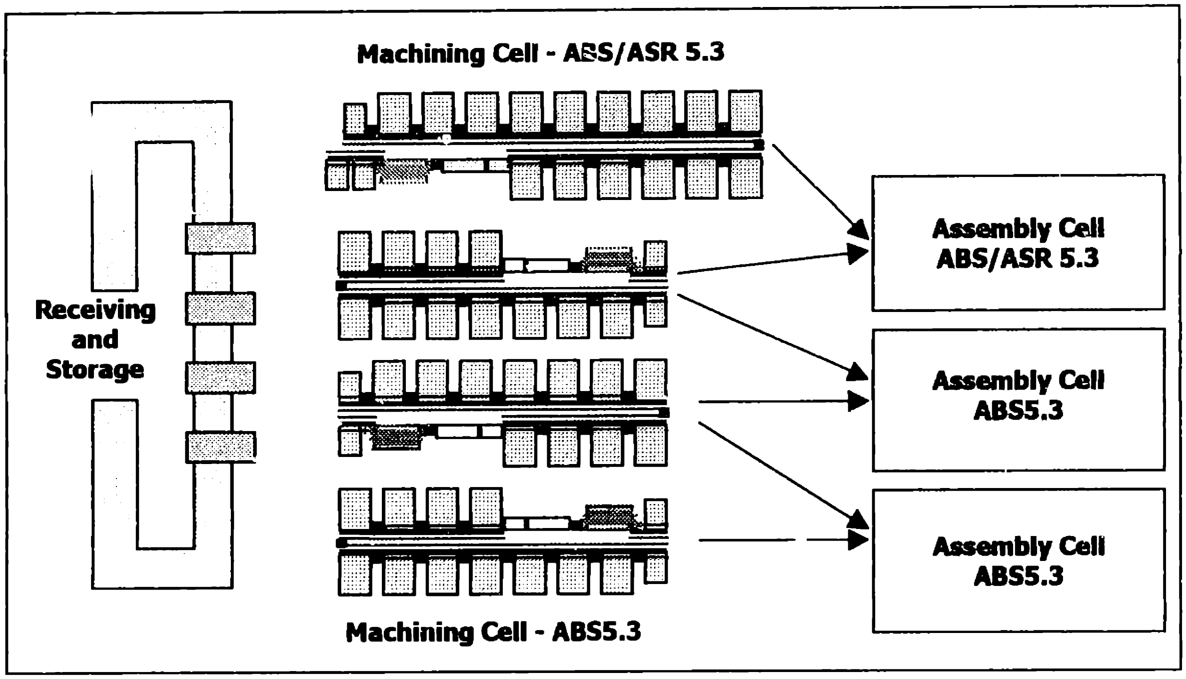


Figure 4-4. Proposed New ABS Manufacturing System Design

In the following sections, details of the design processes are explained including considerations during design decisions and some alternative designs.

### 4.3.1. Group Products

A manufacturing cell is a group of machines or processes of functionally dissimilar types that are physically placed together and dedicated to the manufacture of a specific range of parts [30]. Therefore, the selection of part types for cells is one of the first decision factors. It is important to take advantage of similar attributes of different types of products during their manufacture. Acceptable equipment utilization rate or balanced machine loads can be achieved by the proper selection of product types. For this kind of decision, Group Technology (GT) may be used (see [31], [32], [33] for details).

The basic concept of group technology is relatively simple: to identify and bring together parts that are related by similar attributes and then to take advantage of similarities to develop simplified and rationalized procedures in all stages of design and manufacture [31, p15]. With this simple concept, group technology is applied to several areas such as (see [33] for details):

- Part family identification
- Engineering design
- Process planning
- Production planning and control systems
- Cellular manufacturing

However, in this cell design, group technology is not used since grouping products is relatively simple – ABS housings and ASR housings. This is because major differences in machining processes occur between ABS housings and ASR housings while differences within the ABS housing family or the ASR housing family are small enough to be neglected (e.g., slight difference in the number of holes). A machining process map has been used to identify the different processes required for each type of product.

| Product family | | ABS | | | | | | | | | | | | ASR | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Customer | | Toyota | Altima | Nissan QW | Mustang | Cobra | GM Wcar | Subaru | Mazda | MMMA | GM Fcar | Mazda 3CH | CDW | GM Fcar | GM Wcar | CDW |
| Product number | | | | | | | | | | | | | | | | |
| ABS housing number | | 9 265 270 127 | 9 265 270 128 | 9 265 270 110 | 9 265 270 112 | 9 265 270 113 | 9 265 270 114 | 9 265 270 115 | 9 265 270 116 | 9 265 270 117 | 9 265 270 119 | 9 265 270 120 | 1 265 270 980 | 9 265 270 111 | 9 265 270 118 | 9 265 270 130 |
| Tool Number | Re-Entry Block# | | | | | | | | | | | | | | | |
| T53201 | Beginning | x | x | x | x | x | x | x | x | x | x | x | | D=76mm | D=76mm | D=76mm |
| T53160 | 60000 | | | | | | | | | | | | | x | x | x |
| T53102 | 2000 | | | | x | x | | | x | x | | | | | | x |
| T53103 | 3000 | x | x | x | x | x | x | x | x | x | x | x | | x | x | x |
| T53104 | 4001 | x | x | | | | x | x | x | x | x | | | x | x | x |
| T53105 | 5001 | | | x | x | x | | | | | | x | | | | |
| T53106 | 6001 | x | x | | | | x | x | x | x | x | | | | | x |
| T53107 | 7001 | | | x | x | x | | | | | | x | | | | |
| T53208 | 8000 | | | | | | | | | | | | | x | x | |
| T53104 | 4002 | x | x | | | | x | x | x | x | x | | | x | x | x |
| T53105 | 5002 | | | x | x | x | | | | | | x | | | | |
| T53106 | 6002 | x | x | | | | x | x | x | x | x | | | | | x |
| T53107 | 7002 | | | x | x | x | | | | | | x | | | | |
| T53208 | 8000 | x | x | x | x | x | x | x | x | x | x | x | | | | x |
| T53110 | 10000 | x | x | x | x | x | x | x | x | x | x | x | | | x | x |
| T53111 | 11000 | x | x | x | x | x | x | x | x | x | x | x | | x | x | x |
| T53112 | 12000 | x | x | x | x | x | x | x | x | x | x | x | | x | x | x |
| T53219 | 19000 | x | | | x | x | x | | | x | x | | | x | x | x |
| T53213 | 13000 | | | | | | x | | | | x | | | x | x | x |
| T53216 | 16000 | | | | x | x | | | | | | | | | | |
| T53117 | 17000 | x | | | x | x | x | | | x | x | | | x | x | x |
| T53218 | 18000 | | | | x | x | x | | | | x | | | x | x | x |
| T53121 | 21000 | | x | x | | | x | | | | x | | | | | |
| T53122 | 22000 | | x | x | | | x | | | | x | | | | | |
| T53132 | 32000 | | | | | | | | | | | | | x | | |
| T53346 | 46000 | | | | | | | | | | | | | | x | x |
| T53223 | 23000 | x | x | x | x | x | x | x | x | x | x | x | | x | x | x |
| T53125 | 25000 | x | x | x | x | x | x | x | x | x | x | x | | | | |
| T53137 | 37001 | | | | | | | | | | | | | x | x | |
| T53106 | 6001 | | | | | | | | | | | | | x | x | |
| T53110 | 10000 | | | | | | | | | | | | | x | | |
| T53214 | 14000 | | | | | | | | | | | | | | x | |
| T53106 | 6002 | | | | | | | | | | | | | x | x | |
| T53126 | 26000 | | | | | | | | | | | | | x | x | x |
| T53135 | 35000 | | | | | | | | | | | | | | | x |
| T53136 | 36000 | | | | | | | | | | | | | x | x | x |
| T53127 | 27000 | | | | | | | | | | | | | x | x | x |
| T53128 | 28000 | x | x | x | x | x | x | x | x | x | x | x | | x | x | x |
| T53129 | 29000 | x | x | x | x | x | | x | x | x | | x | | | | x |
| T53130 | 30000 | | | | | | x | | | | x | | | x | x | |
| T53137 | 37001 | | | | | | | | | | | | | | | x |
| T53214 | 14000 | | | | | | | | | | | | | | | x |
| T53231 | 31000 | | | | | | | | | | | | | x | x | x |
| T53233 | 33000 | | | | | | | | | | | | | | x | x |
| T53135 | 35000 | x | x | x | x | x | x | x | x | x | x | x | | | | |
| T53137 | 37001 | x | x | x | x | x | x | x | x | x | x | x | | | | |
| T53138 | 38000 | | | | | | | | | | | | | x | | |
| T53139 | 39000 | | | | | | | | | | | | | x | x | x |
| T53215 | 15000 | | x | x | | | | x | x | | | x | | | | |
| T53117 | 17000 | | x | x | | | | x | x | | | x | | | | |
| T53140 | 40000 | x | x | x | x | x | x | x | x | x | x | x | | x | x | x |
| T53141 | 41000 | x | x | x | x | x | x | x | x | x | x | x | | x | x | x |
| T53142 | 42000 | | | | | | | | | | | | | x | x | x |
| T53137 | 37002 | x | x | x | x | x | x | x | x | x | x | x | | x | x | x |
| T53138 | 38000 | | | | | | | | | | | | | | x | x |
| T53243 | 43000 | x | x | x | x | x | x | x | x | x | x | x | | x | x | x |
| T53244 | 44000 | x | x | x | x | x | x | x | x | x | x | x | | x | x | x |
| T53245 | 45000 | | | | | | | | | | | | | x | | |
| T53233 | 33000 | | | | | | | | | | | | | x | | |
| T53147 | 47000 | x | x | x | x | x | x | x | x | x | x | x | | x | x | x |
| T53148 | 48001 | x | x | x | x | x | x | x | x | x | x | x | | x | x | x |
| T53149 | 49001 | x | x | | | | x | x | x | x | x | | | x | x | x |

Table 4-1. Machining Process Map for Each Type of Housing

By analyzing the machining process map, it is identified that there should be two types of cells to accommodate two very different types of housings – ABS housings and ASR housings. To ensure the flexibility of this new manufacturing system, cells for ABS housings are decided to have capability for all types of ABS housings, and one cell is decided to have capability for both ABS and ASR housings. Further grouping by customer or demand volume may be possible but is not considered in this stage.

### 4.3.2. Takt Time Calculation

In the manufacturing system design process, it is important to define customers and identify demand volumes for the system. For this activity, the capability of the customer's production lines, marketing analysis and the analysis of product data of similar preceding products are good sources for data acquisition. However, since an alternative lean manufacturing system is pursued to replace the current system, current customer demand data is available and, therefore, extensively used.

For the machining cells, following constraints are identified based on the available data.

| | | |
|---|---|---|
| Time Frame | Jan – Jun 1998 | For this time period, reliable data is available and the time appears to be long enough to cover fluctuations of the demand. |
| Average Production | 81,698 units / month | Total ABS and ASR housing units per month |
| Peak Production | 101,342 units / month | In March '98 |
| Lowest Production | 66,218 units / month | In January '98 |
| Operation Constraint | 3 shifts | 5 days / week |

Table 4-2. Constraints for New Production System Design

After identifying the customer demand, the maximum volume capacity and the ideal range of machine cycle times need to be determined. In the linked cell manufacturing system, the maximum volume capacity is decided by the maximum machine cycle time or minimum takt time. The takt time is calculated as the ratio of available time to average forecasted customer demand as in equation 4-1. The average customer demand varies according to the time period (Figure 4-5), so the takt time changes periodically.

$$\text{Takt Time} = \frac{\text{Available Time}}{\text{Average Customer Demand}} \qquad \text{(Equation 4-1)}$$

where Available Time = Total Time Available for Production – Maintenance Time – Time Allowances.

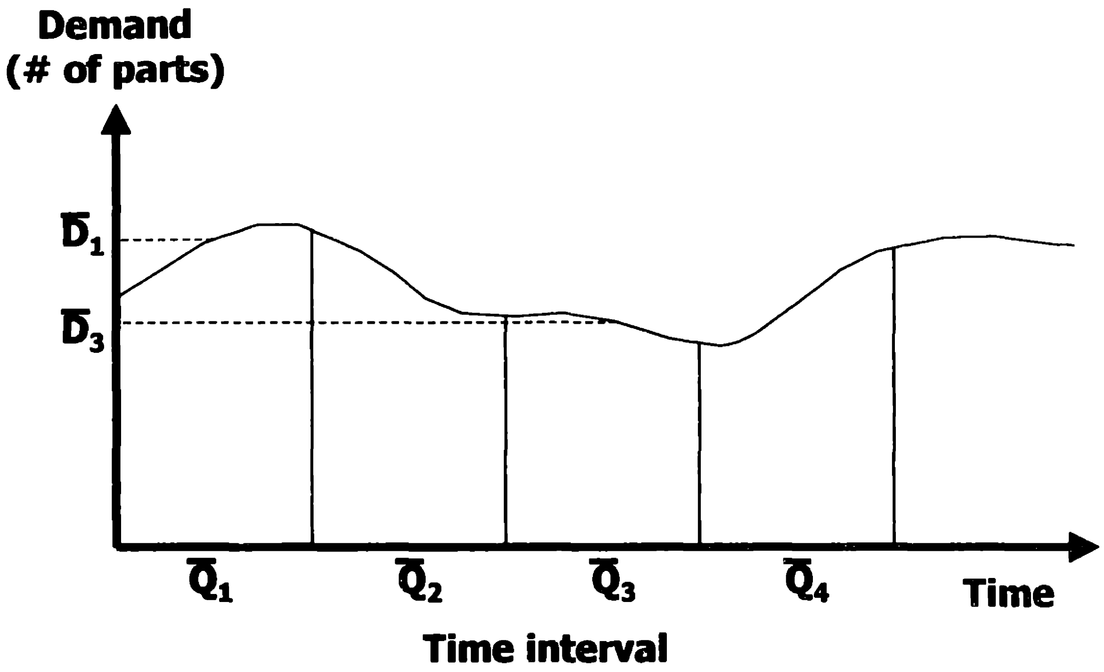


Figure 4-5. Customer Demand Fluctuation with Time and Average Customer Demand

Since the takt time is calculated based on the average demand and a production system has to respond to a range of operating conditions, demand fluctuation should be considered in the cell capacity calculation – minimum cell cycle time calculation. Usually, this is done by giving extra capacity to a cell, for example, 30 %, as in Figure 4-6. In this case, extra cell capacity is ensured by limiting the maximum machine cycle time to less than the minimum cell cycle time or minimum takt time.

