

# **Axiomatic Design of Manufacturing Systems**

# **Introduction to Manufacturing System**

**"What is a manufacturing system?"**

**"What is an ideal manufacturing system?"**

**"How should we design a manufacturing system?"**

**"Can a manufacturing system be designed in a rational way based on scientific principles?"**

# **Introduction to Manufacturing System**

**The design of manufacturing systems has an important effect on**

**Manufacturing productivity**

**Return on investment**

**Market share**

**Worker's satisfaction**

**Environment**

# **Introduction to Manufacturing System**

- Manufacturing systems consist of machines, materials, people, and information.**
- The goal of a manufacturing system is to improve customer satisfaction through improvements in the quality of products, short delivery time, and high labor productivity.**
- Manufacturing systems must be designed to satisfy a specific set of FRs and constraints.**

# Evolution of cost, quality and worker's satisfaction

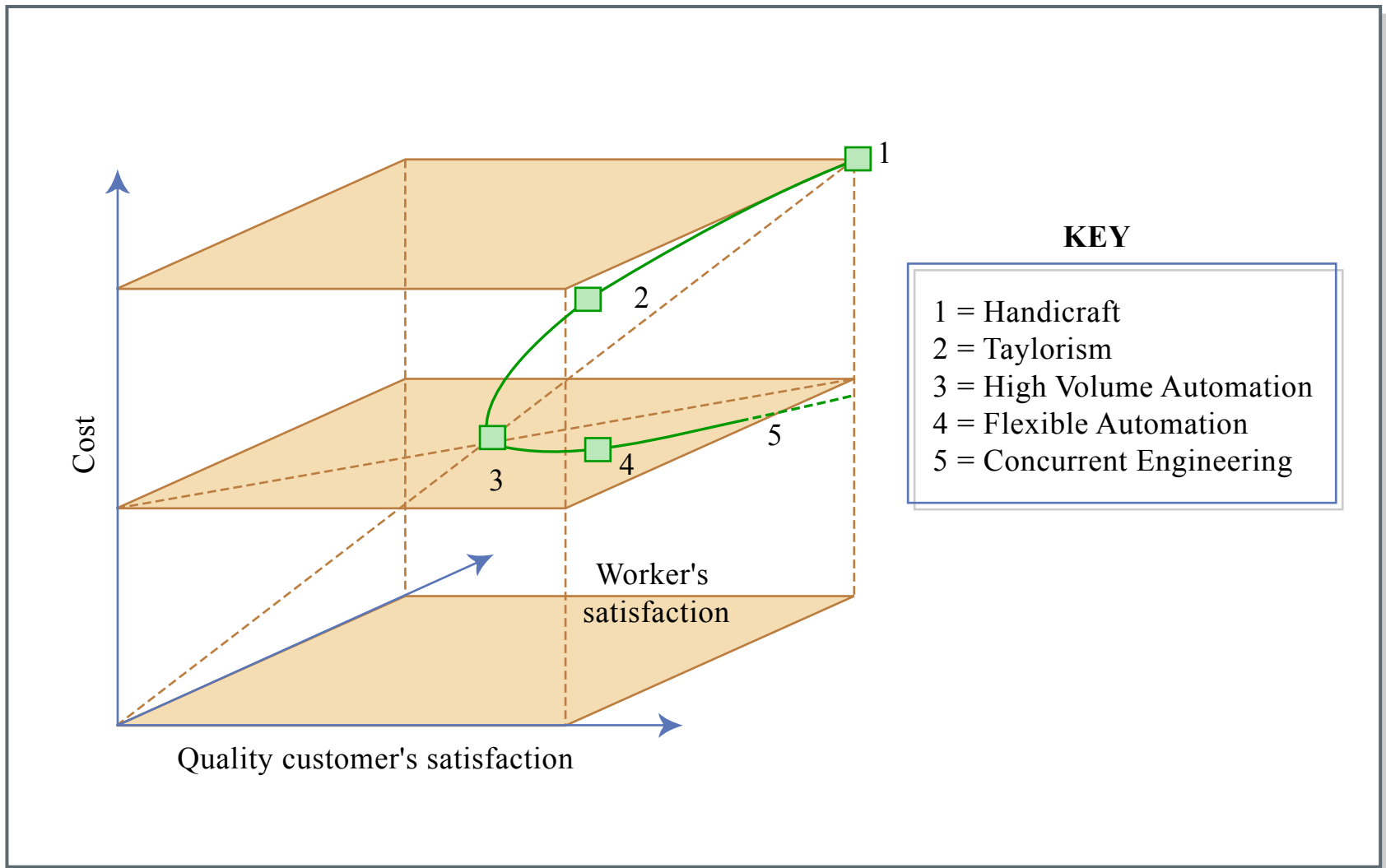


Figure by MIT OCW. After Sohlenius, 2005.

# Introduction to Manufacturing System

Is there "the" IDEAL MANUFACTURING SYSTEM?

**NO.**

**An ideal manufacturing system is not time-invariant!**

**The design of an ideal manufacturing system depends**

**Functional requirements (FRs)**

**Constraints (C).**

# **Introduction to Manufacturing System**

## **2. To reduce the capital investment**

**Mass production**

**Capacity planning for machines**

**Group technology**

**Transfer lines**

**Flexible manufacturing systems**

## **3. In recent years, to reduce the materials cost**

**Manufacturing system design**

**– Lean manufacturing system**

# Driving Forces for Manufacturing Systems

## (From Sohlenius 2005)

The 50's	The 60's	The 70's	The 80's	The 90's
Efficiency of manual labor	Efficiency of machine-tool utilization	Minimize capital cost for products in process  Order control customer adapt	Quality & productivity holistically	Customer, concurrent design, lean production, environment

Figure by MIT OCW.



