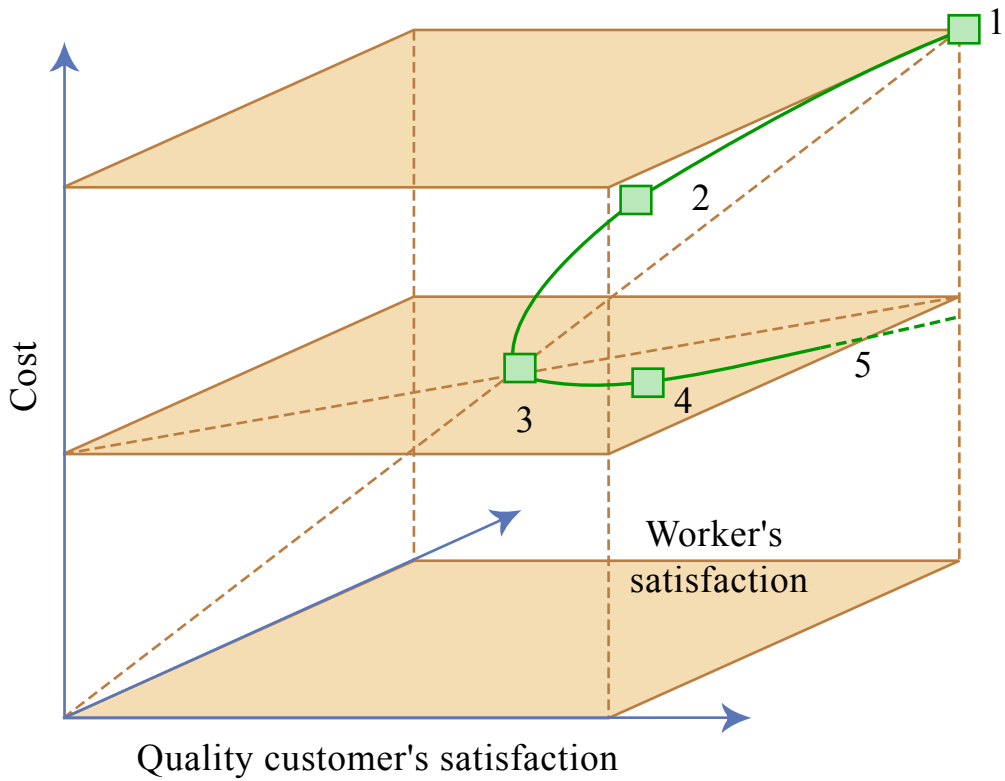
Chapter 6

Design of Manufacturing Systems II
"Pull System"

Evolution of cost, quality and worker's satisfaction: *1. Handicraft, 2.Taylorism, 3. High volume automation, 4. Flexible automation, 5. Concurrent engineering* (From Sohlenius, 2005)



KEY

1 = Handicraft
2 = Taylorism
3 = High Volume Automation
4 = Flexible Automation
5 = Concurrent Engineering

Figure by MIT OCW. After Sohlenius, 2005.

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)