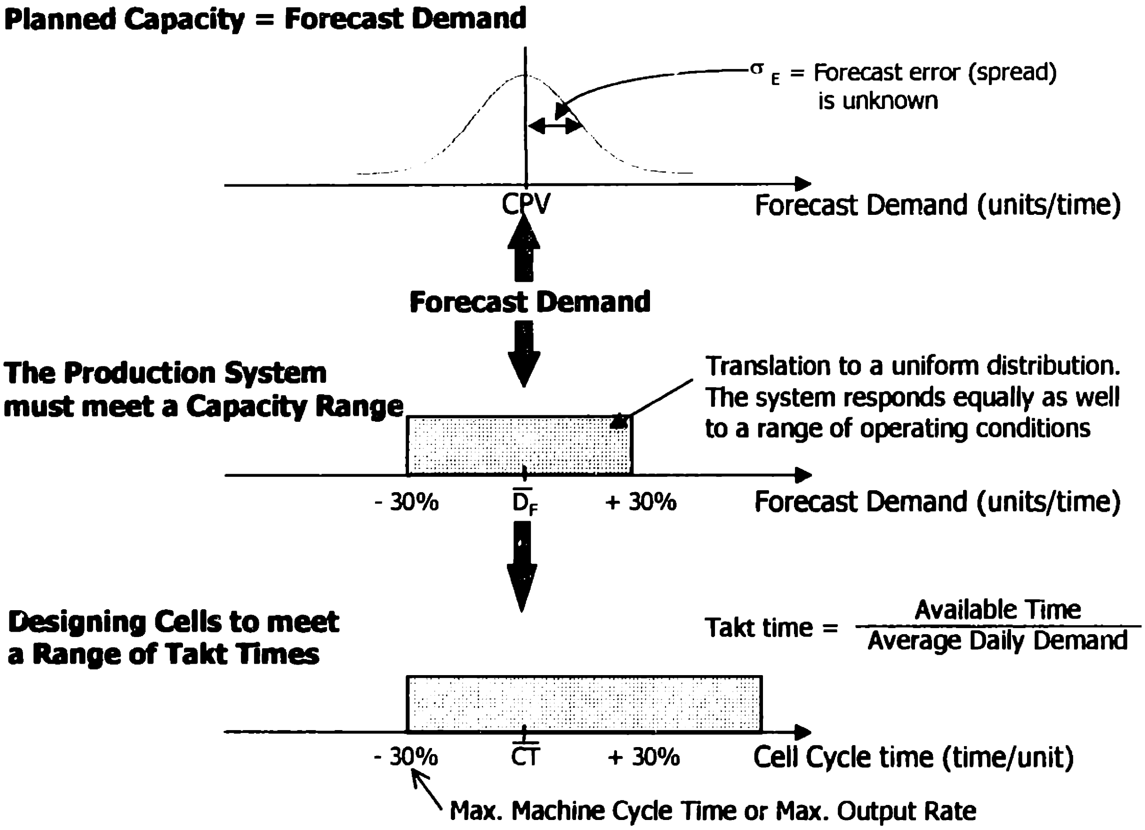


Figure 4-6. Determination of Machine Cycle Time Range [83]

In this project, the range of takt time is determined by calculating the takt times at both the average demand and the peak demand. With this approach, about 24 % extra capacity to meet increased demand is ensured. When demand is decreased, it can be easily dealt with by the operator, who controls the cell production rate. The takt time calculation process is as follows:

1. Available Time Calculation

Available time is calculated by multiplying the total available time for production by Overall Equipment Effectiveness (OEE) rather than subtracting maintenance time and time allowances from total available time. This is easier to calculate since OEE for the current system is already available and more plausible since the new production system is a substitute for the current system. For the OEE calculation, please see Appendix 2.

The total available time for production in a 3 shift operation model with 8 hours of working per shift is 24 hours. With an OEE of 78 %, the available time becomes:

$$3 \times 8\text{h} \times 0.78 = 18.7 \text{ hours}$$

An OEE of 78 % corresponds to 60 minutes of planned downtime, 85 minutes of unplanned downtime, and a scrap-rate of 2.5 % per shift. This is a very conservative calculation, considering that many reports show that an 85 % OEE is easily achieved with an effective lean manufacturing system.

### 2. Customer Demand Calculation

From Table 4-2, the average monthly demand is 81,698 units/month provided that the production were done according to the demand (This assumption is valid since the new system is a substitute for the existing system. The new system should be designed to have at least the same capacity as the current system). Assuming 20 working days per month, the average daily demand is 4,084.9 units/day. (81,698 / 20 = 4,084.9) As for the peak demand, since the peak monthly demand is 101,342 units/month, the peak daily demand is 5,067.1 units/day (101,342 / 20 = 5,067.1)

### 3. Takt Time Calculation

With an average daily demand of 4,084.9 units/day and 18.7 hours of production time, the takt time is calculated by equation 4-1:

$$\text{Takt Time}_{\text{System, Average}} = \frac{18.7 \text{ hours}}{4084.9 \text{ units}} = 16.4 \text{ sec/unit}$$

This takt time based on the average demand has meaning only when comparing the costs of two systems under the same operational conditions. For the design of the cell, the takt time based on the peak demand is used to ensure the volume capacity of the system to respond to the demand fluctuation. With a peak daily demand of 5,067.1 units/day and 18.7 hours of available production time, the takt time becomes:

$$\text{Takt Time}_{\text{System, Peak}} = \frac{18.7\ \text{hours}}{5067.1\ \text{units}} = 13.2\ \text{sec/unit}$$

From the above takt time calculation, a 13.2 second takt time is obtained. However, considering many empirical studies, this time is too short to be achieved by a cell while maintaining a low level of complexity for operations. This is because 13.2 second or 16.4 second is too short for making operator's work loops and the pace of a cell is determined by operator's work loops. For example, to achieve 13.2 seconds takt time, operators are likely to be tied with one very fast machine, which prevents from taking advantage of the flexibility that a cell can provide. In addition, larger investment will be required since we can not use simpler machines that are the major source of cellular manufacturing to save the investment. In this context, a plural number of cells are needed to increase the takt time to a reasonable range.

In fact, the decision on the number of cells is an optimization between several factors such as number of machines, number of operators, cost / complexity of machines, etc. For example, if a large number of cells are implemented, the number of machines may increase due to the increased number of cells, but since an increased number of cells also increases the takt time, the number of machines per cell can be decreased. In addition, the machine complexity according to the cycle time, which is limited by the takt time, should be considered. Decreasing the number of machines in a cell means increasing the work content for each machine and increased work content may contribute to increased machine complexity. The number of operators will also change according to the takt time.

Despite the complexity in this decision process, we picked a 4 cell model, since empirical evidence suggests that a takt time less than 30 seconds causes a high level of complexity in operating a cell and a 3 cell model requires a larger number of machines than a 4 cell model (see Appendix 4 for detailed calculation). In this decision, machine complexity or number of operators is not considered since it is assumed that major investment and cost come from the number of machines. However, since machine is likely to be more complex as its work contents increase and machines in the 3-cell model have more work contents than those in 4-cell model, this assumption is valid.

With this 4 cell model, the cell takt time will be:

$$\text{Takt Time}_{\text{System, Average}} = 4 \times 16.4 = 65.6 \text{ sec/unit}$$

$$\text{Takt Time}_{\text{System, Peak}} = 4 \times 13.2 = 52.8 \text{ sec/unit}$$

One of these 4 cells has to be an ABS/ASR cell. One ABS/ASR cell is enough to satisfy the demand for ASR housings, because the average demand for ASR housings is 5,315.3 units/month and even the peak demand is 7,231 units/month while a cell has a capacity of 25,500 units/month. To have only one cell for both ABS and ASR housings makes sense because ASR housings need approximately 30 % more operations, hence more machines would be idle if ASR housing machining is not grouped into one cell.

### 4.3.3. Standardizing Machining Process

So far, two constraints on the cell design are identified and they are as follows:

- Each cell has 100% capability for all types of ABS housings. One cell has additional capability for all types of ASR housings.
- Takt time of each cell is 52.8 seconds.

To meet the first constraint, all possible combinations of machining processes for the entire ABS/ASR housing family should be investigated and then general steps of machining processes that incorporate all machining processes for each type of housing should be developed. This is necessary since, as seen in Table 4-1, each product type requires slightly different machining processes. The result is shown in Table 4-3.

|  | ABS Operation | Tool Change | Operation Time |
|---|---|---|---|
| H | Mill F100 & F500 | 6 | 15.25 |
| H | 1 Pass Motor Bore F100 | 6 | 9.625 |
| H | Accumulator Drill F500 | 6 | 10.25 |
| H | Damper Drill F500 | 6 | 10.25 |
| H | Dia. 20 Mtg. Hole F500 | 6 | 9.25 |
| (H) | M10 Drill (3) F100 | 6 | 11.25 |
|  | Thread Mill (2) F100 | 6 | 11.25 |
|  | M5 Tap Drill (2) F100 | 6 | 9.625 |
|  | M5 Tap (2) F100 | 6 | 13.25 |
|  | 3.2 mm (2) F100 | 6 | 9.75 |
|  | 5.9 mm Dia. (2) (?F100?) | 6 | 9 |
|  | 5.15 or 4.8 (2) Throttle F500 | 6 | 9 |
|  | 2 mm Drill (2) F500 | 6 | 10.5 |
| x | 6 mm spotface Drill (2) F500 | 6 | 9.5 |
| x | 4.57 Dia. (2) F500 | 6 | 10 |
| x | 3.2 mm (5) F500 | 6 | 18.5 |
|  | C-Ring Mill (4) F500 | 6 | 19.5 |
|  | C-Ring Mill (2) Sealed F500 | 6 | 6 |
|  | M8 Tap Drill (4) F500 | 6 | 8.5 |
|  | M8 Tap (1) F500 | 6 | 8.5 |
|  | Finish Accumulator F500 | 6 | 11.5 |
|  | Dia 16 Drill (1) F600 | 6 | 8.5 |
|  | Dia 9 Drill (6) F600 | 6 | 14.5 |
|  | Dia 11 Drill (2) F600 | 6 | 7.5 |
|  | Dia 3.2 (6) F6[illegible] | 6 | 22.5 |
|  | Thread Mill (4) F600 | 6 | 17 |
|  | Jasu tripan (4) (?F600?) | 6 | 7.5 |
|  | Formtap (4) F600 (or thread, it's the SAME) |  |  |
| H | Dia. 20 Mtg Hole (1) F300 (1) F400 | 6 | 13 |
| H | 1 Pass P.E. Drill (1) F300 (1) F400 | 6 | 11.5 |
|  | 9 mm Dia (3) F300 (3) F400 | 6 | 13 |
|  | 5.9 mm Dia (1) (???) | 6 | 8 |
|  | 3.2 mm Dia. (7) F300 + F400 | 6 | 22.5 |
|  | Mill F200 | 6 | 16.5 |
|  | 3.64 Dia (6) F200 | 6 | 15 |
|  | AV Rough (4) F200 | 6 | 11.5 |
|  | EV Rough (4) F200 | 6 | 11.5 |
|  | 3.2 mm drill (2) F200 | 6 | 10.5 |
|  | AV Fin (4) F200 | 6 | 12.5 |
|  | EV Fin (4) F200 | 6 | 12.5 |
|  | Sugino |  | 67.5 |
|  | Rinse/Dry |  | 720 |
|  | Pallet Change |  | 6 |

x need angular index
H need HP or better spindle

|  | ABS Operation | Tool Change | Operation Time |
|---|---|---|---|
| H | Mill F100 & F500 | 6 | 15.25 |
| H | 1 Pass Motor Bore F100 | 6 | 9.625 |
| H | Accumulator Drill F500 | 6 | 10.25 |
| H | Damper Drill F500 | 6 | 10.25 |
| H | Dia. 20 Mtg. Hole F500 | 6 | 9.25 |
| (H) | M10 Drill (3) F100 | 6 | 11.25 |
|  | Thread Mill (2) F100 | 6 | 11.25 |
|  | M5 Tap Drill (2) F100 | 6 | 9.625 |
|  | M5 Tap (2) F100 | 6 | 13.25 |
|  | 3.2 mm (2) F100 | 6 | 9.75 |
|  | 5.9 mm Dia. (2) (?F100?) | 6 | 9 |
|  | 5.9 mm spot (4) F100 | 6 | 11.25 |
|  | 3.2 mm drill additional (?F100?) | 6 | 11.25 |
| H | ISD 1 pass (2) F100 | 6 | 10.75 |
|  | 6 mm spotface (2) F100 | 6 | 9.25 |
|  | 4.3 mm drill (2) F100 | 6 | 12.25 |
| (H) | ISD Groove (2) F100 | 6 | 12.25 |
|  | 5.15 or 4.8 (2) Throttle F500 | 6 | 9 |
|  | 2 mm Drill (2) F500 | 6 | 10.5 |
| x | 6 mm spotface Drill (2) F500 | 6 | 9.5 |
| x | 4.57 Dia. (2) F500 | 6 | 10 |
| x | 3.2 mm (5) F500 | 6 | 18.5 |
|  | C-Ring Mill (4) F500 | 6 | 19.5 |
|  | C-Ring Mill (2) Sealed F500 | 6 | 6 |
|  | M8 Tap Drill (4) F500 | 6 | 8.5 |
|  | M8 Tap (1) F500 | 6 | 8.5 |
|  | Finish Accumulator F500 | 6 | 11.5 |
|  | 5.65 Dia. RVR (2) F500 | 6 | 10.5 |
| x | 6.8 mm Spotface (2) F500 | 6 | 11.5 |
| x | 4.3 mm Drill (2) F500 | 6 | 11.5 |
| x | 4.2 mm Spotface (2) F500 | 6 | 11.5 |
| x | 3.2 mm Dia (4) Add. F600 | 6 | 12.5 |
|  | Dia 16 Drill (1) F600 | 6 | 8.5 |
|  | Dia 9 Drill (6) F600 | 6 | 14.5 |
|  | Dia 11 Drill (2) F600 | 6 | 7.5 |
|  | Dia. 3.2 (6) F600 | 6 | 22.5 |
|  | Thread Mill (4) F600 | 6 | 17 |
|  | Jasu tripan (4) (?F600?) | 6 | 7.5 |
|  | Formtap (4) F600 (or thread) |  |  |
|  | 5.9 Dia (4) F600 | 6 | 10.5 |
|  | 3.2 mm (2) Add. F600 | 6 | 12 |
| H | Dia. 20 Mtg Hole (1) F300 (1) F400 | 6 | 13 |
| H | 1 Pass P.E. Drill (1) F300 (1) F400 | 6 | 11.5 |
|  | 9 mm Dia (3) F300 (3) F400 | 6 | 13 |
|  | 5.9 mm Dia (1) (???) | 6 | 8 |
|  | 3.2 mm Dia. (7) F300 + F400 | 6 | 22.5 |
|  | 5.9 mm Dia (8) (???) | 6 | 14 |
|  | 3.2 mm Dia. (4) (???) | 6 | 16.5 |
|  | Mill F200 | 6 | 16.5 |
|  | 3.64 Dia. (6) F200 | 6 | 15 |
|  | AV Rough (4) F200 | 6 | 11.5 |
|  | EV Rough (4) F200 | 6 | 11.5 |
|  | 3.2 mm drill (2) F200 | 6 | 10.5 |
|  | AV Fin. (4) F200 | 6 | 12.5 |
|  | EV Fin. (4) F200 | 6 | 12.5 |
|  | ASV (2) Rough | 6 | 8.5 |
|  | USV (2) Rough | 6 | 8.5 |
|  | 3.2 mm (4) Add. | 6 | 13.5 |
|  | 2.5 mm (4) Add. | 6 | 15.5 |
|  | ASV & USV Fin Add.(4) | 6 | 11.5 |
|  | Sugino |  | 102.5 |
|  | Rinse/Dry |  | 720 |
|  | Pallet Change |  | 6 |

Table 4-3. General Machining Steps Used in a Machining Cell (ABS, ASR)

With these general machining steps, we can proceed to group the machining processes to assign them to each machine. In this grouping work, several factors should be considered such as takt time, machine requirements, fixturing, and working face of a housing block.