# **Numerical Control Machine Tool in 1951**

**J. T. Parsons, (Traverse City, Michigan)**

**Small machine shop with milling machine and dial gages**

**U.S. Air Force funding of the Servo-mechanisms Lab (Gordon Brown, Jay Forrester, etc.)**

**Controversy on credit for NC machine tool development**

**Parsons received a National Technology Medal from President Ronald Reagan**

# Manufacturing Systems Concept proposed in 1960's by M. Eugene Merchant (1970)

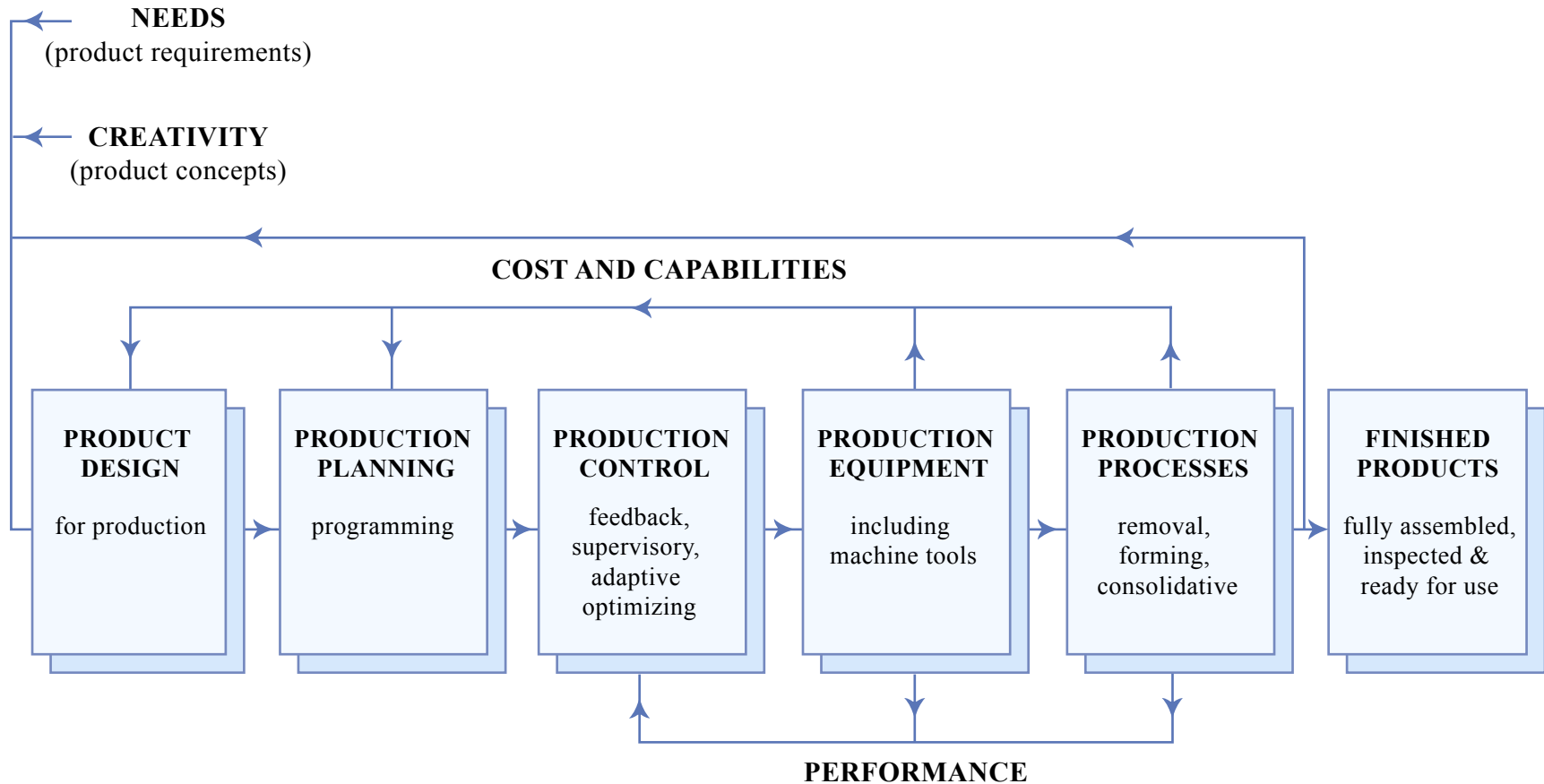


Figure by MIT OCW.

# **CIRP Definition of Manufacturing System**

**The manufacturing system is defined as “an organization in the manufacturing industry for the creation of production. In the mechanical and electrical engineering industries a manufacturing system in general has an integrated groups of functions: They are the sales, design, manufacturing production, and shipping functions. A research function may provide a service to one or more of the other functions.**

# **Introduction to Manufacturing System**

**FRs and Cs have been selected implicitly and intuitively and are affected by**

- 1. Cost structure of the manufacturing enterprise**
- 2. Available technologies**
- 3. Performance measurements**
- 4. Competitive factors**