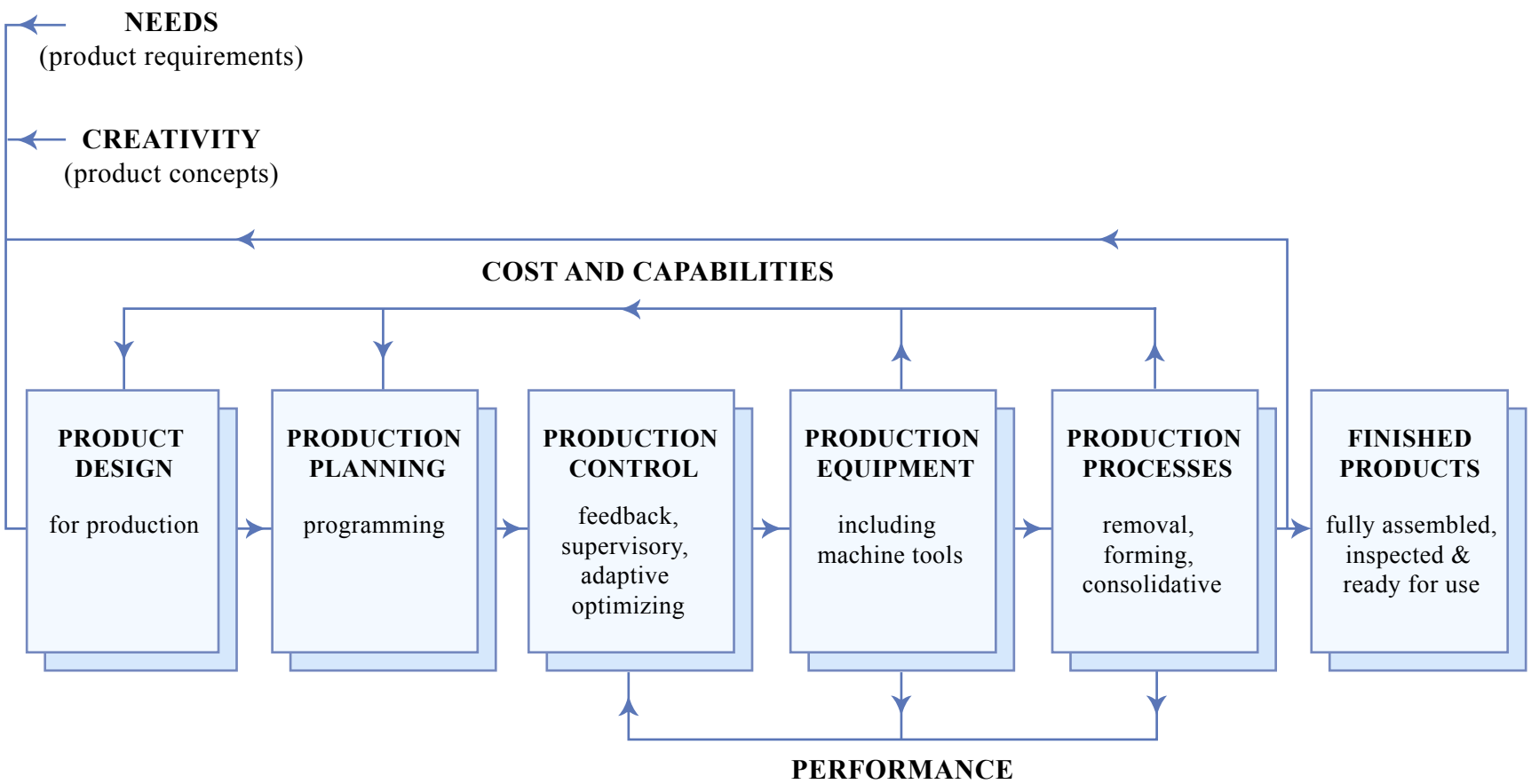


Figure by MIT OCW.

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

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.

Axiomatic Design Steps
for
a "Pull System"

Step 1. Choose FRs in the Functional Domain

FR1 = Maximize the return on investment (ROI)

$$ROI = \frac{Sales - Cost}{Investment}$$

Axiomatic Design Steps

Step. 2. Mapping of FRs in the Physical Domain to Determine DPs

$DP1^a$ = Manufacturing system to provide products at a minimum cost

or

$DP1^b$ = Manufacturing system design to provide products customers demand

Axiomatic Design Steps

Step 3. Decompose FR1 in the Functional Domain – Zigzagging between the domains

FR11 = Increase the sales revenue

FR12 = Minimize the manufacturing cost

FR13 = Minimize manufacturing investment

$$ROI = \frac{Sales - Cost}{Investment}$$

Axiomatic Design Steps

Step 4. Find the Corresponding DP1x's by Mapping FR1x's in the Physical Domain

Decomposition of $DP1^a$

$DP1^a1$ = Maximization of production output

$DP1^a2$ = Unit cost minimization

$DP1^a3$ = Machine utilization

Decomposition of $DP1^b$

$DP1^b1$ = Product design and manufacture to maximize customer satisfaction

$DP1^b2$ = Target production cost

$DP1^b3$ = Investment in production with a systems thinking approach

Axiomatic Design Steps

Step 5. Determine the Design Matrix

The second design represented by DP1^{a}x's satisfies FR1x.

$$\begin{Bmatrix} FR11 \\ FR13 \\ FR12 \end{Bmatrix} = \begin{bmatrix} 000 \\ XX0 \\ XXX \end{bmatrix} \begin{Bmatrix} DP1^{a}1 \\ DP1^{a}3 \\ DP1^{a}2 \end{Bmatrix} \quad (2)$$

Similarly, the second design represented by DP1^{b}x's satisfies FR1x.

$$\begin{Bmatrix} FR11 \\ FR12 \\ FR13 \end{Bmatrix} = \begin{bmatrix} X00 \\ XX0 \\ XXX \end{bmatrix} \begin{Bmatrix} DP1^{b}1 \\ DP1^{b}2 \\ DP1^{b}3 \end{Bmatrix} \quad (4)$$