- Takt Time

Since the cell takt time is 52.8 seconds, the sum of all machining processes, pallet change time and tool change time should be less than 52.8 seconds. The manual operation time is excluded since two fixtures with rotating pallets are implemented and this decouples manual operations from machine operations. Two fixtures with rotating pallets and a wall between them are requested by a production engineer considering the safety of operators. The high pressure of the cutting fluid required for deburring during machining may be harmful to the operator's health.

- Machine Requirements

  Some of the machining processes require high horsepower or more precise spindles due to the nature of the processes. For example, boring of a large diameter hole requires large horsepower to keep the given tolerance and drilling of some holes requires tight tolerances due to the staking process used in assembly. The number of tools used in a set of machining processes also affects the selection of a machine since this number determines the size and the type of tool magazine, which may affect the tool change time.

- Fixturing

  There are some angled holes in the housings and they demand either a rotating fixture or an angular index. Since this type of fixturing costs much more, machining processes which need this type of fixturing should be grouped together and assigned to one machine.

- Faces of a Housing Block

  Machining steps are grouped by their working faces on a housing block. There are two benefits with this approach: 1) better traceability of defects or production problems and 2) easy fixturing. This is possible by splitting up the steps of machining into small segments. This grouping helps to eliminate unnecessary machining time such as fixture rotating and tool change time.

The result of all these considerations is shown in Table 4-4 and 4-5.

|  | ABS Operation | F100 | F200 | F300 | F400 | F500 | F600 | CT | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | Station |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H | Mill F100 & F500 | x |  |  |  | x |  | 15.3 | x |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |
| H | 1 Pass Motor Bore F100 | x |  |  |  |  |  | 9.6 | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| H | Accumulator Drill F500 |  |  |  |  | x |  | 10.3 | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| H | Damper Drill F500 |  |  |  |  | x |  | 10.3 | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| H | Dia. 20 Mtg. Hole F500 |  |  |  |  |  |  | 9.3 |  | x |  |  |  |  |  |  |  |  |  |  |  |  | 2 |
|  | 5.9 mm Dia. (2) (?F100?) | (x) |  |  |  |  |  | 9.0 |  | x |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 5.15 or 4.8 (2) Throttle F500 |  |  |  |  | x |  | 9.0 |  | x |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 2 mm Drill (2) F500 |  |  |  |  | x |  | 10.5 |  | x |  |  |  |  |  |  |  |  |  |  |  |  |  |
| (H) | M10 Drill (3) F100 | x |  |  |  |  |  | 11.3 |  |  | x |  |  |  |  |  |  |  |  |  |  |  | 3 |
|  | Thread Mill (2) F100 | x |  |  |  |  |  | 11.3 |  |  | x |  |  |  |  |  |  |  |  |  |  |  |  |
|  | M5 Tap Drill (2) F100 | x |  |  |  |  |  | 9.6 |  |  | x |  |  |  |  |  |  |  |  |  |  |  |  |
|  | M5 Tap (2) F100 | x |  |  |  |  |  | 13.3 |  |  | x |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 3.2 mm (2) F100 | x |  |  |  |  |  | 9.8 |  |  |  | x |  |  |  |  |  |  |  |  |  |  | 4 |
|  | 3.2 mm Dia. (7) F300 + F400 |  |  | (x) | (x) |  |  | 22.5 |  |  |  | x |  |  |  |  |  |  |  |  |  |  |  |
| x | 6 mm spotface Drill (2) F500 |  |  |  |  | x |  | 9.5 |  |  |  |  | x |  |  |  |  |  |  |  |  |  | 5 |
| x | 4.57 Dia. (2) F500 |  |  |  |  | x |  | 10.0 |  |  |  |  | x |  |  |  |  |  |  |  |  |  |  |
| x | 3.2 mm (5) F500 |  |  |  |  | x |  | 16.5 |  |  |  |  | x |  |  |  |  |  |  |  |  |  |  |
|  | C-Ring Mill (4) F500 |  |  |  |  | x |  | 19.5 |  |  |  |  |  | x |  |  |  |  |  |  |  |  | 6 |
|  | C-Ring Mill (2) Sealed F500 |  |  |  |  | x |  | 6.0 |  |  |  |  |  | x |  |  |  |  |  |  |  |  |  |
|  | M8 Tap Drill (4) F500 |  |  |  |  | x |  | 8.5 |  |  |  |  |  | x |  |  |  |  |  |  |  |  |  |
|  | M8 Tap (1) F500 |  |  |  |  | x |  | 8.5 |  |  |  |  |  | x |  |  |  |  |  |  |  |  |  |
|  | Finish Accumulator F500 |  |  |  |  | x |  | 11.5 |  |  |  |  |  |  | x |  |  |  |  |  |  |  | 7 |
|  | Dia 16 Drill (1) F600 |  |  |  |  |  | x | 8.5 |  |  |  |  |  |  | x |  |  |  |  |  |  |  |  |
|  | Thread Mill (4) F600 |  |  |  |  |  | x | 17.0 |  |  |  |  |  |  | x |  |  |  |  |  |  |  |  |
|  | Jasu trepan (4) (?F600?) |  |  |  |  |  | (x) | 7.5 |  |  |  |  |  |  | x |  |  |  |  |  |  |  |  |
|  | Dia 9 Drill (6) F600 |  |  |  |  |  | x | 14.5 |  |  |  |  |  |  |  | x |  |  |  |  |  |  | 8 |
|  | Dia.11 Drill (2) F600 |  |  |  |  |  | x | 7.5 |  |  |  |  |  |  |  | x |  |  |  |  |  |  |  |
|  | Dia. 3 2 (6) F600 |  |  |  |  |  | x | 22.5 |  |  |  |  |  |  |  | x |  |  |  |  |  |  |  |
|  | Formtap (4) F600 (or thread, it's the SAME) |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| H | Dia. 20 Mtg Hole (1) F300 (1) F400 |  |  | x | x |  |  | 13.0 |  |  |  |  |  |  |  |  | x |  |  |  |  |  | 9 |
| H | 1 Pass P.E. Drill (1) F300 (1) F400 |  |  | x | x |  |  | 11.5 |  |  |  |  |  |  |  |  | x |  |  |  |  |  |  |
|  | 9 mm Dia (3) F300 (3) F400 |  |  | x | x |  |  | 13.0 |  |  |  |  |  |  |  |  | x |  |  |  |  |  |  |
|  | 5 9 mm Dia (1) (???) |  |  | (x) | (x) |  |  | 8.0 |  |  |  |  |  |  |  |  | x |  |  |  |  |  |  |
|  | Mill F200 |  | x |  |  |  |  | 16.5 |  |  |  |  |  |  |  |  |  | x |  |  |  |  | 10 |
|  | 3 64 Dia (6) F200 |  | x |  |  |  |  | 15.0 |  |  |  |  |  |  |  |  |  | x |  |  |  |  |  |
|  | 3 2 mm drill (2) F200 |  | x |  |  |  |  | 10.5 |  |  |  |  |  |  |  |  |  | x |  |  |  |  |  |
|  | AV Rough (4) F200 |  | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 11 |
|  | EV Rough (4) F200 |  | x |  |  |  |  | 18.5 |  |  |  |  |  |  |  |  |  |  | x |  |  |  |  |
|  | AV Fin (4) F200 |  | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | EV Fin (4) F200 |  | x |  |  |  |  | 20.5 |  |  |  |  |  |  |  |  |  |  | x |  |  |  |  |
|  | Sugino |  |  |  |  |  |  | 67.5 |  |  |  |  |  |  |  |  |  |  |  | x | x |  | 12,13 |
|  | Rinse/Dry (batch of 12) |  |  |  |  |  |  | 30.0 |  |  |  |  |  |  |  |  |  |  |  |  |  | x | 14 |
|  | Pallet Change |  |  |  |  |  |  | 6.0 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  | station's operation time: | 45 | 38 | 45 | 32 | 38 | 43 | 45 | 45 | 46 | 42 | 39 | 34 | 34 | 30 |  |

x need angular index

H need HP or better spindle

manual labour 8 sec (not relevant though, due to workpiece-changer)

Table 4-4. Grouping of Machining Processes for ABS Housing

|  | ABS/ASR Operation |  | Operation Time |
|---|---|---|---|
| H | Mill F100 & F500 |  | 15.25 |
| H | Accumulator Drill F500 |  | 10.25 |
| H | Damper Drill F500 |  | 10.25 |
| H | Dia. 20 Mtg Hole F500 |  | 9.25 |
|  | Pallet Change |  | 6 |
| **STATION #1** |  | total | **51** |
| H | 1 Pass Motor Bore F100 |  | 9.625 |
| (H) | M10 Drill (3) F100 |  | 11.25 |
|  | Thread Mill (2) F100 |  | 11.25 |
|  | 5.9 mm Dia (2) (?F100?) |  | 0 |
|  | 5.9 mm spct (4) F100 |  | 13.5 |
|  | Pallet Change |  | 6 |
| **STATION #2** |  | total | **51.625** |
|  | M5 Tap Drill (2) F100 |  | 9.625 |
|  | M5 Tap (2) F100 |  | 13.25 |
|  | 3.2 mm (2) F100 |  | 0 |
|  | 3.2 mm drill additional (?F100?) |  | 14.25 |
|  | Pallet Change |  | 6 |
| **STATION #3** |  | total | **43.125** |
| H | ISD 1 pass (2) F100 |  | 10.75 |
|  | 6 mm spotface (2) F100 |  | 9.25 |
|  | 4.3 mm drill (2) F100 |  | 12.25 |
| (H) | ISD Groove (2) F100 |  | 12.25 |
|  | Pallet Change |  | 6 |
| **STATION #4** |  | total | **50.5** |
|  | 5.15 or 4.8 (2) Throttle F500 |  | 9 |
|  | 5.65 Dia. RVR (2) F500 |  | 10.5 |
|  | 2 mm Drill (2) F500 |  | 10.5 |
|  | Pallet Change |  | 6 |
| **STATION #5** |  | total | **36** |
| x | 6.8 mm Spotface (2) F500 |  | 11.5 |
| x | 6 mm spotface Drill (2) F500 |  | 9.5 |
| x | 4.57 Dia. (2) F500 |  | 10 |
| x | 4.3 mm Drill (2) F500 |  | 11.5 |
|  | Pallet Change |  | 6 |
| **STATION #6** |  | total | **48.5** |
| x | 4.2 mm Spotface (2) F500 |  | 11.5 |
| x | 3.2 mm Dia (4) Add. F500 |  | 0 |
| x | 3.2 mm (5) F500 |  | 23.5 |
|  | M8 Tap Drill (4) F500 |  | 8.5 |
|  | Pallet Change |  | 6 |
| **STATION #7** |  | total | **49.5** |
|  | C-Ring Mill (4) F500 |  | 19.5 |
|  | C-Ring Mill (2) Sealed F500 |  | 6 |
|  | M8 Tap (1) F500 |  | 8.5 |
|  | Finish Accumulator F500 |  | 11.5 |
|  | Pallet Change |  | 6 |
| **STATION #8** |  | total | **51.5** |
|  | Dia. 16 Drill (1) F600 |  | 8.5 |
|  | Dia. 9 Drill (6) F600 |  | 14.5 |
|  | Dia 11 Drill (2) F600 |  | 7.5 |
|  | 5.9 Dia (4) F600 |  | 10.5 |
|  | Pallet Change |  | 6 |
| **STATION #9** |  | total | **47** |
|  | Dia. 3.2 (6) F600 |  | 0 |
|  | 3.2 mm (2) Add. F600 |  | 27 |
|  | Thread Mill (4) F600 |  | 17 |
|  | Pallet Change |  | 6 |
| **STATION #10** |  | total | **50** |
|  | Formtap (4) F600 (or thread) |  |  |
|  | Jasu tripan (4) (?F600?) |  | 7.5 |
| H | Dia. 20 Mtg Hole (1) F300 (1) F400 |  | 13 |
| H | 1 Pass P.E. Drill (1) F300 (1) F400 |  | 11.5 |
|  | 9 mm Dia (3) F300 (3) F400 |  | 13 |
|  | Pallet Change |  | 6 |
| **STATION #11** |  | total | **51** |
|  | 5.9 mm Dia (1) (???) |  | 0 |
|  | 5.9 mm Dia (8) (???) |  | 14.5 |
|  | 3.2 mm Dia (7) F300 + F400 |  | 0 |
|  | 3.2 mm Dia (4) (???) |  | 31.5 |
|  | Pallet Change |  | 6 |
| **STATION #12** |  | total | **52** |
|  | Mill F200 |  | 16.5 |
|  | 3.64 Dia (6) F200 |  | 15 |
|  | AV Rough (4) F200 |  | 0 |
|  | ASV (2) Rough |  | 12.5 |
|  | Pallet Change |  | 6 |
| **STATION #13** |  | total | **50** |
|  | EV Rough (4) F200 |  | 0 |
|  | USV (2) Rough |  | 12.5 |
|  | 3.2 mm drill (2) F200 |  | 0 |
|  | 3.2 mm (4) Add |  | 16.5 |
|  | 2.5 mm (4) Add |  | 15.5 |
|  | Pallet Change |  | 6 |
| **STATION #14** |  | total | **50.5** |
|  | AV Fin (4) F200 |  | 0 |
|  | EV Fin (4) F200 |  | 0 |
|  | ASV & USV Fin Add (4) |  | 23 |
|  | Pallet Change |  | 6 |
| **STATION #15** |  | total | **29** |
|  | Sugino (x3) |  | 34.167 |
| **STATION #16, #17, #18** |  | total | **34.167** |
|  | Rinse/Dry |  | 30 |
| **STATION #19** |  | total | **30** |

Table 4-5. Grouping of Machining Processes for ABS/ASR Housing

As for deburring and washing/drying processes, due to the nature of the processes, they cannot be broken down into small segments, which results in parallel processing for deburring and the use of continuous processing for washing/drying.

## 4.3.4. Machine Selection

Since all constraints are identified in the previous sections, machines can be chosen to meet these constraints while considering cost. Acquisition of appropriate machines is important in order to compensate for the increased number of machines compared to the current system. Slower, simpler, and less expensive machines that fulfill the given requirements and constraints should be purchased.

In this project, some operations need highly accurate and powerful CNC machining centers like the CHIRON FZ 12 W magnum [40]. However, for other operations, less expensive machines such as the Miyano TSV-C35, Miyano OKK V1 or Okuma MX-45VAE [41] [42] are considered.

### 4.3.5. Design of Cell Layout

In designing the cell layout, operator's ergonomic issues and inspection implementation are major concerns. For example, to separate workers from machines and to facilitate walking, a U-shaped cell is chosen with slight modification. Considering the relatively heavy ABS housing unit, a rail to move parts is implemented along the part flow. To ensure highest quality, successive check is implemented by adding an inspection station right after every machining process. We may have to add more operators to the cell due to inspection operations that are done manually, but as shown in chapter 4, quality affects system complexity so much that this type of effort is needed. These inspection stations may be removed after the processes become stable enough not to produce any defective part.

Figure 4-7 shows the layout of the ABS housing machining cell. The numbers in the stations on the outer side represent station cycle times and those on the inner side indicate manual operation times.