# **Introduction to Manufacturing System**

**Historically the FRs of a manufacturing system have changed to deal with the most costly item in manufacturing.**

**1. At the beginning of the 20th century, labor cost was thought to be the dominant cost item.**

**To minimize the labor content.**

**Division of labor (F. W. Taylor)**

**More efficient and automated machines**

# Introduction to Manufacturing System

## The Effect of Competitive Factors on Manufacturing Systems

### 1. *Demand Rate >> Manufacturing Capacity*

Mass production – Henry Ford's era for automobiles

### 2. *Demand Rate << Manufacturing Capacity*

Flexible manufacturing system that responds to customer preference

# Introduction to Manufacturing System

- **How do societal changes affect the design of manufacturing systems?**
  - Globalization leading to specialization among nations
  - Environmental concerns leading to
    - Clean mfg operations
    - Life cycle issues
    - Re-manufacturing
- **Over-capacity of many consumer oriented products (cars, DRAMs, etc.)**
  - Supply exceeds the demand
  - Customer satisfaction
- **Customer demands**
  - Mass customization
  - Flexible manufacturing system

# Introduction to Manufacturing System

Much of the research in the field of manufacturing systems has been

1. To increase the efficiencies of existing operations and manufacturing processes
2. To optimize inventory levels
3. To maximize the utilization of manufacturing capacity

rather than through

*a rational design* of manufacturing systems.