Axiomatic Design Steps

Step 6. Zigzag

Decompose FR11, FR12 and FR13 by going from the Physical to the Functional Domain and determine the corresponding DPs (Level 3)

Step 6-a. Decompose FR11 (Increase the sales revenue) and DP11 (*Product design and manufacture to maximize customer satisfaction) *and determine DPs

FR111 = Sell products at the highest acceptable price

FR112 = Increase market share (volume)

DP111 = Customer perceived value of product improved

DP112 = Broad product applications

$$\begin{Bmatrix} FR111 \\ FR112 \end{Bmatrix} = \begin{bmatrix} X0 \\ XX \end{bmatrix} \begin{Bmatrix} DP111 \\ DP112 \end{Bmatrix} \qquad (6)$$

Axiomatic Design Steps

Step 6. Zigzag

$$SR = \sum_{i=1}^{n} (\mathrm{Price}_i \times Volume_i)$$

Step 6-a. Decompose FR11 (Increase the sales revenue) and DP11 (*Product design and manufacture to maximize customer satisfaction) *and determine DPs

FR111 = Sell products at the highest acceptable price

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(6)

$$\begin{Bmatrix} FR111 \\ FR112 \end{Bmatrix} = \begin{bmatrix} X0 \\ XX \end{bmatrix} \begin{Bmatrix} DP111 \\ DP112 \end{Bmatrix}$$

Axiomatic Design Steps

Step 6-b. Decompose FR12 (Minimize the manufacturing cost) and Determine DPs

FR12 (Minimize the production cost) may be decomposed with DP12 (Target production cost) in mind as

FR121 = Reduce material costs
FR122 = Reduce operational activity costs
FR123 = Reduce overhead

The corresponding DPs may be stated as:

DP121 = Target price given to suppliers
DP122 = Targeted performance of operational activities
DP123 = Right size business processes

The elements of the production cost are the cost of raw materials and components, the direct cost, indirect cost, and administrative costs or overhead.

Axiomatic Design Steps

Step 6-b. Decompose FR12 (Minimize the manufacturing cost) and Determine DPs

FR12 (Minimize the production cost) may be decomposed with DP12 (Target production cost) in mind as

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DP121 = Target price given to suppliers
DP122 = Targeted performance of operational activities
DP123 = Right size business processes

Design Matrix

$$\begin{Bmatrix} FR121 \\ FR122 \\ FR123 \end{Bmatrix} = \begin{bmatrix} X00 \\ 0X0 \\ 00X \end{bmatrix} \begin{Bmatrix} DP121 \\ DP122 \\ DP123 \end{Bmatrix}$$

Axiomatic Design Steps

Step 6-c. Decompose FR13 (Minimize manufacturing investment) and select DPs

FR13 (Minimize production investment) may be decomposed with DP13 (Investment in production with a system thinking approach) in mind as

FR131 = Acquire machines with cycle time ≤ the minimum takt time

FR132 = Ensure flexibility to accommodate capacity increments at lowest cost

FR133 = Develop flexible tooling

FR134 = Ensure flexibility to accommodate future products

Axiomatic Design Steps

FR131 = Acquire machines with cycle time *(less than or equal to)* the minimum takt time

FR132 = Ensure flexibility to accommodate capacity increments at lowest cost

FR133 = Develop flexible tooling

FR134 = Ensure flexibility to accommodate future products

The corresponding DPs may be stated as:

DP131 = Machine design focused on customer demand pace and value added work

DP132 = Linked cell manufacturing systems

DP133 = Flexible tooling design

DP134 = Movable machines and reconfigurable stations to enable new cell design

Axiomatic Design Steps

Step 6-c. Decompose FR13 (Minimize manufacturing investment) and select DPs

FR13 (Minimize production investment) may be decomposed with DP13 (Investment in production with a system thinking approach) in mind as

Design Matrix

$$\begin{Bmatrix} FR131 \\ FR132 \\ FR133 \\ FR134 \end{Bmatrix} = \begin{bmatrix} X000 \\ XX\ 00 \\ 00\ X\ 0 \\ 000\ X \end{bmatrix} \begin{Bmatrix} DP131 \\ DP132 \\ DP133 \\ DP134 \end{Bmatrix}$$

Axiomatic Design Steps

Step 7. Fourth Level Decomposition

Step 7-a. FR11 – Sales Revenue Branch

Functional requirement FR111 (Sell products at the highest acceptable price) must be decomposed with DP111 (Customer perceived value of product improved).