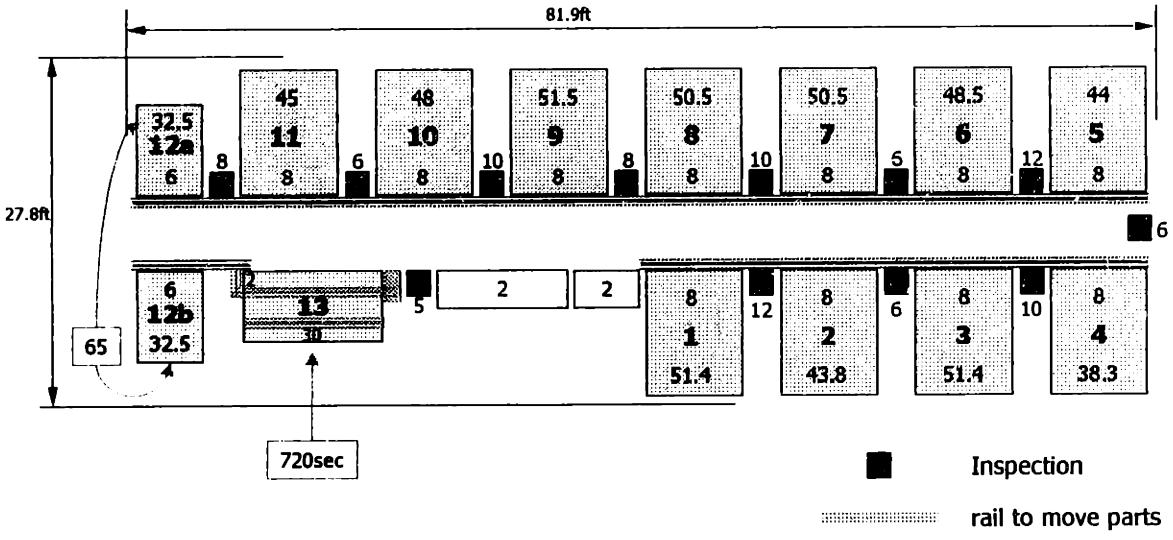


Figure 4-7. ABS Housing Machining Cell

The configuration of the stations in the cell has been chosen in this way because of the parallel processing of parts at the deburr stations (12a and 12b). With this configuration, it is easier for an operator to handle the parts at these stations. This is more evident in the ABS/ASR cell design as seen in Figure 4-7.

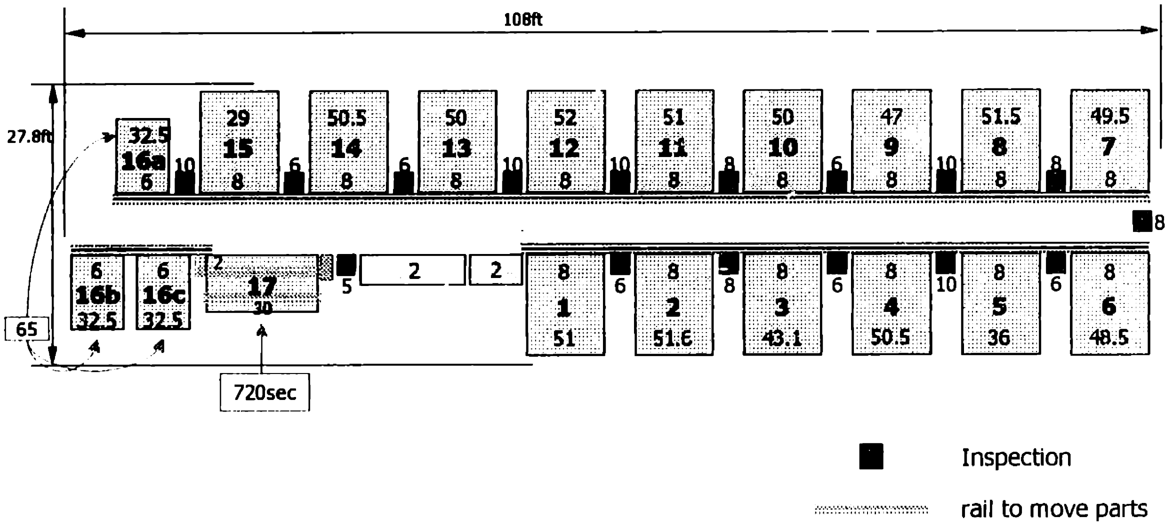


Figure 4-8. ABS/ASR Housing Machining Cell

### 4.3.6. Operator's Work Loops

One of the benefits of a linked cell manufacturing system is that the volume flexibility is controlled by the number of operators in a cell. In a cell, by simply adding more operators and reconfiguring work loops, the production rate of a cell can be increased within the designed cell capacity. This benefit is possible by separating operators from machines, allowing operators to walk rather than being stuck to one machine.

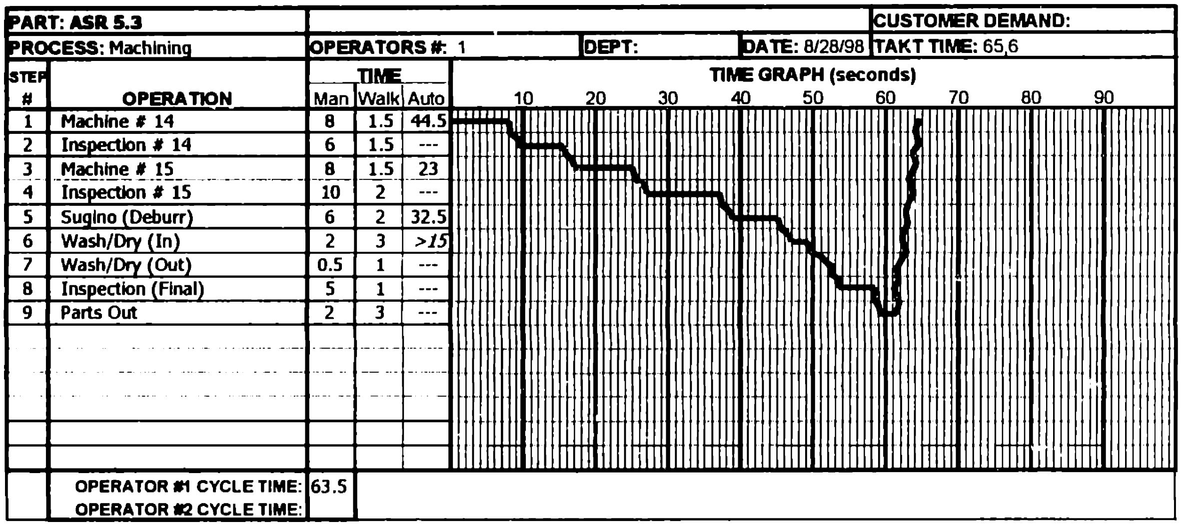
In the design of the machining cells, man-machine separation is realized by the automated pallet changer in each machine, which was originally implemented for the operator's safety. The operator is loading the parts into a hydraulic fixture on the pallet changer, while the machine is processing another part. After automated processing, the pallet changer moves the finished part out of the machining side of the machine and opens the hydraulic fixtures while moving the previously clamped, unprocessed part to the machining side. On his/her next loop, the operator just takes out the unclamped finished part and clamps a new one into the fixture. This way, two parts are always in the machine. One is being processed and the other one is waiting either for processing or for the operator to take it to the next station.

With this walking operator, it is required to standardize the operator's work content to have a stable operation time. With this stable operation time, we can decide operator's work loops so that the time taken for an operator to finish his/her work loop becomes less than the cell takt time. Two factors need to be considered in this work-loop decision: manual operation time and walking time.

As for manual operations at a machine, many of them are linked to part loading and unloading. In a lean manufacturing environment, usually only loading is done by an operator manually, while unloading is done automatically. This is because automated part loading is typically expensive due to the high degree of accuracy required. However, unloading can be done by simple devices or by simply using gravity which reduces much of the manual operation time. With automated unloading, an operator can arrive with a part at the station, load the part into the machine, and then pick up the finished part and move to the next station while hitting the walk-away switch to start the machine.

Walking time is another factor that affects the work-loop decision. Since walk time is non-value adding time, it needs to be minimized. There are some general principles to do this. For example, by minimizing the width of a machine and moving machines closer to each other, walk time can be reduced. In addition, the width of the aisle inside a cell should not be more than 4 ft for the same reason.

Based on these two factors, manual operation time and walking time, operators' work loops are decided. During this calculation, a helpful tool is the standard work combination chart. This chart shows the manual operation time, walk time and automated machining time at a station and clearly states the standardized operators' work contents to meet the takt time. This chart is shown in Figure 4-9.



**PART: ASR 5.3**
**CUSTOMER DEMAND:**
**PROCESS:** Machining
**OPERATORS #:** 1
**DEPT:**
**DATE:** 8/28/98
**TAKT TIME:** 65,6

| STEP # | OPERATION | TIME Man | Walk | Auto |
|---|---|---|---|---|
| 1 | Machine # 14 | 8 | 1.5 | 44.5 |
| 2 | Inspection # 14 | 6 | 1.5 | --- |
| 3 | Machine # 15 | 8 | 1.5 | 23 |
| 4 | Inspection # 15 | 10 | 2 | --- |
| 5 | Sugino (Deburr) | 6 | 2 | 32.5 |
| 6 | Wash/Dry (In) | 2 | 3 | *>15* |
| 7 | Wash/Dry (Out) | 0.5 | 1 | --- |
| 8 | Inspection (Final) | 5 | 1 | --- |
| 9 | Parts Out | 2 | 3 | --- |

**OPERATOR #1 CYCLE TIME:** 63.5
**OPERATOR #2 CYCLE TIME:**

Figure 4-9. Standard Work Combination Chart – Operator 1, ABS/ASR Housing Machining Cell

The results of this calculation are shown in Figure 4-10 ~ 4-13. Two models are developed: one is for the case of operating a cell to meet average demand and the other is for peak demand. These models are based on the takt times for average demand and peak demand.

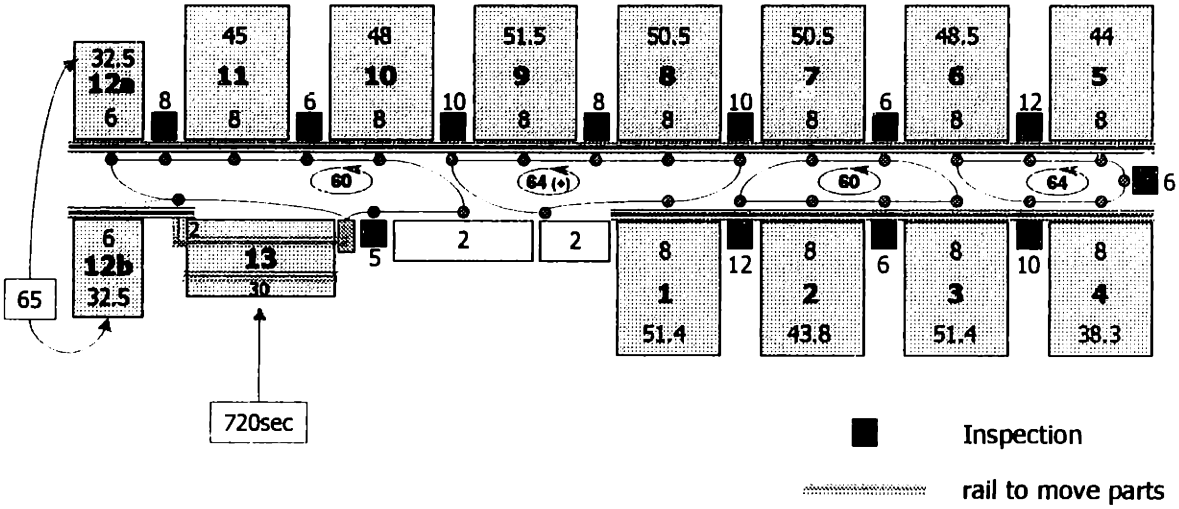


Figure 4-10. Operators' Work Loops for Average Demand in ABS Housing Cell (4 Operators)

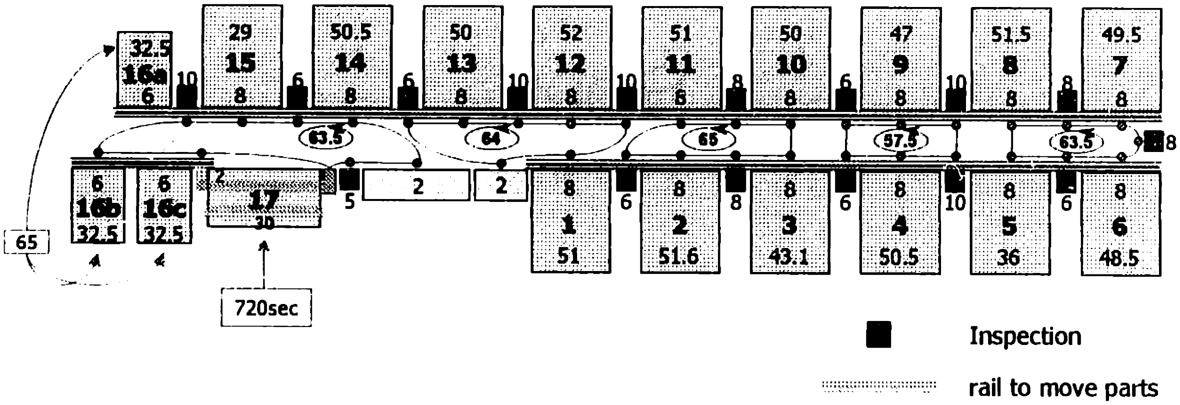


Figure 4-11. Operators' Work Loops for Average Demand in ABS/ASR Housing Cell (5 Operators)

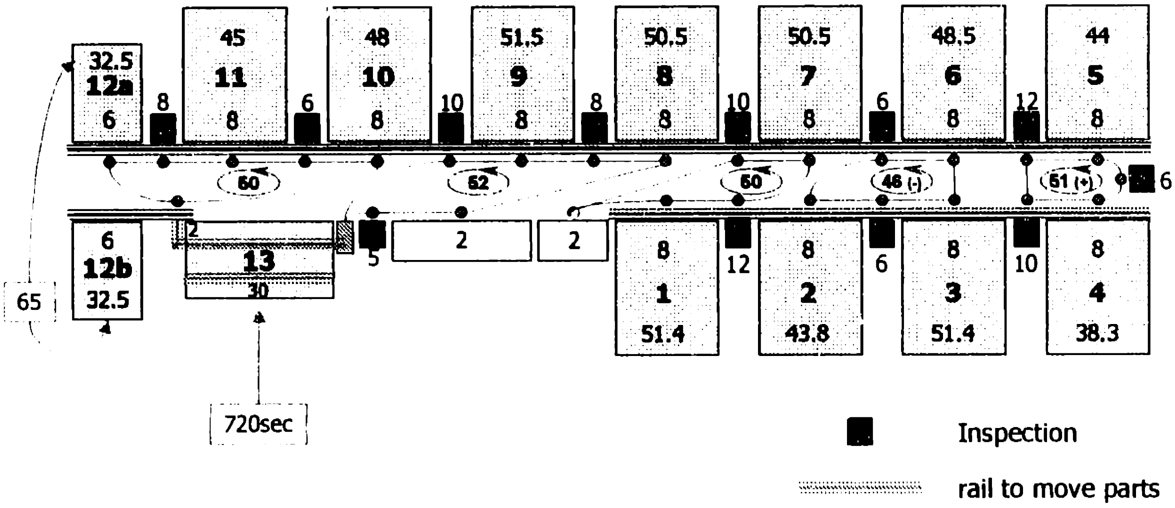


Figure 4-12. Operators' Work Loops for Peak Demand in ABS Housing Cell (5 Operators)

