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Design of Manufacturing Systems to Support Volume Flexibility

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ABSTRACT

This paper presents an Axiomatic Design framework for manufacturing system design and illustrates how lean cellular manufacturing can achieve volume flexibility. Axiomatic Design creates a design framework by mapping the functional requirements of a system to specific design parameters. Volume flexibility is often neglected as a requirement of manufacturing systems. Very few industries are fortunate enough to experience stable or predictable product demand. In reality, demand is often volatile and uncertain. It is important that manufacturing system designers are aware of manufacturing system types which can accommodate volume flexibility and follow a structured design methodology that assures that all requirements are met by the system.

INTRODUCTION

Recent decades have led to the development and proliferation of many new paradigms in manufacturing. With the advent of Numerically Controlled (NC) and later Computer Numerically Controlled (CNC) machine tools and robotics, the complexity of manufacturing systems has grown considerably. In many instances, the advantages and limitations of these new tools were not understood. This confusion led to many costly mistakes in manufacturing system design. Many companies believed that automation was the wave of the future and invested in expensive automated systems only to find that they were not cost effective.

There are two reasons why such mistakes have been made and continue to be made. First, the manufacturing field as a whole does not fully understand the advantages and disadvantages of different types of manufacturing systems. Since the mid-1970's the variety of manufacturing system types has grown considerably. Since that time, Flexible Manufacturing Systems, Agile Production Systems, and Lean Cellular Systems, have become accepted types of manufacturing systems. Prior to that, the main types of systems were limited to Job Shops ("jumbled flow" systems), Disconnected Flow Lines (Batch Production), and Transfer Lines. The development of new system types complicates manufacturing system design considerably. Careful consideration of the requirements of the system is required to support an informed system type selection.

A major reason why highly automated manufacturing systems may not be cost effective is that product demand can be very unpredictable. Generally, the more automated the system is, the less flexible it is in terms of volume. An automated transfer line, for example may be the most cost effective type of system available at a particular production rate. If demand increases or decreases, however, an automated system is either unable to meet the demand or must take a variable cost increase (overtime, etc.) to do so. In many industries, demand is volatile and uncertain. As a result, the forecast of demand is rarely accurate. Figure 1 illustrates that even with an accurate forecast, demand will be normally distributed about the forecast. If the forecast is skewed, the actual distribution will be shifted either to the left or right.

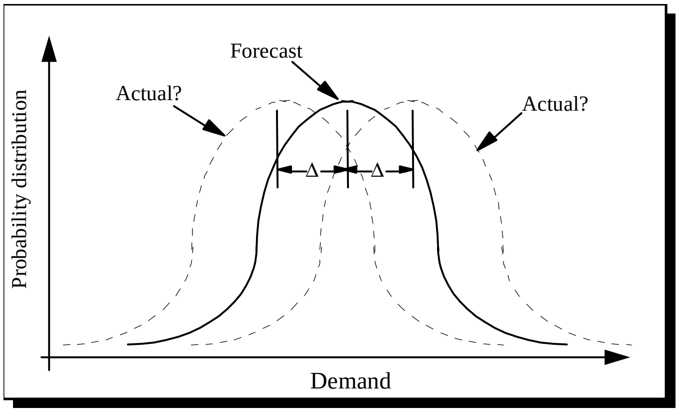


Figure 1. The uncertainty of the demand forecast

The problem of forecasting is magnified as the leadtime required to construct and validate a manufacturing system increases. As this leadtime increases, a longer range forecast is required. The deviation (Δ) between the forecast and the actual demand can be expected to increase the farther into the future the forecast predicts.

The second reason for ineffective manufacturing system designs is that there has been no structured methodology to follow. Tools such as Quality Function Deployment (QFD) and Axiomatic Design have proven to be very helpful for product design, so similar tools are needed to assist the designers of manufacturing systems. This paper presents an approach for the use of Axiomatic Design for Manufacturing System Design. This approach aids the designer to make informed decisions at each step in the design process based upon the requirements of the product to be manufactured, the workers who will operate the system, and the final customer.