# **Introduction to Manufacturing System**

**What are typical manufacturing systems?**

**Typically, manufacturing systems are classified in terms of the physical machine arrangement.**

**Production job shop**

**Transfer lines**

**Flow lines**

**group technology**

**Lean, linked cell manufacturing systems**

# **Introduction to Manufacturing System**

**The cost of most manufacturing systems varies depending on**

**Production volume**

**Degree of automation**

**Labor cost**

**Equipment costs**

**Location.**

# **Introduction to Manufacturing System**

**What is wrong with the way manufacturing systems have been designed in recent years?**

# Introduction to Manufacturing System

Two manufacturing systems that have two *identical sets of machines* may have *significantly different production rates and cost*, depending on the design of manufacturing system.

# **Basic Requirements of a Manufacturing System**

**A manufacturing system must be designed consistent with the design axioms to be most efficient and reliable.**

**In a "push" system, we must be sure that a decoupled system is created to maintain the independence of FRs.**

**In these machines, "decouplers" are used to create functional independence and satisfy various functional requirements while the part is subject to various processes in the manufacturing system.**

# **Basic Requirements of a Manufacturing System**

**For manufacture of random sets of different types of parts that require a number of different processes, a “pull system” appears to be the better than a “push system”.**

**In a "pull system", the production rate is gated by the rate at which the finished part leaves the manufacturing system.**

**The "pull" system is neither inherently better nor worse than a "push" system – it is simply a matter of having to satisfy different sets of FRs.**

## **Theorem 25 ("Push" System vs "Pull" System)**

**When identical parts are processed through a manufacturing system, a "push" system can be designed with the use of decouplers (that control queues) to maximize the productivity, whereas when irregular parts requiring different operations are processed, a "pull" system is the most effective system.**

# **Elements of Manufacturing Systems**

**What are the key elements of a manufacturing system?**

**A manufacturing system – a subset of the production system – consists of people, information and "things".**



# Elements of Manufacturing Systems

To make all these machines and people work together for the common goal of the system,

we must deal with

information -- *generation, collection, processing, transmission, and interpretation of information.*

Information is typically embedded in hardware and software.

It forms the interface between diverse elements of a manufacturing system, and integrates the functions of the system. Without the proper management of information, a modern manufacturing system cannot function.

# **Axiomatic Design of Fixed Manufacturing Systems for Identical Parts**

Highest-Level Design of a Fixed Manufacturing System

FR1 = Maximize the return on investment  
(ROI)

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**DP1 = Dedicated automated machine that can produce the desired part at the specified production rate.**

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Highest-Level Design of a Fixed Manufacturing System

**DP1 = Dedicated automated machine that can produce the desired part at the specified production rate.**

The FRs of the dedicated and automated machine may be written as

**FR11 = Process the wafers**

**FR12 = Transport the wafers**

# **Axiomatic Design of Fixed Manufacturing Systems for Identical Parts**

**FR11 = Process the wafers**

**FR12 = Transport the wafers**

**Corresponding DPs :**

**DP11 = Process modules**

**DP12 = Robots**

**Cs:**

**C1= Throughput rate**

**C2 = Manufacturing cost**

**C3 = Quality of the product**

**C4 = Yield (production of acceptable products divided by the total output)**

## **“Push system”**

**A conflict can arise  
in scheduling the robot motion  
if two processes are completed  
within the time it takes  
for robot to pick up and deliver a wafer  
(i.e., single robot motion).**

# Decoupling of processes from transport

Design equation

$$\begin{Bmatrix} FR11 \\ FR12 \end{Bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} \begin{Bmatrix} DP11 \\ DP12 \end{Bmatrix}$$

The original system was a coupled design.

# Decoupling of processes from transport

Design equation

$$\begin{Bmatrix} FR11 \\ FR12 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP11 \\ DP12 \end{Bmatrix} \quad (6.1)$$

Since this machine processes exactly identical parts, a "push" system may be designed, where the part will be supplied to the machine on a regular time interval T.