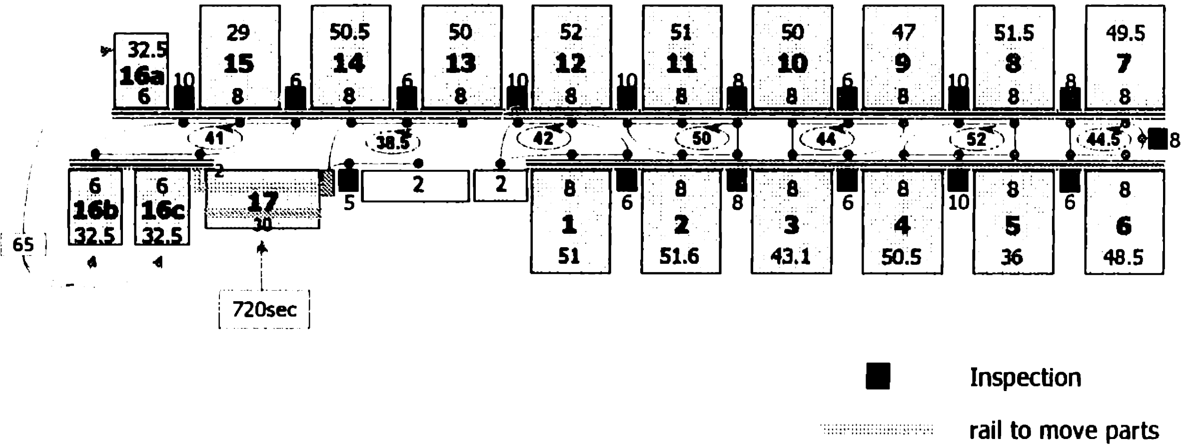


Figure 4-13. Operators' Work Loops for Peak Demand in ABS/ASR Housing Cell (7 Operators)

### 4.3.7. Link Cells to Other Sub-Systems

Since this project is limited to the conversion of the current machining area to a lean manufacturing system, linkage of cells is not studied extensively. However, a brief vision of the whole manufacturing system including assembly cells is shown in Figure 4-4. Since the current assembly lines are designed without considering manufacturing cells, they have very short cycle time of 20 ~ 26 seconds. Due to this wrong design, machining cells and assembly cells (lines) can not be linked in a one-to-one way. In this context, if assembly cells (lines) were designed along with machining cells while considering takt time and costs involved with cell implementation, the expected layout of plant and material handler loops would be like Figure 4-14.

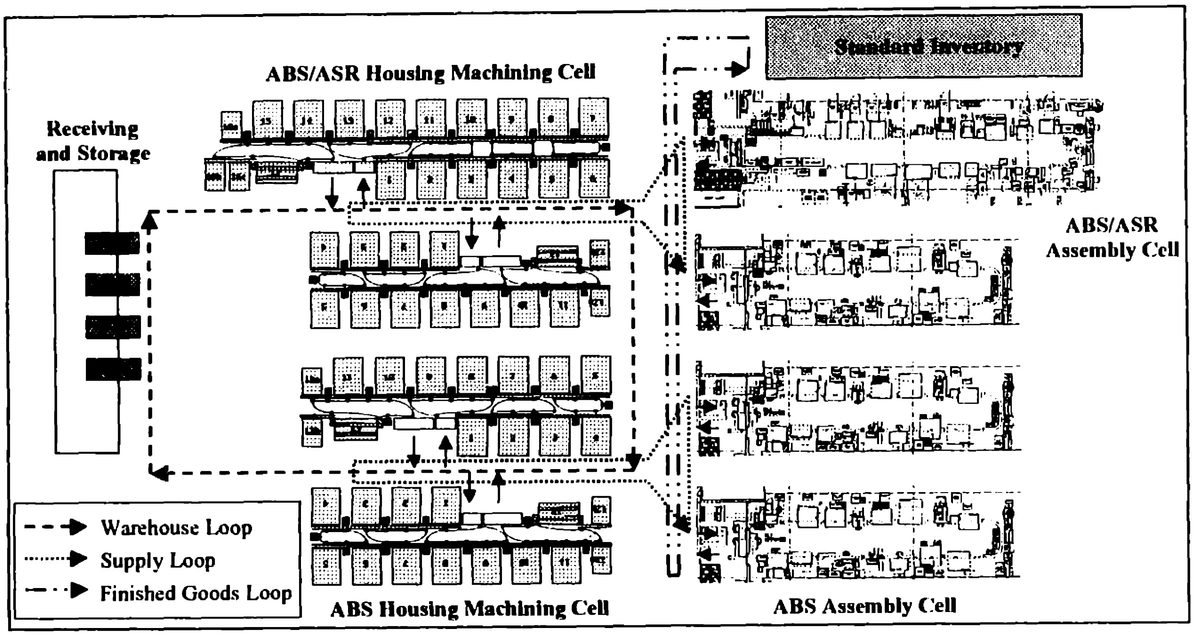


Figure 4-14. Sketch of the New Production System Layout Including Assembly Line Modification

In this sketch, four machining cells are linked to four assembly cells one by one. The receiving area is moved to the other side of the building to facilitate the material handler's loop. Two material handlers move finished housings to final assembly cells, and one material handler moves finished ABS or ASR units to the standard inventory area where shipping takes place. Cell configurations are slightly changed to share one material handler for two cells.

## 4.4. Comparison of Two Systems in terms of Complexity Metrics

In this section, current machining system and new designed machining system are compared in terms of the complexity metrics suggested in chapter III. System complexity measured by these metrics is strongly linked to the indirect cost of machining and the controllability of the system.

### 4.4.1. Complexity of the Existing Manufacturing System

#### 4.4.1.1. Relationships Between System Components

Number of product flow paths

Since there are 26 machining centers, 8 deburring machines, and 2 washing machine, the total number of product flow path is (from equation 3-11)

$$Nf = \prod_{i=1}^{n_p} m_i = \prod_{i=1}^{5} m_i = m_{machining} \times m_{deburring} \times m_{washing,\, deburring} = 26 \times 8 \times 2 = 416$$

If assembly were included, this number would be increased to 416*3 = 1248.

If considering the product type, each ABS housing has,

18 (machining) * 8 (deburring) * 2 (washing and drying) * 3 (assembly) = 864 flow paths

Each type of ASR housings has,

4 (machining) * 8 (deburring) * 2 (washing and drying) * 3 (assembly) = 192 flow paths

Here, the number of machines in machining processes for ASR housing is 4 rather than 8. This is because 8 machining centers are dedicated to ASR units and 2 machines are grouped together to machine ASR housings due to fixturing difficulties and longer cycle time.

### Number of crossings in flow paths

Since all parts are moved by AGVs, crossings during the transportation don't happen many times except few disruptions by people, forklift or other AGVs. In this case, crossings by the share of machines would affect system complexity dominantly so that we may count this number only. If we assume that there is no predefined route and parts are moved to any machine available in next process, the total number of crossings may be calculated as follows (using equation 3-12):

$_{26}C_2$ (pick 2 flows from 26 machining centers) * 8 (number of deburring machines) + $_{8}C_2$ (pick 2 flows from 8 deburring machines) * 2 (number of washing machine) + $_{2}C_2$ (pick 2 flows from 2 washing machines) * 3 (number of assembly lines) = 2600 + 56 + 3 = 2659.

### Total travel distance of a part

Total travel distance of a part from storage area to the assembly area is approximately calculated to be 1300ft. The distance from the warehouse to the plant is excluded in this number.

### Number of combinations of product and machine match

If there is only one type of product in the machining area, the number of possible combinations of product and machine match is just one. This number can be amazingly increased if we consider the product variety that is provided by this machining area. There are 12 types of housings for ABS units and 3 types for ASR units. If we assume that every machine is capable of all types of housings and each machine can freely choose the product type, the total number of product flow path will be increased to $15^{26}$ * $15^{8}$ * $15^{2}$ = $15^{36}$ order.

In fact, several activities done to eliminate the need of setup changeovers decrease the number of combinations of product and machine match. For example, usually a few types of product are chosen to be produced for one day and some machines are dedicated to a certain type of product. In addition to that, due to the fixture differences between

ABS and ASR units, 2 cells (8 machines) are dedicated to ASR units. Assumptions to reflect the real situations are as follows:

- One cell of 4 machines for ABS units is dedicated to a certain type of ABS housing.
- Two cells share the setup, which means two cells produce one product type.
- 3 types of ABS and 1 of ASR are produced for a day
- Right after parts get machined, they are moved to deburring machines by AGVs.
- After unloaded from deburring machines, parts are directly headed to washing and drying machines.

In this case, the total number of combinations will be

$$ {}_{12}C_2 * {}_3C_1 * 2^2 * 4^8 * 4^2 = 66 * 3 * 4 * 4^{10} = 830472192 \text{ order} $$

Here, first ${}_{12}C_2$ is the number of incidents when choosing 2 types ABS housings out of 12 types since there is one type of housing produced daily, which has a dedicated cell. $2^2$ for 2 types of ABS produced by 2 set of cells assuming 2 cells per set. $4^8$ stands for 4 types of ABS and ASR housings by 8 deburring machines and $4^2$ is for 2 washing/drying machines.

This result shows that to produce all 15 types of products every day instead of 4 types increases system complexity critically (from 830472192 to $15^{36}$).

### 4.4.1.2. Elementary System Components

Number of elementary system components

The number of elementary system components are as follows:

| | | |
|---|---|---|
| Machine | Machining center | 26 |
| | Deburring machine | 8 |
| | Washing and drying machine | 2 |
| Stations | Repackaging | 2 |
| | Final inspection | 2 |
| | In-process inspection | 7 |
| People | Machining center operator | 7 |
| | Deburring machine operator | 2 |
| | Final inspector | 2 |
| | Repackaging operator | 4 |
| | Other operators (setup man, supervisor, etc.) | 6 |

Total number of system components is 68.

## Complexity of each elementary components

### A. Reliability of elementary components

By using of the formula for calculating the reliability of the system components (equation 3-16), the reliability of machining center is as follows:

| Type of product | March 1998 | April 1998 | May 1998 | June 1998 |
|---|---|---|---|---|
| ABS housing | 76.4% | 79.5% | 82.3% | 77.8% |
| ASR housing | 72.1% | 76.6% | 78.2% | 53.1% |

Here, the setup time is included in the unplanned downtime since the setup doesn't occur periodically in a predefined way. The number used here is based on the data collected from 12 machining centers for ABS housings and 4 machining centers for ASR housings.

Since the data for deburring machines or washing machine are not available, it is assumed that they may have approximately similar level of reliability as that of machining center.

B. Quality outputs

By using of the formula for calculating the quality outputs of the system components (equation 3-17), quality outputs are as follows:

| Type of product | March 1998 | April 1998 | May 1998 | June 1998 |
|---|---|---|---|---|
| ABS housing | 95.2% | 98.0% | 96.5% | 98.1% |
| ASR housing | 93.9% | 95.4% | 98.6% | 96.9% |

Here again, the data for other system components are not available, it is assumed that they may have approximately similar level of quality output as that of machining center.

C. Time outputs

*Cycle time*

Length of cycle time for machining operations is approximately 25 minutes for getting 6 parts completed. Cycle time for deburring is approximately 70 seconds for ABS unit, and 100 seconds for ASR units. Washing and drying takes 720 seconds for each unit. Variations of cycle time are trivial since all machines are numerically controlled.

*Setup time*

There is huge variation in setup time depending on the machine conditions and degree of change over. If new parts do not obstruct machining of the previous parts, the changeover is simply confined to change the program and it takes only 30 seconds. However, if new parts obstruct machining of the existing parts on the fixture, it takes about half an hour since existing parts should be removed from the fixture. The worst scenario is to change fixture itself and it takes more than one day.

### 4.4.1.3. People

- Process improvements: 1 point → process improvements are performed by outside personnel
- Accessibility to the information: 3 points→ Much of the information is accessible by using of intranet but the computing environment is not good for operators.

Engineers have pretty good computing environment and they can access to almost every information they need with his computer.

- Number of suggestions → Data is not available.

#### 4.4.1.4. Inventory

There are raw material inventory covering about 12.1 days and work in process inventory covering 2.4 days. Total inventory can cover 14.5 days of production.

#### 4.4.1.5. Scheduling

Scheduling is done by floor supervisors in the morning based on the inventory level and the MRP scheduling.

### 4.4.2. Complexity of the Designed Manufacturing System

#### 4.4.2.1. Relationships Between System Components

Number of product flow paths

Since there are 4 cells, the number of flow paths is 4 and if assembly line is included, it will be 4*3=12. Considering the product type, ABS housing has 8 flow paths and ASR housing has only 1 flow path. If further improvements such as assigning certain product types to one cell, or link machining cells to assembly cells, this number can be decreased to 1 or 2 for each product type. It depends on the level of optimization between the system flexibility and the system complexity.

Number of crossings in flow paths

In this new machining area, crossings during the transportation are decided by the design of material handler operation loops. From suggested material handler work loops, 2 crossings happen at the assembly cells.

As for crossings by the share of machines that affect system complexity dominantly in current system, the number of them is decreased to zero since there is no share of machines. When assembly lines are included, 3 crossings happen but can be eliminated by linking machining cells to assembly cells.

Total travel distance of a part

Physical length of designed ABS/ASR cell is 108 ft and the width of inside aisle of the cell is about 4-5 ft. Since the distance from the storage area or to the assembly area is decided by the layout design, it can be greatly reduced. It we assume 100 ft for both distances, the maximum total distance of a part may be 100 + 2*108 + 4*2 + 100 = 424 ft. Note that this is 1/3 of the 'average' value of travel distance in the existing system.

Number of combinations of product and machine match

This metric may have the most enormous advantage under lean production environment. Even if we assume that all 12 types of ABS housings and 3 types of ASR housings are produced every day, the number of combinations of product and machine match is $15*12^3 = 25920$. Considering the product type assignment to each cell, if we assume each cell produces 3 product types and ABS/ASR cell produces only one type of ASR housing, this number becomes $3^3 = 27$. Further, if we consider the fact that cell operates almost independently from other cells, this number may be decreased to three per each cell.

Compared with the existing system, since the production in machining cells will be pulled from the assembly line, no one needs to decide what to produce and how many to produce. Following the signals from the assembly lines will be enough.

#### 4.4.2.2. Elementary System Components

Number of elementary system components

The number of elementary system components is as follows:

| | | |
|---|---|---|
| Machine | Machining center | 15 + 12*3 = 51 |
| | Deburring machine | 3 + 2*3 = 9 |
| | Washing and drying machine | 1 + 1*3 = 4 |
| Stations | Repackaging | 0 |
| | Final inspection | 0 |
| | In-process inspection | 16 + 12*3 = 52 |
| People | Cell operators | 17 - 22 |
| | Repackaging operator | 0 |
| | Other operators (setup man, material handler, etc.) | 2 |

The maximum number of system components is 138, which is 2 times of that of existing system. However, if sub-level components such as fixtures and tools were considered, existing system would have more elementary system components than proposed system.