AXIOMATIC DESIGN

Axiomatic Design was developed in the late 1970's by Dr. Nam P. Suh. Suh set out to develop "a firm scientific basis for design, which can provide designers with the benefit of scientific tools that can assure them complete success." [Suh, 1990] Until this time, design was considered to be a purely creative process that could not be formalized. "However, the fact that there are *good design solutions* and *unacceptable design solutions* indicates that there exist *features* or *attributes* that distinguish between good and bad designs. Furthermore, since this creative process permeates all fields of human endeavor ranging from engineering to management, the *features* associated with a good design may have *common elements*. These *common elements* may then form the basis for developing a unified theory for the synthesis process." [Suh, 1990]

Axiomatic Design is a formalized methodology to structure the design process and to assess the quality of various designs. The methodology was named "Axiomatic Design" because it is based upon axioms. Axioms are fundamental truths that are always observed to be valid and for which there are no counterexamples or exceptions. [Suh, 1990] To date, two Axioms have been developed. They are axiom 1, "The Independence Axiom" and axiom 2, "The Information Axiom."

THE INDEPENDENCE AXIOM – The first Design Axiom states: "In an acceptable design, the [Design Parameters (DPs)] and the [Functional Requirements (FRs)] are related in such a way that a specific DP can be adjusted to satisfy its corresponding FR without affecting other functional requirements." [Suh, 1990] If no DP affects more than one FR, the design is said to be uncoupled. In order to visually assess coupling, one can write the *design equation*. The design equation is a mathematical representation of the interactions between FRs and DPs. A design equation should be written for each transition between domains and at each decomposition level. The design equations have the following forms:

For the transition from FRs to DPs:

$$\{\mathrm{FRs}\} = [\mathrm{A}]\{\mathrm{DPs}\}$$

For the transition from DPs to PVs:

$$\{\mathrm{DPs}\} = [\mathrm{B}]\{\mathrm{PVs}\}$$

The {FRs}, {DPs}, and {PVs} matrices are column matrices with the number of rows corresponding to the number of FRs at the given decomposition level. The [A] and [B] matrices are square matrices. These are called the *design matrices*. Figure 2 shows examples of the three categories of designs: uncoupled, coupled, and decoupled.

An uncoupled design is ideal. Notice that DP1 affects only FR1, DP2 affects only FR2, and so on. In uncoupled designs, Xs appear only along the diagonal of the matrix. Coupled designs are unacceptable. Note that DP1 affects FR1 and FR2; DP2 affects FR2 and FR3; and DP4 affects FR2 and FR4. Visually, one can identify a design as coupled if Xs appear on both sides of the diagonal. Decoupled designs are more acceptable than coupled designs. If Xs appear only on one side of the diagonal, the design is decoupled. Decoupled designs are better, but still not ideal because they are path dependent. The final solution depends upon the order in which the DPs are implemented.

THE INFORMATION AXIOM – Axiom 2, the Information Axiom, states: "Minimize the information content of the design". An alternative statement is "The best design is a functionally uncoupled design that has the minimum information content." [Suh, 1990] Information content is related to the probability that a particular design will satisfy the Functional Requirements. If several uncoupled design alternatives exist, Axiom 2 can be used to choose the best among them.

MAPPING AND DECOMPOSITION – The Axiomatic Design approach involves mapping through four design domains. Each translation or transition to a new domain represents a refinement of the design.

$$\begin{Bmatrix} \mathrm{FR1} \\ \mathrm{FR2} \\ \mathrm{FR3} \\ \mathrm{FR4} \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ O & X & O & O \\ O & O & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} \mathrm{DP1} \\ \mathrm{DP2} \\ \mathrm{DP3} \\ \mathrm{DP4} \end{Bmatrix}$$

Uncoupled

$$\begin{Bmatrix} \mathrm{FR1} \\ \mathrm{FR2} \\ \mathrm{FR3} \\ \mathrm{FR4} \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ O & X & X & X \\ O & X & X & O \\ X & O & O & X \end{bmatrix} \begin{Bmatrix} \mathrm{DP1} \\ \mathrm{DP2} \\ \mathrm{DP3} \\ \mathrm{DP4} \end{Bmatrix}$$

Coupled

$$\begin{Bmatrix} \mathrm{FR1} \\ \mathrm{FR2} \\ \mathrm{FR3} \\ \mathrm{FR4} \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ O & X & O & O \\ O & X & X & O \\ X & O & X & X \end{bmatrix} \begin{Bmatrix} \mathrm{DP1} \\ \mathrm{DP2} \\ \mathrm{DP3} \\ \mathrm{DP4} \end{Bmatrix}$$

Decoupled

Figure 2. Examples of uncoupled, coupled, and decoupled design matrices.