## “Push system”

Number of modules  $n_i$  needed for each process corresponding to T.

$$n_i = \text{Int} \frac{\tau_i}{T} = \text{Int} \left[ \frac{\tau_i}{\left( \frac{3,600}{m} \right)} \right] \quad (6.2)$$

where

**T = Cycle time**

**M = No. of wafers per hour**

## “Push system”

Total number of modules,  $n$ , required to process the wafers:

$$n = \sum_{i=1}^N n_i \quad (6.3)$$

where

$N$  is the number of tasks, i.e., processes.

## **“Push system”**

**Decompose FR12 (Transport the wafers) as**

FR121 = Decouple the process times

FR122 = Minimize the total process time  
 $T_C$  (or minimize the number of  
modules)

**The corresponding DPs are:**

DP121 = Decouplers with  $q$ 's

DP122 = The minimum value of  $T_C$

## “Push system”

Design equation

$$\begin{Bmatrix} FR121 \\ FR122 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP121 \\ DP122 \end{Bmatrix} \quad (6.4)$$

## “Push system”

Total process time  $T_c$

$$T_C = t_P + t_T + \sum_{i=1}^N q_i$$

where

$t_P$  is the total process time

$t_T$  is the total transport time.

## “Push system”

To minimize  $T_C$ , we must satisfy the following two conditions:

$$\begin{aligned}\sum_{i=1}^N \frac{\partial T_C}{\partial q_i} &= 0 \\ \sum_{i=1}^N \frac{\partial^2 T_C}{\partial q_i^2} &> 0\end{aligned}\quad (6.5)$$

where  $N$  = number of processes.

Since  $T_C$  is not a continuous function, we have to solve it approximately.

## **“Push system”**

### **Analytical Solution for Queues in Decouplers**

**Having designed the manufacturing system, we must replace those X's with mathematical expressions if they can be modeled.**

## “Push system”

$T_i$  = Time the wafer has to be picked up upon the completion of process  $j$  in Module  $i$

$$T_i = t_P + t_T \quad (6.6)$$

where

$t_P$  = total process time up to and including the  $i$ -th module  
 $t_T$  = accumulated transport time up to  $i-1$  (normalized times)



## “Push system”

$T_i$  (Time the wafer has to be picked up upon the completion of process  $j$  in Module  $i$ ), may be written as

$$T_i = t_P + t_T = \sum_{j=1}^i t_{P,j} + \sum_{j=1}^{i-1} t_{T,j} \quad (6.7)$$

**Note:** Total process  $t_P$  = sum of the individual process times,  $t_{P,j}$

Transport times,  $t_T$ , = sum of the all robot transport time,  $t_{T,j}$

## “Push System”

$n_R$  = number of pick-up moves the robot can make in a given period  $T$

$$n_R = \frac{T}{t_T} \quad (6.8)$$

## “Push System”

**Time  $\tau_i$**  -- measured from the beginning of each period --  
at which the robot has to pick up a wafer

$$\tau_i = T_i - \text{Int} \left( \sum_{j=1}^i t_{P,j} + \sum_{j=1}^{i-1} t_{T,j} \right) = \sum_{j=1}^i t_{P,j} + \sum_{j=1}^{i-1} t_{T,j} - \text{Int} \left( \sum_{j=1}^i t_{P,j} + \sum_{j=1}^{i-1} t_{T,j} \right) \quad (6.9)$$

where  $\text{Int}(x)$  is a function that rounds  $x$  down to the next nearest integer.

## “Push System”

$$T_1^* - T_1 = q_1$$

$$T_2^* - T_2 = q_1 + q_2$$

$$T_3^* - T_3 = q_1 + q_2 + q_3$$

*etc.*

## “Push System”

$$\tau_i^* - \tau_i = \sum_{j=1}^i q_j = a_{ij} q_j \quad (6.11)$$

where the matrix  $a_{ij}$  is defined as

$$a_{ij} = \begin{cases} 0 & \text{when } i > j \\ 1 & \text{when } i < j \end{cases}$$

## “Push System”

We can approximately determine  $\tau_i^*$  by solving Eq. (6.9), by determining where the decouplers may be needed, and by approximating the values of queues.