Complexity of each elementary components

A. Reliability of elementary components

Just because new system design is not implemented yet, no data is available for reliability of elementary components. We, however, can infer from some characteristics of new design. As for machines, since simple general machining centers are adopted in cells, the reliability may increase. For example, current machining centers should perform all machining processes for every type of products with more than 20 tools. Machining centers in new system, however, are required to perform only 4-5 processes by using 3-4 tools. These machines have less horse powers, less but enough accuracy compared to current machines. In addition, setup changeover occurs periodically according to predefined schedule within a minute.

B. Quality outputs

We should use our guess again here for the same reason as above. In designed cells, there are several attributes to prevent defects. One of them is inspection station implemented after every machining process. Every part coming out of every machining process will be checked and if problem occurs, the production itself will be stopped. Due to this operation strategy and the single piece flow, parts following the defected part are ensured to be processed right. The production is resumed only after the problem is solved by cooperation of operators, supervisors and engineers and root causes of defects are eliminated to prevent problems from occurring again. With this short response to problems and limination of root causes, the quality outputs are ensured. In addition to this, since the operation itself is simple, the machine has less chance to go wrong, which will contribute to better quality outputs. Further, extensive use of poka-yoke devices and continuous improvement (Kaizen) activities contributes to better quality outputs.

Compared to current 3-5% defects rate, quality outputs with less than 1% defects are expected. Usually lean plants have ppm level of defects.

### C. Time outputs

#### ***Cycle time***

There are two takt time models: 65.6 seconds and 52.8 seconds. In a lean cell, every cycle time should be less than takt time. With 65.6 seconds takt time, the longest machining cycle time is about 46 seconds and the operator cycle time is about 64 seconds. Variation of cycle time is trivial since all machines are numerically controlled and even for the operators, there is a 2 seconds' gap between the takt time and the operator walk loop time to compensate the variations.

#### ***Setup time***

Setup time for new cells is trivial. The only thing subject to changes is the program and it can be done almost instantly. Since operations are segmented into very small numbers like 4-5 processes, fixtures do not need to be changed and in addition, it's easy to design them. With single piece flow, there is no need to wait for machine to finish previously loaded parts as is the case in existing setup changeover.

### 4.4.2.3. People

This metric is also guessed on the basis of leading companies' examples.

- Process improvements: 5 points →

Team members can adjust process design based on fluctuation in customer demand in terms of volume and mix.

- Accessibility to the information: 5 points →

Most employees understand how the whole system works and how their jobs are related to those of other colleagues. The general inforamtion about the whole system is open to every employee.

- Number of suggestions →

Toyota plant in Georgetown, Kentucky is considered as the leading lean company [20]. In this plant,

*Number of suggestions each employee makes for a year*
: Exact data is not available but 7700 team members make hundreds of thousands of suggestions in a year. Some team members have contributed more than 1,000 suggestions

*Number of suggestions implemented for a year*
: More than 90,000 suggestions are adopted each year.

*Budgets to improve employee feedback system*
: more than 90 million dollars are saved by employee suggestions and 3.2 million dollars are paid back to the employees to encourage the suggestions.

#### 4.4.2.4. Inventory

For new cellular system, raw material inventory covering about 2 days and work in process inventory covering 4 hours of production is expected. Total inventory can cover 2.2 days of production.

#### 4.4.2.5. Scheduling

For new cellular system, scheduling activity is easier since now the only scheduling activity is to pull finished goods at the end of the line. Internal scheduling is done by the system itself since pull system is implemented. In addition, variation of system is less than that of existing system, so that the system output is more predictable, which makes scheduling activity much easier.

## 4.5. Cost Comparison between the Existing System and the Proposed System

In fact, the cost comparison between existing system and designed system has not been done according to the complexity metrics proposed. Instead, it is more based on Activity Based Costing system and done for machining area as a whole. Every single cost center related to production in the machining area is searched and identified such as energy, warehouse, forklift, etc. For this reason, it may not be adequate to claim that proposed system has less cost due to its lower level of complexity. However, at least, this cost comparison shows that lean production system design is less costly than the existing mass production system. This result may support the assumption in I – 2: cost is proportional to manufacturing system complexity.

Cost comparison is mainly done by Weidemann, M. and Roschmann, H. with helps from the cost department of Bosch Charleston Plant. The results are summarized by Figure 4-15 ~ 4-19. Due to confidential reasons, actual numbers are modified to ratios and other details such as cost centers are not described in this thesis. However, details on approaches and methods used in this cost comparison can be found in [36].

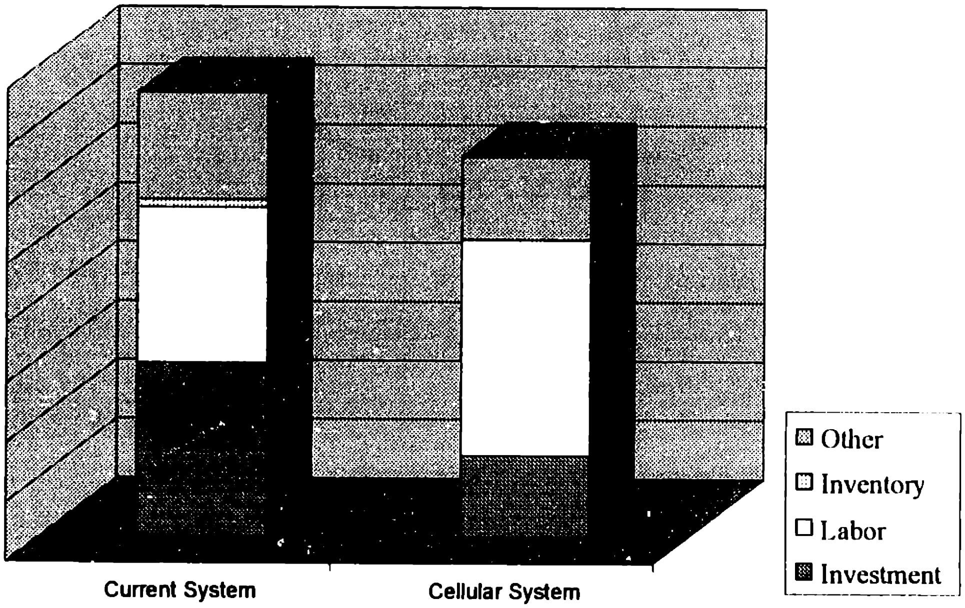


Figure 4-15. Cost Comparison by Cost Type per Unit

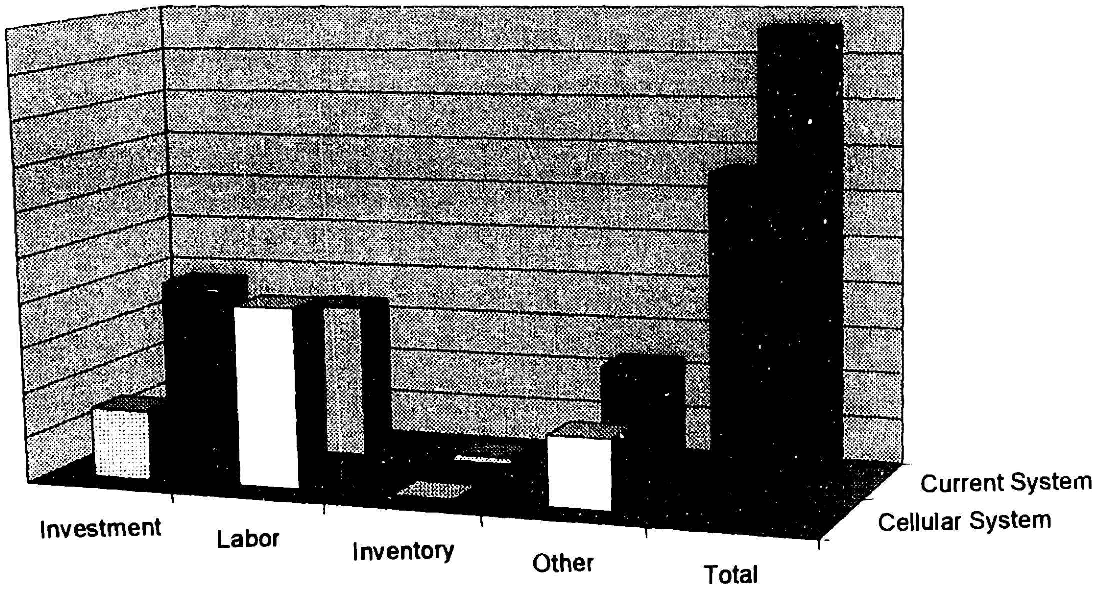


Figure 4-16. Cost Comparison by Cost per Hour

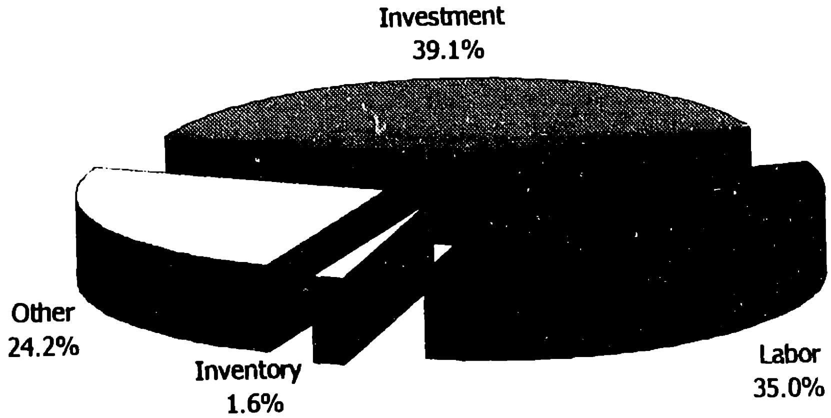


Figure 4-17. Cost Structure of the Current System

Figure 4-18. Cost Structure of Proposed System: Takt Time 65.6 seconds (Average Demand)

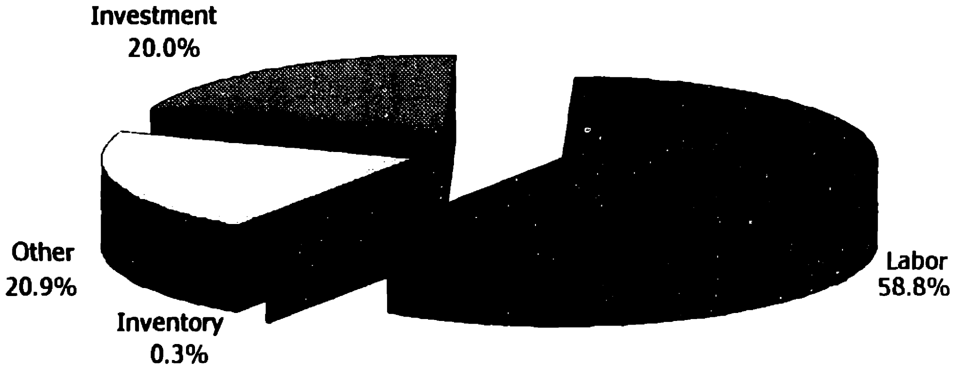


Figure 4-19. Cost Structure of Proposed System: Takt Time 52.8 seconds (Peak Demand)

## 4.6. Summary

In this case study, it is proven that the lean manufacturing system is less complex than existing mass production system with the same product variety in terms of complexity metrics provided. The comparison of values of each metric is shown in Table 4-6.

<table>
<tr><th colspan="3">Metrics</th><th>Current System</th><th>New System Design</th></tr>
<tr><td colspan="5"><b>Relationships between system components</b></td></tr>
<tr><td colspan="3">Number of flow paths</td><td>416 (1248 when including assembly line)</td><td>4 (12 when including assembly lines)</td></tr>
<tr><td colspan="3">Number of crossings in flow paths</td><td>2659</td><td>0</td></tr>
<tr><td colspan="3">Total travel distance of a part</td><td>1300 ft</td><td>424 ft</td></tr>
<tr><td colspan="3">Number of combinations of product and machine match</td><td>$15^{36}$ (830,472,192 when considering current constraints)</td><td>25920 ( 27 when considering equivalent constraints)</td></tr>
<tr><td colspan="5"><b>Elementary system components</b></td></tr>
<tr><td colspan="3">Number of elementary system components</td><td>66</td><td>138</td></tr>
<tr><td rowspan="4">Complexity of each elementary component</td><td colspan="2">Reliability of elementary system components</td><td>79% for ABS<br>70% for ASR</td><td>N/A but better reliability is expected.</td></tr>
<tr><td colspan="2">Quality outputs</td><td>96.95% for ABS<br>96.20% for ASR</td><td>N/A but less than 0.1% is expected.</td></tr>
<tr><td rowspan="2">Time outputs</td><td>Cycle time</td><td>Approximately 25 minutes for a machining center</td><td>Less than the takt time – 65.6 seconds</td></tr>
<tr><td>Setup time</td><td>30 secs to one day</td><td>Less than a minute</td></tr>
<tr><td rowspan="3"><b>People</b></td><td colspan="2">Process improvements</td><td>1 point</td><td>5 points</td></tr>
<tr><td colspan="2">Information accessibility</td><td>3 points</td><td>5 points</td></tr>
<tr><td colspan="2">Number of suggestions adopted</td><td>N/A</td><td>12.9 suggestions per one team member are adopted</td></tr>
<tr><td colspan="3">Inventory</td><td>14.5 days</td><td>2.2 days</td></tr>
</table>

Table 4-6. Summary of Complexity Comparison

## 4.7. Advantages and Limitations of Provided Complexity Metrics

Advantages of approaching to the system complexity with provided metrics are:

- It is relatively easy to measure.
- Loose quantification to avoid developing 'precisely wrong' metrics
- Provide quantifiable metrics that enable comparison of two systems in terms of their complexities.
- Identify attributes of complexity of manufacturing system
- Give insights to production system designers on what their designs should be like.

Limitations of this metrics approach are:

- There is no absolute standard to compare – for example, in case of one system with 100 flow paths and the other system with 200 flow paths, provided metric tell the later is more complex but it does not tell how much different they are.
- Metrics have many dimensions – it is difficult to compare the relative contributions to system complexity of these metrics. For example, when a system with 100 flow paths and 10 crossings is compared to the other system with 200 flow paths but 0 crossings, provided metrics do not tell which system is more complex.
- Calculations may depend on product types (e.g., discrete product / continuous product) or quality of product 'variety'
- Metrics are not generally applicable to other types of systems. They are applicable only to manufacturing systems.

# CHAPTER 5. CONCLUSION / SUMMARY

This thesis suggests a system complexity approach to explain how product variety affects manufacturing systems. To explain this, metrics to measure complexity of manufacturing systems are developed based on the notion of complexity sources in manufacturing systems (these metrics are summarized in Table 5-1). In terms of these metrics, the impacts of product variety on manufacturing systems are shown – product variety increases system complexity critically. The most important advantage with this approach may be that it shows how product variety increases each complexity metric, which eventually contributes to the complexity of a manufacturing system. In addition, it is shown how 'lean' concepts affect each complexity metric and finally eliminate system complexity. To support this argument, a case study is presented. In this case study, it is shown that conversion from the existing mass production system to the lean manufacturing system reduces system complexity while ensuring better system performance under the same product variety.