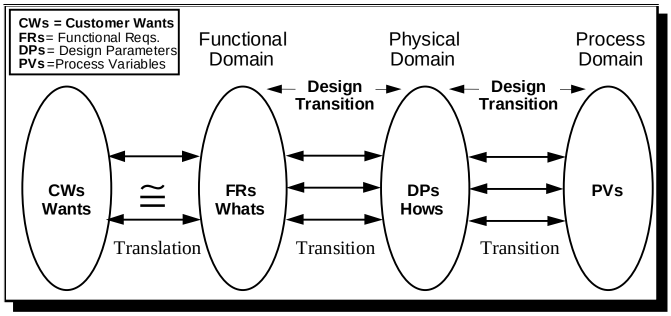


Figure 3. Domain Relationships

In the Customer Domain, the designer lays out the Customer's wants for the system. These Customer Wants (CWs) are translated into Functional Requirements (FRs) in the Functional Domain. FRs are then mapped to Design Parameters (DPs) in the Physical Domain. DPs are physical realizations of the FRs. Finally, DPs are mapped to Process Variables (PVs) in the Process Domain. The mapping process involves zig-zagging between different levels of the domains in order to fully define the FRs, DPs, and PVs.

AN AXIOMATIC DESIGN APPROACH FOR MANUFACTURING SYSTEM DESIGN

The authors have found that in practice, decomposition in two domains is most effective, even though the Axiomatic Design methodology indicates that it should be carried out in three domains (Functional, Physical, and Process). In the case of manufacturing system design, the decomposition takes place in the Functional and Physical Domains.

DOCUMENTATION OF CUSTOMER WANTS AND CONSTRAINTS – The first step in the design process is to clearly document the Customer Wants and Constraints. In the case of manufacturing system design, the Customer Wants include things such as details of the products to be produced, the expected demand for the products, and any other requirements that the customer places on the system. Next, the constraints must be documented. The constraints will typically include such things as investment cost, operating expense, limits on the workforce, ergonomic concerns, etc..

SELECTION OF THE SYSTEM TYPE – After the Customer Wants and Constraints have been identified and documented, the design can proceed with decomposition of Functional Requirements (FRs) and Design Parameters (DPs). In manufacturing system design, Functional Requirements represent "What the system must accomplish." Design Parameters represent "How the system accomplishes it." Following the Zig-zag decomposition method, FR1 and DP1 are defined first. In the following manufacturing system design, FR1 has the general form: "Produce products X, Y, Z, etc.". DP1 defines what type of manufacturing system will be used. It is at this point where the most appropriate type of manufacturing system is selected based upon the Customer Wants and Constraints. DP1 will therefore be "Lean Assembly Cell", "Automated Transfer Line", etc..

It is necessary for manufacturing system designers to understand each type of system and the advantages and disadvantages of each. This paper considers five system types: automated transfer lines, Job Shops, Flexible Manufacturing Systems (FMS), Agile Cells, and “Lean” Cells. There are other types of manufacturing systems and in reality the lines between the types is often hard to distinguish. This fact is the motivation for using the Axiomatic Design methodology to describe the attributes of a manufacturing system.

Automated Transfer Lines – Manufacturing systems using dedicated automation use machines that were specially designed with a particular model of product in mind. These systems tend to be expensive due to the engineering and custom development required. Examples of dedicated automation include traditional American automobile engine production lines and automotive component assembly lines. These systems generally support very few different products or models. Due to the relative high cost to retool these systems, they are typically used for products with long life cycles. American automotive engines for example have life cycles of five to ten years.