$$\{\tau_i^* - \tau_i\} = [a_{ij}] \{q_j\} \quad (6.12)$$

## “Push System”

$$\{q\} = [a]^{-1} \{\Delta\tau\} = \frac{1}{|a_{ij}|} [A] \{\Delta\tau\} = [A] \{\Delta\tau\} \quad (6.13)$$

where

$$\Delta\tau = \tau_i - \tau_i^*$$

$[a] \equiv$  matrix with elements  $a_{ij}$

$|a_{ji}| \equiv$  determinant of matrix  $[a] = \prod_{i=1}^N a_{kk} = 1$

$$[A] = Adj [a_{ij}] = [A_{ji}]$$

$$A_{ji} = (-1)^{i+j} M_{ji}$$

$M_{ji} \equiv$  minor of  $a_{ji}$

Equation (6.13) can be solved iteratively. To solve Eq. (6.13), we need to know  $\{\Delta\tau\}$ , which can be approximated by estimating reasonable values for  $\tau_i^*$  and by solving Eq. (6.9) for  $\tau_j$ . The value for  $\tau_j^*$  can be estimated by adding transport time to  $\tau_i^*$ , since  $|\tau_i^* - \tau_j^*| > t_T$ , for all  $j$ 's except  $j=i$ . The solution can be improved by successive substitution of the improved values of  $\tau_i^*$ . The determinant  $|a_{ij}|$  of the triangular matrix  $\{a\}$  is equal to the product of the diagonal elements.

Since the best solution is the one that makes the total cycle time  $T_C$  a minimum, we must seek for a set of values of  $q_i$  that yield a minimum value for the total queue,  $\Sigma q_i$ . When the precise control of processing time is critical, the queue  $q_i$  associated with the process should be set to equal to zero.

To solve Eq. (6.12) for the best set of queues  $q$ 's, Oh (1998) and Oh and Lee (1999) developed an optimization software program based on genetic algorithm. Multiplying these  $q$ 's by  $T$ , we can obtain actual values of queues.



## Example 6.1 Determination of the queues of a fixed manufacturing system that processes identical parts

Steps	Modules	Temp. (C)	Duration +- tolerance (Seconds)
1	A	35	50 + 25
2	B	80	45 +/- 0
3	C	10	60 + 20
4	D	50	70 +10
5	E	68	35 +/- 0

The process times in Modules B, and E must be precise because of the critical nature of the process. The cycle time is assumed to be the process time plus the transport time both for placement and pick-up of the wafer.

The robot must pick up the wafers from a supply bin (load-lock) and deliver it Module A and when the process is finished, it must pick up the container from Module G and place it on a cassette. These operations take 6 seconds each.