As described in the introduction, there is a two-way interaction between the production system design and the product design (including product portfolio design). It is that performance of a production system is affected by its product design and also the product variety can be extended by the production system. Considering this relationship, production system should be designed to have minimum complexity while accommodating whole product variety that is required by customers. On the other hand, products should be designed to provide whole product variety required by customers while minimizing the complexity of a given production system. Therefore, manufacturing system complexity can be reduced either by lean manufacturing system design or by proper product design. To achieve minimum level of complexity of manufacturing systems, both lean manufacturing system design and product design that is adequate to the production system should be pursued. In other words, product families should be centered on grouped sub-systems or cells by tying product design according to the linked-cell manufacturing capability. In this context, the contribution of this thesis may lie in providing a tool that can be used in this process to assess the impacts of produce design or manufacturing system design on manufacturing systems.

<table>
<tr><th colspan="3">Metrics</th><th>How to measure</th></tr>
<tr><td colspan="4"><b>Relationships between system components</b></td></tr>
<tr><td colspan="3">Number of flow paths</td><td>$N_f = \prod_{i=1}^{n_p} m_i$</td></tr>
<tr><td colspan="3">Number of crossings in flow paths</td><td>$N_c = \sum_{i=1}^{n_p-1} {}_{m_i}C_2 \times m_{i+1} + \sum_{i=1}^{n_p-1} N_{ct,i}$</td></tr>
<tr><td colspan="3">Total travel distance of a part</td><td>$D_t = \frac{\sum_{j=1}^{N_f}\sum_{i=1}^{n_p-1} d_{ji}}{N_f}$</td></tr>
<tr><td colspan="3">Number of possible combinations of product and machine match</td><td>$N_m = \prod_{k=1}^{n_s}\prod_{j=1}^{n_{p_k}}\prod_{i=1}^{m_j} V_i$</td></tr>
<tr><td colspan="4"><b>Elementary system components</b></td></tr>
<tr><td colspan="3">Number of elementary system components</td><td>$N_e = \sum_{i=1}^{n_p} m_i + s_i + p_i$</td></tr>
<tr><td rowspan="4">Complexity of each elementary component</td><td colspan="2">• Reliability of elementary system components</td><td>$R = \frac{T_t - T_r - T_o}{T_t - T_r}$</td></tr>
<tr><td colspan="2">• Quality outputs</td><td>$S_y(\%) = \frac{n_t - n_d}{n_t} \times 100$ (or FTTC)</td></tr>
<tr><td rowspan="2">• Time outputs</td><td>Cycle time</td><td>(Length) Mean cycle time of a system component<br>(Variation) Variance of cycle time</td></tr>
<tr><td>Setup time</td><td>Same as Time outputs</td></tr>
<tr><td colspan="4"><b>People</b></td></tr>
<tr><td colspan="3">Process improvements</td><td>5 point survey questions</td></tr>
<tr><td colspan="3">Information accessibility</td><td>5 point survey questions</td></tr>
<tr><td colspan="3">Number of suggestions</td><td>• Suggestions per employee<br>• Suggestions implemented<br>• Budgets to improve employee feedback system</td></tr>
<tr><td colspan="3"><b>Inventory</b></td><td>Production days that existing inventory can cover.</td></tr>
<tr><td colspan="3"><b>Scheduling</b></td><td>N/A</td></tr>
</table>

Table 5-1. Summary of system complexity metrics

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# APPENDIX

## 1. Lean Production

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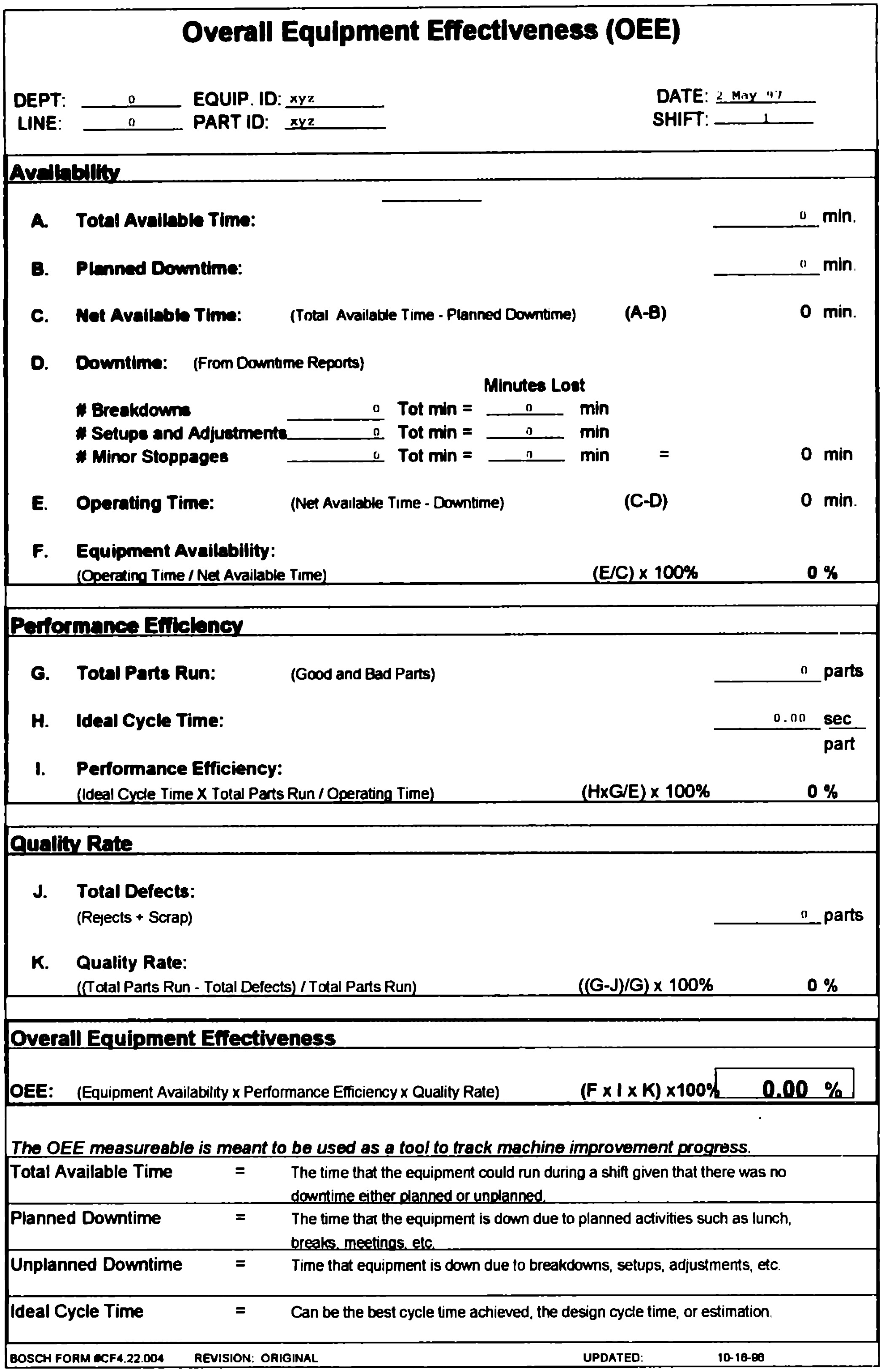
## 2. Overall Equipment Effectiveness (OEE) Calculation

Overall Equipment Effectiveness (OEE) can be calculated by simply following the steps provided in the Figure A-1. In fact, OEE has some flaws from the system viewpoint. For example, the pursuit to increase OEE can lead to the pursuit of increasing machine utilization rate. In fact, increasing machine utilization rate is not bad itself. However, blind efforts to increase machine utilization rate without considering their impacts on the whole system may lead to sub-optimizations or wastes such as over production (remember the famous phrase, 'you get what you measure.'). It is a waste to produce products simply to keep machines busy, which is one way to increase the OEE.

Another flaw is to consider setup time as unplanned downtime. This often leads to avoiding setup changeovers, which results in large run size and consequently worsens the responsiveness to the change or increase the inventory level. In this sense, setup changeover should not be unplanned activity. Unplanned setup indicates that the system is not controllable. Controllability of the system should go first, and then the efficiency of the system can be pursued in a much easier way than when pursuing only the efficiency.



## Overall Equipment Effectiveness (OEE)

DEPT: 0 EQUIP. ID: xyz DATE: 2 May 97
LINE: 0 PART ID: xyz SHIFT: 1

**Availability**

**A. Total Available Time:** 0 min.

**B. Planned Downtime:** 0 min.

**C. Net Available Time:** (Total Available Time - Planned Downtime) (A-B) 0 min.

**D. Downtime:** (From Downtime Reports)

| | | | Minutes Lost | | | |
|---|---|---|---|---|---|---|
| **# Breakdowns** | 0 | Tot min = | 0 | min | | |
| **# Setups and Adjustments** | 0 | Tot min = | 0 | min | | |
| **# Minor Stoppages** | 0 | Tot min = | 0 | min | = | 0 min |

**E. Operating Time:** (Net Available Time - Downtime) (C-D) 0 min.

**F. Equipment Availability:**
(Operating Time / Net Available Time) (E/C) x 100% 0 %

**Performance Efficiency**

**G. Total Parts Run:** (Good and Bad Parts) 0 parts

**H. Ideal Cycle Time:** 0.00 sec/part

**I. Performance Efficiency:**
(Ideal Cycle Time X Total Parts Run / Operating Time) (HxG/E) x 100% 0 %

**Quality Rate**

**J. Total Defects:**
(Rejects + Scrap) 0 parts

**K. Quality Rate:**
((Total Parts Run - Total Defects) / Total Parts Run) ((G-J)/G) x 100% 0 %

**Overall Equipment Effectiveness**

**OEE:** (Equipment Availability x Performance Efficiency x Quality Rate) (F x I x K) x100% **0.00 %**

*The OEE measureable is meant to be used as a tool to track machine improvement progress.*

| | | |
|---|---|---|
| Total Available Time | = | The time that the equipment could run during a shift given that there was no downtime either planned or unplanned. |
| Planned Downtime | = | The time that the equipment is down due to planned activities such as lunch, breaks, meetings, etc. |
| Unplanned Downtime | = | Time that equipment is down due to breakdowns, setups, adjustments, etc. |
| Ideal Cycle Time | = | Can be the best cycle time achieved, the design cycle time, or estimation. |

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Figure A-1. Overall Equipment Effectiveness (OEE) Calculation Sheet [20]

# 3. ABS, ASR and VDC.

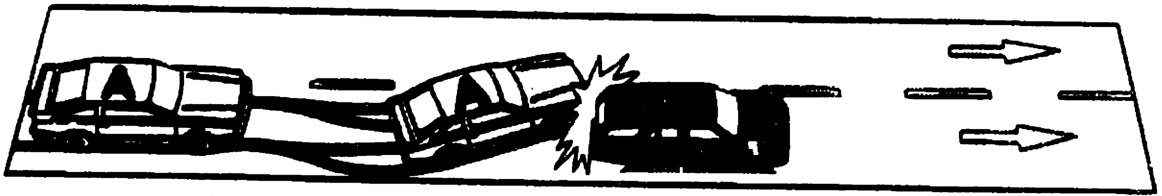
## 3.1. ABS (Anti-lock Braking System)

**Advantages of ABS system**

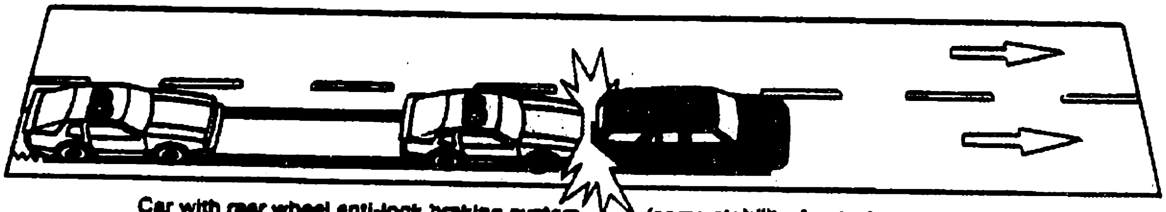
- Reduced stopping distances
- Directional stability
- Steering control
- Adaptive to various vehicle loading

**ABS safety benefits**

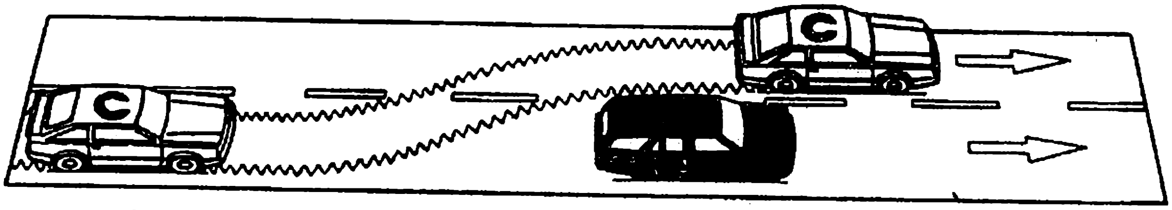
The safety benefits of ABS can be described by Figure A-2.



Car without anti-lock braking system (all wheels lock, skidding, unsteerable)



Car with rear wheel anti-lock braking system (some stability, front wheels lock, still unsteerable)



Car with 4-wheel anti-lock braking system (wheels don't lock, vehicle stable and steerable)

Figure A-2. Safety Benefits of ABS (Courtesy of Bosch Charleston Plant)

**ABS Function**

1. Driver applies brake
2. ECU detects impending wheel lock condition via wheel speed sensors
3. Brake pressure to wheel(s) is regulated by ABS hydraulic unit
4. ABS system continues operation until road conditions change (increased friction) or vehicle stops
5. ABS enables driver to maintain control of vehicle steering while braking

## 3.2. ASR (Traction Control System)

**ASR Definition**

1. Traction Control – prevents wheel slip
2. Includes ABS function
3. Active situations

- Aggressive acceleration
- Low friction surfaces

**ASR Function**

1. Driver applies acceleration.
2. ECU detects drive wheel slip via wheel speed sensors.
3. ABS/ASR ECU triggers engine intervention.

- Spark retard & throttle relaxer

4. ABS/ASR hydraulic unit applies brake pressure to slipping wheel until traction is restored.
5. ABS/ASR system can be de-activated to enable the driver to dig out of the snow.

## 3.3. VDC (Vehicle Dynamics Control)

**VDC Function (See Figure A-3)**

1. VDC assists the driver in maintaining directional stability
2. Steering angle, yaw, and lateral sensors determine unstable condition

- Understeer → Unit brakes inner rear wheel

- **Oversteer → Unit brakes outer front wheel**

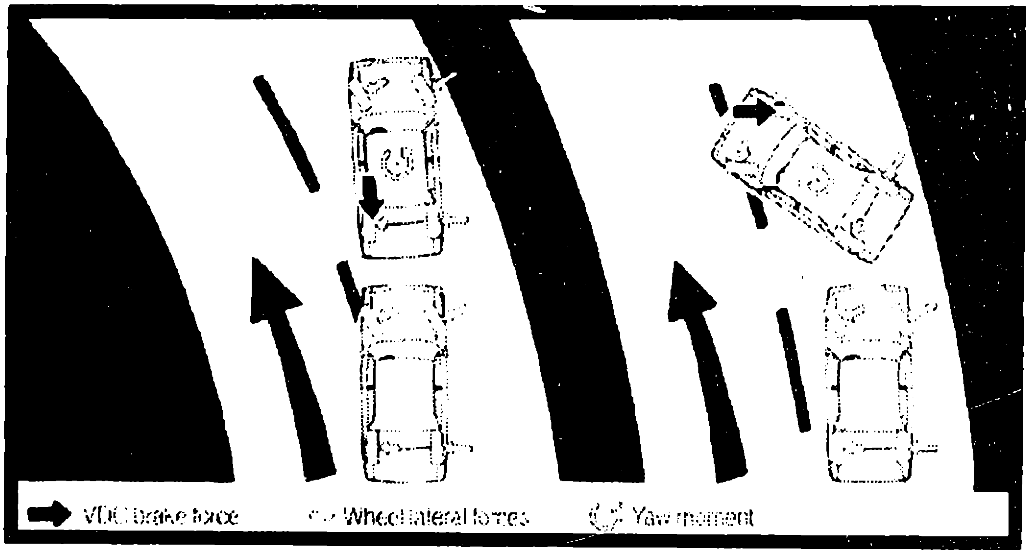


Figure A-3. Interactive Vehicle Dynamics (VDC) – Functions and Benefits

## 4. Comparison between the 3-Cells Model and the 4-Cells Model

Takt time for the 3-cells model is 13.2 X 3 = 39.6 seconds for the peak demand model or 16.4 X 3 = 49.2 seconds for the average demand model. Since the 4-cells model is developed for the peak demand case, takt time of 39.6 seconds is used for the 3-cells model.