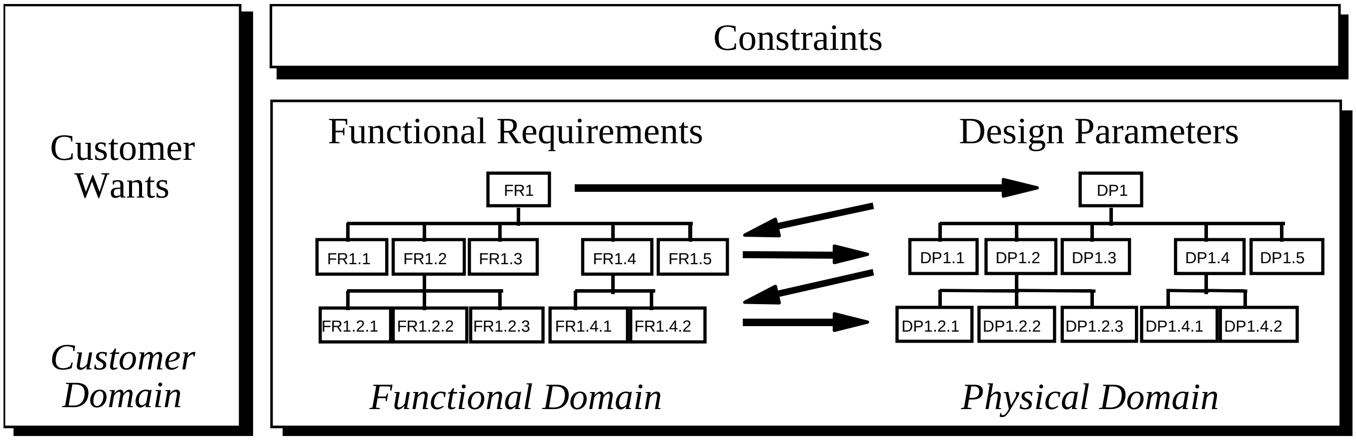


Figure 4. Axiomatic Design Approach for Manufacturing Systems

Dedicated automation is usually used only in cases where product demand requires a low cycle time. Dedicated automation is most effective for products which have a constant demand. This is because the majority of costs associated with these systems is fixed. Generally, dedicated automation requires a fixed amount of labor to support its operation. Therefore, these systems are most profitable only at the production level for which they were designed.

Job Shop – A Job Shop style manufacturing system uses standard flexible machines which are not oriented or configured for any particular product. Instead, products flow from machine to machine in which ever order is necessary. Parts are not automatically transferred from one machine to another. Job Shops generally produce in batches. For instance, a batch of 100 parts of a particular type is processed at one machine, then the batch is transported to the next machine. The machines in Job Shops generally have long change-over times, are labor intensive, and require complex scheduling. However, the Job Shop is the most flexible system type in terms of product variety for low volume products.

Flexible Manufacturing System – A Flexible Manufacturing System (FMS) is essentially an automated Job Shop. [Black, 1991] The machines are organized in a similar way and support a wide variety of products. Generally, material transport between machines is automated with robots or Automated Guided Vehicles (AGVs). Machine change-overs may be automated in Flexible Manufacturing Systems. An FMS requires less direct labor, but more investment than a Job Shop. As in Job Shops, machines are generally operated in parallel and are not designed or specified based on Takt time. This type of operation can increase system-wide change-over times and cause problems in the identification of quality problems.

Agile Cell – Agile Cells consist of clusters of modular machines which function in a similar manner to an FMS. Agile cells conform to the RRS Design Principles: Reusable, Reconfigurable, and Scalable. [Dove, 1995] The modular machines are built around a common architecture. This facilitates quick exchanges of modules when one fails or a new product must be produced. This also supports capacity increases and decreases by adding or removing modules. To date, Agile Cells have been utilized primarily in electronics fabrication where high equipment cost, short product life cycles, and delicate part handling are necessary.

Manufacturing Cell – Manufacturing Cells are often associated with the Toyota Production System (TPS). Cells tend to be flexible both in terms of volume and product mix. Cells give workers more control over the manufacturing system. The inherent flexibility of the worker is harnessed to build various products or models with zero change-over time between them. Workers also enable volume flexibility. If demand for a particular product family increases, more workers are assigned to the cell responsible for that product family. When demand decreases, workers are removed from the cell.

In order to achieve this volume flexibility, the worker must be separated from the machine. In a transfer line, each worker often sits along the line and is responsible for a few work tasks as the part moves by. In a cell, the worker moves along a designated work loop. He/she advances with the part from one station to the next and performs all necessary operations at those stations. As demand increases, work loops can be redefined so that there are more loops, or workers can be added to each loop.

Sometimes, workers are added or removed from automated transfer lines to make adjustments in production rate. This process is often called line 'rebalancing'. Rebalancing involves repositioning operations along the line and trying to give an equal amount of work content to each worker. Rebalancing often requires that hardware be moved around the line and workers become accustomed to new procedures. In contrast, Lean Cells require no physical rebalancing. No hardware needs to be moved, and workers operate the cell in the same manner they always have. The only difference is that there may be a different number of workers in the cell, or work loops change in the number or type of operations.