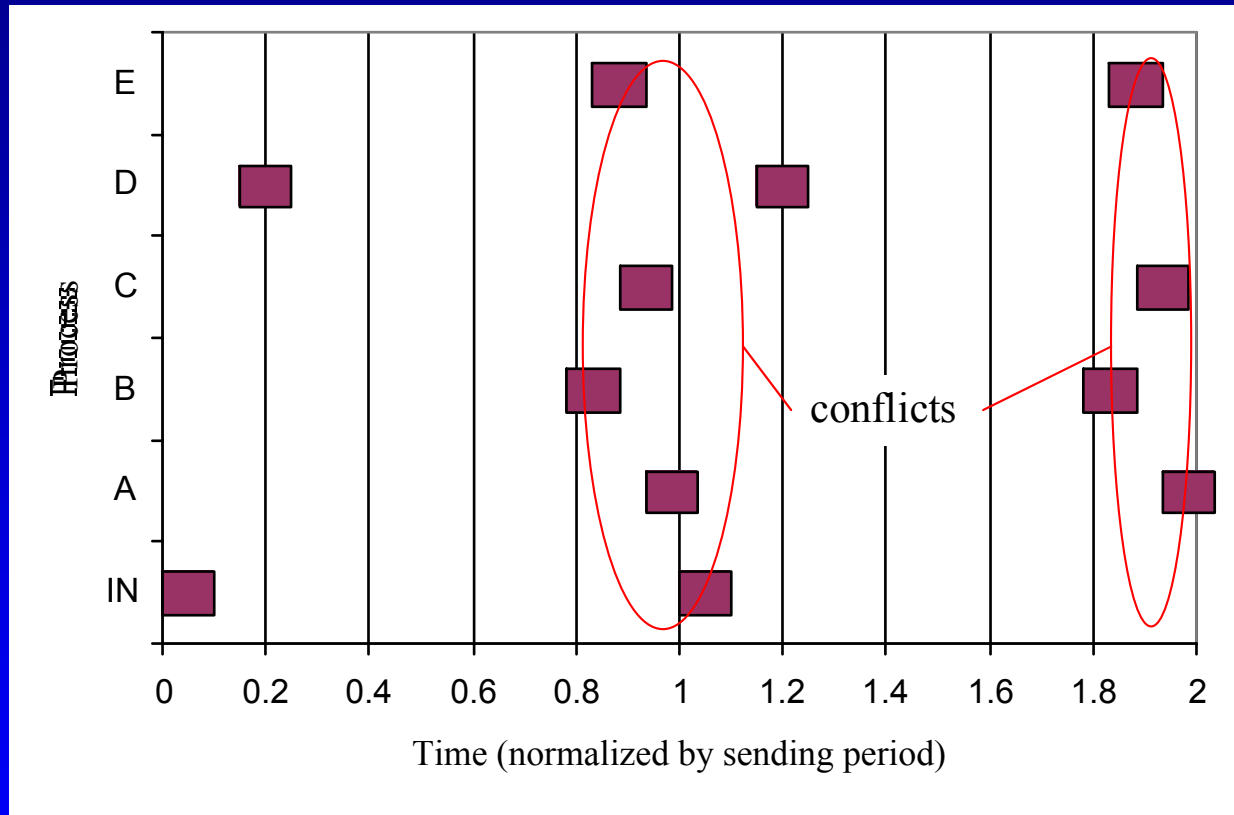
## Solution

The number of modules is dependent on the process time  $T_C$  and the desired throughput rate. The required number of modules is as follows:

<u>Modules</u>	<u>Number of Modules</u>
<b>A</b>	<b>2</b>
<b>B</b>	<b>1</b>
<b>C</b>	<b>2</b>
<b>D</b>	<b>2</b>
<b>E</b>	<b>1</b>

Without any decouplers, there are simultaneous demands for the service of the robot as shown in Fig. ex.6.1.a, which shows the time the process is finished in each of the modules within a given period  $T$ .

# Original Pick-up Time



The original pick-up time without any decouplers. There are conflicts among the transport demands from Modules A, B, C, E, and IN, since it takes the robot 0.1 normalized time to travel between the modules.

# “Push System”

## Solution for $q$ 's

The best solution was obtained by finding a set of values that give the shortest cycle time  $T_C$  solving Eq. (6.12) repeatedly and using a genetic algorithm. The solution yields the following values for  $q$ 's.