Two constraints are given on the calculation of the number of necessary machines:

1. The sequence of the operations should be kept for the engineering purpose. In fact, the sequence is closely related to the chip formation inside the ABS/ASR housings.
2. Processing times cannot be shortened. Bosch's machining technology (especially with the speed) is in its extreme level, so that there is not much room for further improvement.

Grouping of the machining processes to meet the takt time is done in the same way as the 4-cells model case. Table A-1 shows machine grouping for the ABS housing cell and Table A-2 shows the ABS/ASR housing cell case.

According to Table A-2 and Table A-3, 20 machines for the ABS housing cell and 28 machines for the ASR housing cell are needed to meet the takt time of 39.6 seconds. Since there are 2 ABS cells and 1 ABS/ASR cell, the total number of machines is 20 X 2 + 28 = 68 machines. With the 4-cells model, the total number of machines 14 X 3 + 19 = 61 machines. This difference is due to the fact that some of machines in the 3-cells model are heavily underutilized because of long cycle times[4]. Therefore, the 4-cells model has fewer number of machines than the 3-cells model. Due to this fact[5], the 4-cells model is selected and developed further.

---

[4] Because tool changeover time is relatively long (6 seconds), the rotation of part requires special fixture, and quality check is much easier, machining on different faces is avoided as much as possible.

[5] For the better result, the 3-cells model should be further developed and the costs of each model should be compared. Some other factors may be considered such as product variety, company's strategy, etc.

|  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
| H | Mill F100 & F500 | x |  |  |  | x |  | 15.3 | x |  | 1 |
| H | 1 Pass Motor Bore F100 | x |  |  |  |  |  | 9.6 | x |  |  |
|  | Pallet Change |  |  |  |  |  |  | 6.0 | x | 31 |  |
| H | Accumulator Drill F500 |  |  |  |  | x |  | 10.3 | x |  | 2 |
| H | Damper Drill F500 |  |  |  |  | x |  | 10.3 | x |  |  |
| H | Dia. 20 Mtg. Hole F500 |  |  |  |  |  |  | 9.3 | x |  |  |
|  | Pallet Change |  |  |  |  |  |  | 6.0 | x | 36 |  |
|  | 5.9 mm Dia. (2) (?F100?) | (x) |  |  |  |  |  | 9.0 | x |  | 3 |
|  | 5.15 or 4.8 (2) Throttle F500 |  |  |  |  | x |  | 9.0 | x |  |  |
|  | 2 mm Drill (2) F500 |  |  |  |  | x |  | 10.5 | x |  |  |
|  | Pallet Change |  |  |  |  |  |  | 6.0 | x | 35 |  |
| (H) | M10 Drill (3) F100 | x |  |  |  |  |  | 11.3 | x |  | 4 |
|  | Thread Mill (2) F100 | x |  |  |  |  |  | 11.3 | x |  |  |
|  | M5 Tap Drill (2) F100 | x |  |  |  |  |  | 9.6 | x |  |  |
|  | Pallet Change |  |  |  |  |  |  | 6.0 | x | 38 |  |
|  | M5 Tap (2) F100 | x |  |  |  |  |  | 13.3 | x |  | 5 |
|  | 3.2 mm (2) F100 | x |  |  |  |  |  | 9.8 | x |  |  |
|  | Pallet Change |  |  |  |  |  |  | 6.0 | x | 29 |  |
|  | 3.2 mm Dia. (7) F300 + F400 |  |  | (x) | (x) |  |  | 22.5 | x |  | 6 |
| x | 6 mm spotface Drill (2) F500 |  |  |  |  | x |  | 9.5 | x |  |  |
|  | Pallet Change |  |  |  |  |  |  | 6.0 | x | 38 |  |
| x | 4.67 Dia. (2) F500 |  |  |  |  | x |  | 10.0 | x |  | 7 |
| x | 3.2 mm (6) F500 |  |  |  |  | x |  | 18.5 | x |  |  |
|  | Pallet Change |  |  |  |  |  |  | 6.0 | x | 35 |  |
|  | C-Ring Mill (4) F500 |  |  |  |  | x |  | 19.5 | x |  | 8 |
|  | C-Ring Mill (2) Sealed F500 |  |  |  |  | x |  | 6.0 | x |  |  |
|  | Pallet Change |  |  |  |  |  |  | 6.0 | x | 32 |  |
|  | M8 Tap Drill (4) F500 |  |  |  |  | x |  | 8.5 | x |  | 9 |
|  | M8 Tap (1) F500 |  |  |  |  | x |  | 8.5 | x |  |  |
|  | Finish Accumulator F500 |  |  |  |  | x |  | 11.5 | x |  |  |
|  | Pallet Change |  |  |  |  |  |  | 6.0 | x | 35 |  |
|  | Dia. 16 Drill (1) F600 |  |  |  |  |  | x | 8.5 | x |  | 10 |
|  | Thread Mill (4) F600 |  |  |  |  |  | x | 17.0 | x |  |  |
|  | Jasu tripan (4) (?F600?) |  |  |  |  |  | (x) | 7.5 | x |  |  |
|  | Pallet Change |  |  |  |  |  |  | 6.0 | x | 39 |  |
|  | Dia. 9 Drill (6) F600 |  |  |  |  |  | x | 14.5 | x |  | 11 |
|  | Dia 11 Drill (2) F600 |  |  |  |  |  | x | 7.5 | x |  |  |
|  | Pallet Change |  |  |  |  |  |  | 6.0 | x | 28 |  |
|  | Dia. 3.2 (6) F600 |  |  |  |  |  | x | 22.5 | x |  | 12 |
|  | Formtap (4) F600 (or thread, it's the SAME) |  |  |  |  |  |  |  |  |  |  |
|  | Pallet Change |  |  |  |  |  |  | 6.0 | x | 29 |  |
| H | Dia. 20 Mtg Hole (1) F300 (1) F400 |  |  | x | x |  |  | 13.0 | x |  | 13 |
| H | 1 Pass P.E. Drill (1) F300 (1) F400 |  |  | x | x |  |  | 11.5 | x |  |  |
|  | Pallet Change |  |  |  |  |  |  | 6.0 | x | 31 |  |
|  | 9 mm Dia (3) F300 (3) F400 |  |  | x | x |  |  | 13.0 | x |  | 14 |
|  | 5.9 mm Dia (1) (???) |  |  | (x) | (x) |  |  | 8.0 | x |  |  |
|  | Pallet Change |  |  |  |  |  |  | 6.0 | x | 27 |  |
|  | Mill F200 |  | x |  |  |  |  | 16.5 | x |  | 15 |
|  | 3.64 Dia. (6) F200 |  | x |  |  |  |  | 15.0 | x |  |  |
|  | Pallet Change |  |  |  |  |  |  | 6.0 | x | 38 |  |
|  | 3.2 mm drill (2) F200 |  | x |  |  |  |  | 10.5 | x |  | 16 |
|  | AV Rough (4) F200 |  | x |  |  |  |  |  |  |  |  |
|  | EV Rough (4) F200 |  | x |  |  |  |  | 18.5 | x |  |  |
|  | Pallet Change |  |  |  |  |  |  | 6.0 | x | 35 |  |
|  | AV Fin. (4) F200 |  | x |  |  |  |  |  |  |  | 17 |
|  | EV Fin. (4) F200 |  | x |  |  |  |  | 20.5 | x |  |  |
|  | Pallet Change |  |  |  |  |  |  | 6.0 | x | 27 |  |
|  | Sugino |  |  |  |  |  |  | 67.5 | x x x x |  | 18,19 |
|  | Rinse/Dry |  |  |  |  |  |  | 30.0 | x |  | 20 |

Table A-1. Grouping of Machining Processes for ABS Housing (3-cells model)

|  | [illegible] |  | Operation Time |
|---|---|---|---|
| H | Mill F100 & F500 |  | 15.25 |
| H | Accumulator Drill F500 |  | 10.25 |
|  | Pallet Change |  | 6 |
| **STATION #1** |  | total | **31.5** |
| H | Damper Drill F500 |  | 10.25 |
| H | Dia. 20 Mtg. Hole F500 |  | 9.25 |
|  | Pallet Change |  | 6 |
| **STATION #2** |  | total | **25.5** |
| H | 1 Pass Motor Bore F100 |  | 9.625 |
| (H) | M10 Drill (3) F100 |  | 11.25 |
|  | Thread Mill (2) F100 |  | 11.25 |
|  | 5.9 mm Dia. (2) (?F100?) |  | 0 |
|  | Pallet Change |  | 6 |
| **STATION #3** |  | total | **38.125** |
|  | 5.9 mm spot (4) F100 |  | 13.5 |
|  | M5 Tap Drill (2) F100 |  | 9.625 |
|  | Pallet Change |  | 6 |
| **STATION #4** |  | total | **29.125** |
|  | M5 Tap (2) F100 |  | 13.25 |
|  | 3.2 mm (2) F100 |  | 0 |
|  | 3.2 mm drill additional (?F100?) |  | 14.25 |
|  | Pallet Change |  | 6 |
| **STATION #5** |  | total | **33.5** |
| H | ISD 1 pass (2) F100 |  | 10.75 |
|  | 6 mm spotface (2) F100 |  | 9.25 |
|  | 4.3 mm drill (2) F100 |  | 12.25 |
|  | Pallet Change |  | 6 |
| **STATION #6** |  | total | **38.25** |
| (H) | ISD Groove (2) F100 |  | 12.25 |
|  | 5.15 or 4.8 (2) Throttle F500 |  | 9 |
|  | Pallet Change + Fixture Rotation |  | 8 |
| **STATION #7** |  | total | **29.25** |
|  | 5.65 Dia. RVR (2) F500 |  | 10.5 |
|  | 2 mm Drill (2) F500 |  | 10.5 |
| x | 6.8 mm Spotface (2) F500 |  | 11.5 |
|  | Pallet Change |  | 6 |
| **STATION #8** |  | total | **38.5** |
| x | 6 mm spotface Drill (2) F500 |  | 9.5 |
| x | 4.57 Dia. (2) F500 |  | 10 |
| x | 4.3 mm Drill (2) F500 |  | 11.5 |
|  | Pallet Change |  | 6 |
| **STATION #9** |  | total | **37** |
| x | 4.2 mm Spotface (2) F500 |  | 11.5 |
|  | Pallet Change |  | 6 |
| **STATION #10** |  |  | **17.5** |
| x | 3.2 mm Dia (4) Add. F500 |  | 0 |
| x | 3.2 mm (5) F500 |  | 23.5 |
|  | M8 Tap Drill (4) F500 |  | 8.5 |
|  | Pallet Change |  | 6 |
| **STATION #11** |  | total | **38** |
|  | C-Ring Mill (4) F500 |  | 19.5 |
|  | C-Ring Mill (2) Sealed F500 |  | 6 |
|  | Pallet Change |  | 6 |
| **STATION #12** |  | total | **31.5** |
|  | M8 Tap (1) F500 |  | 8.5 |
|  | Finish Accumulator F500 |  | 11.5 |
|  | Pallet Change |  | 6 |

|  | ABS/ASR Operation |  | Operation Time |
|---|---|---|---|
|  | Dia. 16 Drill (1) F600 |  | 8.5 |
|  | Dia. 9 Drill (6) F600 |  | 14.5 |
|  | Dia.11 Drill (2) F600 |  | 7.5 |
|  | Pallet Change |  | 6 |
| **STATION #14** |  | total | **36.5** |
|  | 5.9 Dia (4) F600 |  | 10.5 |
|  | Pallet Change |  | 6 |
| **STATION #15** |  | total | **16.5** |
|  | Dia. 3.2 (6) F600 |  | 0 |
|  | 3.2 mm (2) Add. F600 |  | 27 |
|  | Pallet Change |  | 6 |
| **STATION #16** |  | total | **33** |
|  | Thread Mill (4) F600 |  | 17 |
|  | Formtap (4) F600 (or thread) |  | 0 |
|  | Jasu tripan (4) (?F600?) |  | 7.5 |
|  | Pallet Change |  | 6 |
| **STATION #17** |  | total | **30.5** |
| H | Dia. 20 Mtg Hole (1) F300 (1) F400 |  | 13 |
| H | 1 Pass P.E. Drill (1) F300 (1) F400 |  | 11.5 |
|  | Pallet Change |  | 6 |
| **STATION #18** |  | total | **30.5** |
|  | 9 mm Dia (3) F300 (3) F400 |  | 13 |
|  | 5.9 mm Dia (1) (???) |  | 0 |
|  | 5.9 mm Dia (8) (???) |  | 14.5 |
|  | Pallet Change |  | 6 |
| **STATION #19** |  | total | **33.5** |
|  | 3.2 mm Dia. (7) F300 + F400 |  | 0 |
|  | 3.2 mm Dia. (4) (???) |  | 31.5 |
|  | Pallet Change |  | 6 |
| **STATION #20** |  | total | **37.5** |
|  | Mill F200 |  | 16.5 |
|  | 3.64 Dia. (6) F200 |  | 15 |
|  | Pallet Change |  | 6 |
| **STATION #21** |  | total | **37.5** |
|  | AV Rough (4) F200 |  | 0 |
|  | ASV (?) Rough |  | 12.5 |
|  | EV Rough (4) F200 |  | 0 |
|  | USV (2) Rough |  | 12.5 |
|  | Pallet Change |  | 6 |
| **STATION #22** |  | total | **31** |
|  | 3.2 mm drill (2) F200 |  | 0 |
|  | 3.2 mm (4) Add. |  | 16.5 |
|  | 2.5 mm (4) Add. |  | 15.5 |
|  | Pallet Change |  | 6 |
| **STATION #23** |  | total | **38** |
|  | AV Fin. (4) F200 |  | 0 |
|  | EV Fin. (4) F200 |  | 0 |
|  | ASV & USV Fin Add.(4) |  | 23 |
|  | Pallet Change |  | 6 |
| **STATION #24** |  | total | **29** |
|  | Sugino (x3) |  | 34.167 |
| **STATION #25, #26, #27** |  | total | **34.167** |
|  | Rinse/Dry |  | 30 |
| **STATION #28** |  | total | **30** |

Table A-2. Grouping of Machining Processes for ABS/ASR Housing (3-cells model)