Criteria for Selection of System Type – Attributes of the product that may dictate the type of system required include the volume demanded, the certainty of that volume forecast, the mix of products to be produced, the expected product life, and physical attributes of the products. Generally, the greater the volume required, the more investment in tooling that can be justified. The certainty of the volume demand forecast also plays a role in the justification of investment. If a forecast is highly certain, automation and fixed-rate capacity will be efficient. If the forecast is highly uncertain, it is probably better to rely more on flexible capacity systems and the inherent flexibility of workers to achieve a broad range of production rates. As the mix of products increases (i.e. more products or models pass through the system), the design should tend away from fixed tooling and toward more flexible systems. If the expected product life is long, greater investment expense can be justified. If the product life is short, consideration must be given to the retooling expense required as the product changes or is replaced.

Some products have other requirements that limit the choices of a manufacturing system. Electronic devices cannot be handled by human hands through much of their production process, hence they must be manufactured in a system with automated material handling. The transfer line and agile cell are the most applicable system types for electronics.

Table 1. Characteristics of various manufacturing system types

	Volume Certainty	**Product Mix**	**Product Life**
Automated Transfer Line	High	Low	Long
Job Shop	Low	High	Short
FMS	Medium	High	Short
Agile Cellular	Medium	Medium	Medium
Lean Cellular	Low	Medium	Medium

DETAILED SYSTEM DESIGN – When DP1 (the system type) is chosen, decomposition returns to the Functional Domain to specify the next level "whats" (FRs). These will be more specific attributes required of the system. After these FRs are fully specified, the corresponding "hows" (DPs) are selected in the Physical Domain. Decomposition continues in this manner until the manufacturing system is fully designed. At each level of decomposition, a design matrix should be developed to verify that the design is uncoupled. It is possible to select a DP to satisfy a particular FR that will have an adverse effect on another FR. In this event, another DP must be sought that will create an uncoupled design.

AXIOMATIC DESIGN OF A VOLUME FLEXIBLE ASSEMBLY SYSTEM

In order to illustrate the proposed Axiomatic Design process for manufacturing system design, the example of an automotive Rack and Pinion steering gear assembly is used. Table 2 lists the Customer Wants and Table 3 contains the list of constraints.

Table 2. Customer Wants

Product	Rack and Pinion gear assembly for J230 and I410 vehicles.
Total Expected Demand	212,000 units anually
Demand Certainty	New vehicles, so highly uncertain (+/- 30%)

Table 3. Constraints

Ergonomics • workers cannot repeatedly lift more than 30 lb. • walking distance must be minimized
Zero Change-over time between J230 and I410
Maximum Investment: $X

The Takt time (or Manufacturing System Cycle time) is calculated from the annual demand. Takt time is calculated by dividing the available daily time by the Average daily demand. In the case of the example,

$$\text{Mean Takt time} = \frac{\text{Available Daily Time}}{\text{Average Daily Demand}} =$$

$$\frac{2\,\frac{\text{shifts}}{\text{day}} \cdot 7.5\,\frac{\text{hours}}{\text{shift}} \cdot 3600\,\frac{\text{sec.s}}{\text{hour}}}{212{,}000\,\frac{\text{units}}{\text{year}} \div 250\,\frac{\text{days}}{\text{year}}} = 64\,\frac{\text{seconds}}{\text{unit}}$$

This is the mean Takt time, based on the expected demand. The upper and lower Takt time limits can be calculated based upon the +/- 30% demand uncertainty.

$$\text{Min. Takt time} = \frac{\text{Mean Takt Time}}{(1 + \text{X\%})} = \frac{64\,\frac{\text{seconds}}{\text{unit}}}{1.3} = 49\,\frac{\text{seconds}}{\text{unit}}$$

$$\text{Max. Takt time} = \frac{\text{Mean Takt Time}}{(1 - \text{X\%})} = \frac{64\,\frac{\text{seconds}}{\text{unit}}}{0.7} = 91\,\frac{\text{seconds}}{\text{unit}}$$

FIRST LEVEL OF DECOMPOSITION: SELECTING THE SYSTEM – Given the Customer Wants and Constraints specified above, the most appropriate assembly system is the Manufacturing Cell. The cell will be able to provide the volume flexibility required to support Takt times from 49 to 91 seconds. It will also be able produce both models (J230 and I410) and support zero change-over time.