$$q_A = 19.7 \text{ sec}$$

$$q_B = 0 \text{ sec}$$

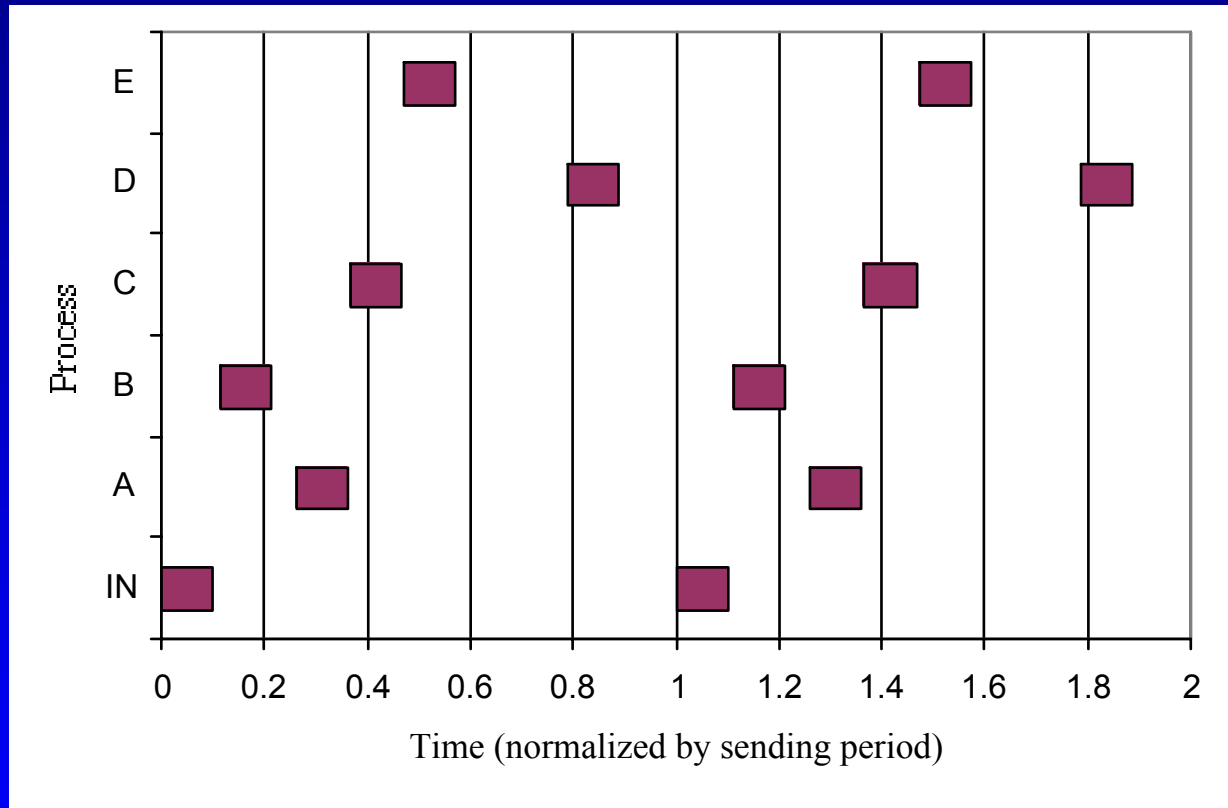
$$q_C = 9.3 \text{ sec}$$

$$q_D = 9.3 \text{ sec}$$

$$q_E = 0 \text{ sec}$$

The queues for B and E are zeros since the tolerance on these two modules is specified to be zero. Therefore, the queues of other modules have been adjusted to make these two queues to be zero.

# Decoupled Design for Pick-up Time



The actual pick-up time for Modules A, B, C, D, and E. A set of queues,  $q_A=19.7$ ,  $q_B=0$ ,  $q_C=9.3$ ,  $q_D=9.3$ , and  $q_E=0$ , are added to the original process times to resolve the transport conflicts. It takes the robot 0.1 normalized time to travel between the modules. Oh (1998) and Oh and Lee (2000).

## **“Push System”**

**One of the interesting results of this solution is that the number of combinations for part flow reduces down from several thousands to a few, because the parts flow through the manufacturing system along deterministic paths.**

**What the concept of decouplers has done is to change a combinatorial problem into a periodic function that repeats itself with a given cycle that is deterministic.**

# What is the main message of this section?

1. When identical parts processed by identical processes, we can use a “Push System”.
2. By decoupling a coupled design, we have reduced a problem that used to be treated as a combinatorial problem to a deterministic problem that can be solved "exactly"!
3. The number of possible combinations was reduced from several thousands to two! The throughput rate is also controlled precisely because the system has been designed with a given throughput in mind.
4. The decoupled design of a manufacturing system that processes identical parts can be modified without much effort.



# What is the main message of this section?

5. The shortcomings of the traditional approach to these problems such as operations research (OR) can be overcome by developing designs that satisfy the Independence Axiom.
6. The ideas presented in this section can be applied to a variety of system problems that involve design, analysis, and optimization.
7. The important message is that if the system design violates the Independence Axiom, it is extremely difficult to achieve the functional requirements of a manufacturing system.
8. This solution does not allow random variations in process times.

*How would you solve the problem with random variations?*