FURTHER DECOMPOSITION: DETAILED SYSTEM DESIGN – After selecting the appropriate DP1 (system type) at the first level of decomposition, it is time to return to the functional domain to specify the next level of Functional Requirements. The FRs will vary based upon which type of system was chosen. For the cell, the second level Functional Requirements are:

- FR1.1: Assembly sequence that supports product's physical attributes
- FR1.2: Sufficient cell capacity
- FR1.3: Volume Flexibility
- FR1.4: “Lean” layout to support work loops
- FR1.5: Transport product from station to station

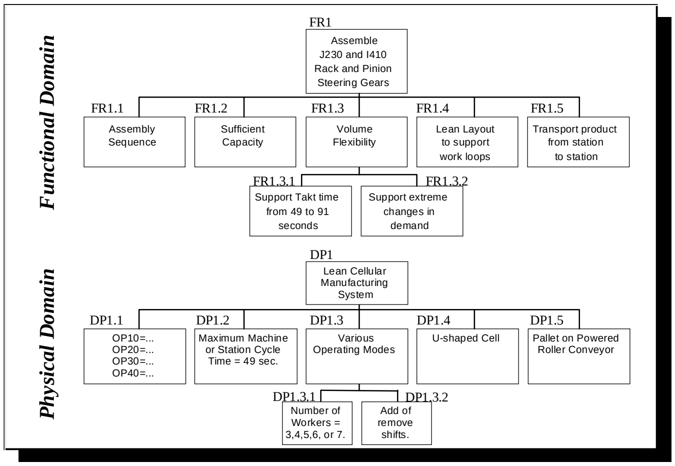


Figure 5. Design Decomposition

Selecting DP1.1 to satisfy FR1.1- "Assembly sequence that supports product's physical attributes" – FR1.1 involves specifying the exact sequence of operations required to manufacture or assemble the product. DP1.1 is the sequential list of operations and the estimated time required to perform them. For this case, DP1.1 is found in Table 4.

Table 4. DP1.1: Operation Sequence

Station	Operation	Time (sec.)
1	Load Housing to Pallet	12
2	Install short pressure line	17
3	Install long pressure line	17
4	Apply Grease to Rack	5
5	Set Rack into Housing	20
6	Assemble Valve into Housing	22
7	Insert Rack Bearing	12
8	Assemble Retaining Ring	5
9	Install Pinion Nut	8
10	Assemble Yoke and Lock Nut	18
11	Preset Yoke	13
12	Calibrate Yoke	10
13	Start R.H. Tie Rod	20
14	Start L.H. Tie Rod	20
15	Torque Tie Rods	25
16	Assemble shipping plugs	8
17	Install dust cover	8
18	Install R.H. boot and clamp	14
19	Install L.H. boot and clamp	14
20	Crimp clamps	15
21	Apply label	5
22	Center Gear	6
23	Pack into shipping pallet	20
	Total:	314

Selecting DP1.2 to satisfy FR1.2: "Sufficient cell capacity" – Cell capacity is based on the bottleneck station or machine. [Goldratt, 1990] The station or machine that requires the greatest cycle time limits the maximum production rate of the entire cell. Therefore, the cycle time of each station or machine must be limited to the minimum Takt time that the cell supports. In the Rack and Pinion steering gear assembly cell example, the constraints yield a minimum takt time of 49 seconds. As a result, the operations must be grouped into stations that do not exceed the 49 second cycle time. Operations must be grouped into stations so that the constraint of walking distance can be minimized. It would not be efficient, for example, to have each operation occupy its own station.

DP1.2 for the example is met by the station groupings shown in Table 5.

Table 5. Max. station cycle time less than or equal to 49sec.

Station	Operations	Time (sec.)
1	Load Housing to Pallet Install short pressure line Install long pressure line	46
2	Apply Grease to Rack Set Rack into Housing Assemble Valve into Housing	47
3	Insert Rack Bearing Assemble Retaining Ring Install Pinion Nut Assemble Yoke and Lock Nut	43
4	Preset Yoke Calibrate Yoke Start R.H. Tie Rod	43
5	Start L.H. Tie Rod Torque Tie Rods	45
6	Assemble shipping plugs Install dust cover Install R.H. boot and clamp Install L.H. boot and clamp	44
7	Crimp clamps Apply label Center Gear Pack into shipping pallet	46
	Total:	314

Selecting DP1.3 to satisfy FR1.3- "Volume Flexibility" – FR1.3 is satisfied by DP1.3: "Various Operating Modes". An operating mode is a particular plan for managing the cell. The mode specifies the number of shifts per day, number of hours per shift, and number of workers per shift. As shown in figure 5, FR1.3 is further decomposed. Its subordinate FRs are FR1.3.1: "Support Takt Time from 49 to 91 seconds" and FR1.3.2: "Support extreme changes in demand". The corresponding Design Parameters are- DP1.3.1: "Number of workers = 7, 6, 5, 4, or 3" and DP1.3.2: "Number of shifts = 1, 2, or, 3."

DP1.3.1 allows the cell cycle time to be varied by varying the number of workers assigned to the cell. In the example, this allows the cell cycle time to vary from 47 seconds to 314 seconds. Table 6 summarizes the cell cycle times for various numbers of workers.

Table 6. Effect of DP1.3.1 (Number of Workers) on FR1.3.1 (Volume Flexibility)

Number of Workers	Cell Cycle Time (seconds)
1	314
2	157
3	104.7
4	78.5
5	62.8
6	52.3
7	47.0

DP1.3.2 indicates that by planning to operate the cell with 2 shifts for the expected demand, extreme changes in demand can be accommodated by adding or removing a shift of operation. By adding a shift, daily production will increase by 33%; and by removing a shift, daily production can be cut by 50%. Daily output could also be varied by adding overtime hours to each shift.

<u>Selecting DP1.4 to satisfy FR1.4: "Lean layout to support work loops"</u> – After defining the process (DP1.1), stations and machines (DP1.2), and Operating Modes (DP1.3), the next step is to develop a line layout that is conducive to work loops while minimizing the walking distance required by the workers. That is, to specify a DP to satisfy FR1.4. A common configuration for a lean cell is a "U" shape. In such a configuration, raw material enters one leg of the "U" and finished products exit the other. DP1.4 for the example will be the layout presented in Figure 6. The number of workers in the work loop could be varied from one to seven to achieve the cell cycle times indicated in table 6.

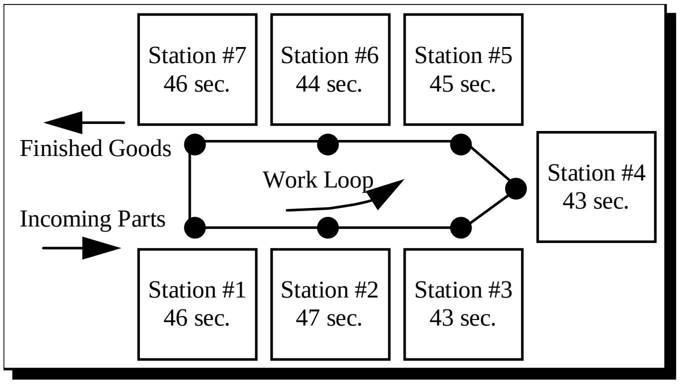
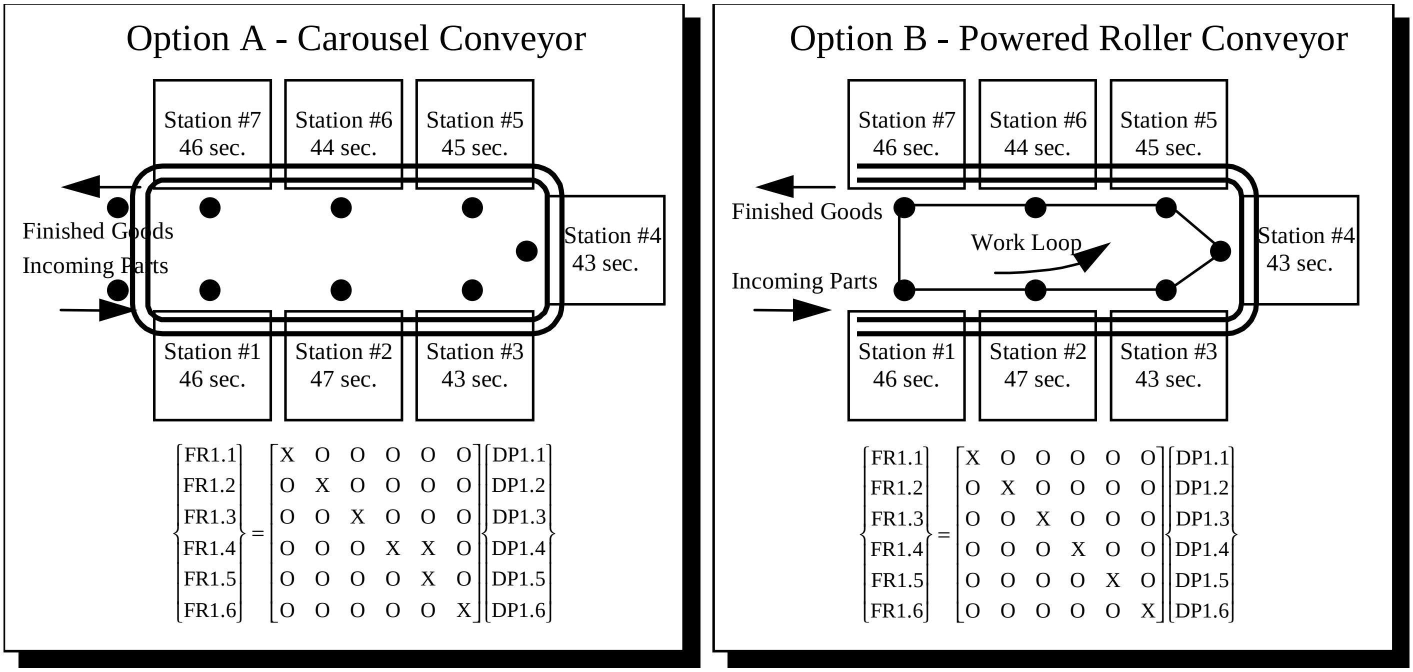


Figure 6. DP1.4- "U-shaped cell"

<u>Selecting DP1.5 to satisfy FR1.5: "Transport product from station to station"</u> – In any manufacturing system requiring the product to be moved from station to station, material handling of the product becomes a major concern. Depending on the system, conveyors and other material handling systems can make up a significant portion of the total investment cost. Material handling options also are important since they can cause coupling in the design. For instance, the selection of a particular material handling option may limit or control the layout of the system. When this is the case, a new material handling option (DP) must be chosen. The Axiomatic Design framework does not allow modification of FRs to accommodate a DP.

Coupling caused by a material handling selection can be illustrated with the Rack and Pinion Steering Gear assembly systems shown in Figure 7. One option for DP1.5 (Option A) is a traditional "carousel" type conveyor. This conveyor type is a continuous chain moving around the manufacturing system in a closed path. Option B is a system of powered rollers that does not require a closed loop. The difficulty with Option A is that


Option A - Carousel Conveyor

Option B - Powered Roller Conveyor

$$\begin{Bmatrix} FR1.1 \\ FR1.2 \\ FR1.3 \\ FR1.4 \\ FR1.5 \\ FR1.6 \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O & O \\ O & X & O & O & O & O \\ O & O & X & O & O & O \\ O & O & O & X & X & O \\ O & O & O & O & X & O \\ O & O & O & O & O & X \end{bmatrix} \begin{Bmatrix} DP1.1 \\ DP1.2 \\ DP1.3 \\ DP1.4 \\ DP1.5 \\ DP1.6 \end{Bmatrix}$$

$$\begin{Bmatrix} FR1.1 \\ FR1.2 \\ FR1.3 \\ FR1.4 \\ FR1.5 \\ FR1.6 \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O & O \\ O & X & O & O & O & O \\ O & O & X & O & O & O \\ O & O & O & X & O & O \\ O & O & O & O & X & O \\ O & O & O & O & O & X \end{bmatrix} \begin{Bmatrix} DP1.1 \\ DP1.2 \\ DP1.3 \\ DP1.4 \\ DP1.5 \\ DP1.6 \end{Bmatrix}$$

Figure 7. Analysis of two material handling options

it does not facilitate the unpacking of incoming parts and the packing of finished goods. This option requires workers on the outside of the line to perform these functions. As a result, the layout does not effectively support work loops, and coupling occurs between FR1.4 and FR1.5. Option B allows workers in the work loop to perform the unpack and pack duties and is therefore an uncoupled design.

CONCLUSION

This paper provides an Axiomatic Design framework for Manufacturing System Design and illustrates its use in designing assembly systems that are volume flexible. The proposed methodology forces the designers to first document the requirements and constraints of the manufacturing system. This Axiomatic Design approach mandates careful consideration and selection of the type of manufacturing system based upon the requirements of the total system. It also provides a structure for the identification and decomposition of the detailed design elements.

Too often plants begin the design process with the system type as an assumption or constraint. It is important to consider many factors when selecting the system type. Volume flexibility is one of these considerations. There are very few industries in which demand is constant or predictable. The selection of a manufacturing system that does not cost effectively accommodate swings in demand will lead to a competitive disadvantage. Manufacturing cells have been proven to accommodate uncertain demand by varying the number of workers assigned to the cell. Cells may not be applicable in every situation, but the authors believe that there are many unexplored applications where they hold great promise.

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