FR111 may be decomposed as follows:

FR1111 = Increase the appeal of products by providing desired functions and features

FR1112 = Increase the reliability of products

FR1113 = On time delivery (for a variety of products)

FR1114 = Decrease variation of the delivery time

FR1115 = Provide effective after sales service

Axiomatic Design Steps

Step 7. Fourth Level Decomposition

Step 7-a. FR11 – Sales Revenue Branch

The corresponding DPs are:

DP1111 = Design of high quality products that meet customer needs as specified by FRs and Cs

DP1112 = Robust design of products

DP1113 = Production based on actual demand

DP1114 = Predictable production output

DP1115 = Service network

The design equation and matrices are as follows:

$$\begin{Bmatrix} FR\ 1111 \\ FR\ 1112 \\ FR\ 1113 \\ FR\ 1114 \\ FR\ 1115 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ 0 & X & X & 0 \\ 0 & X & X & 0 \\ 0 & X & 0 & X \end{bmatrix} \begin{Bmatrix} DP\ 1111 \\ DP\ 1112 \\ DP\ 1113 \\ DP\ 1114 \\ DP\ 1115 \end{Bmatrix}$$

Axiomatic Design Steps

Step 7. Fourth Level Decomposition

FR112 (Increase market share (volume)) must be decomposed with DP112 (Broad product applications).

FR111 may be decomposed as follows:

FR1121 = Development of niche (new or custom) products

FR1122 = Development of multiple solutions within the product line

The corresponding DPs are:

DP1121 = Short product development process

DP1122 = Product variety

The design equation and matrices are as follows:

$$\begin{Bmatrix} FR1121 \\ FR1122 \end{Bmatrix} = \begin{bmatrix} X0 \\ XX \end{bmatrix} \begin{Bmatrix} DP1121 \\ DP1122 \end{Bmatrix} \qquad (10)$$

Axiomatic Design Steps

Step 7-b. FR12 – Production Cost Branch

FR 122 (Reduce operational activity costs) and DP122 (Target production cost) may be decomposed as

FR1221 = Reduce transport costs

FR1222 = Reduce setup costs

FR1223 = Reduce costs of manual operations (mach. load/unload, assembly, inspect.)

FR1224 = Reduce fabrication costs

FR1225 = Reduce maintenance costs

The corresponding DPs are:

DP1221 = Product-flow oriented layout

DP1222 = Setup performed with reduced resources

DP1223 = Effective use of the workforce

DP1224 = Fabrication parameters based on takt time to increase tool life

DP1225 = Total productive maintenance program

The design is an uncoupled design.

Axiomatic Design Steps

Step 8. Fifth Level Decomposition

Step 8-a. FR11 – Sales Revenue Branch

FR 1112 (Increase the reliability of products) and DP1112 (Robust design of products) may be decomposed as

FR11121 = Determine the lowest tolerable stiffness of the product

FR11122 = Determine the design range for manufacturing tolerance

FR11123 = Select manufacturing operations with a system range that is within the design range

The corresponding DPs are:

DP11121 = Mathematical model for stiffness determination

DP11122 = Mathematical model for derivation of design range for PVs

DP11123 = Selected machines with appropriate system range for PVs

The design equation and matrices are as follows:

$$\begin{Bmatrix} FR11121 \\ FR11122 \\ FR11123 \end{Bmatrix} = \begin{bmatrix} X00 \\ XX0 \\ XXX \end{bmatrix} \begin{Bmatrix} DP11121 \\ DP11122 \\ DP11123 \end{Bmatrix} \qquad (12)$$

The design matrix is triangular and thus, it is a decoupled design.

Axiomatic Design Steps

Step 8. Fifth Level Decomposition

Step 8-a. FR11 – Sales Revenue Branch

Functional requirement FR1113 (Decrease mean delivery time) must be decomposed with DP1113 (Production based on actual demand).

FR1113 may be decomposed as follows:

FR11131 = Produce at the customer demand cycle time (or takt time)
FR11132 = Produce the mix of each part type demanded per time interval
FR11133 = Be responsive to the downstream customer's demand time interval

The corresponding DPs are:

DP11131 = Linked-cell manufacturing system balanced to customer demand
DP11132 = Level production
DP11133 = Reduced response time across the production system

The design matrix

$$\begin{Bmatrix} FR11131 \\ FR11132 \\ FR11133 \end{Bmatrix} = \begin{bmatrix} X00 \\ 0X0 \\ XXX \end{bmatrix} \begin{Bmatrix} DP11131 \\ DP11132 \\ DP11133 \end{Bmatrix}$$

A Linked-cell Manufacturing System to Illustrate the Concept.

The machines are arranged in a cellular structure. In this figure, two workers are moving in two loops opposite to the flow of the work piece (Cochran, 1998).

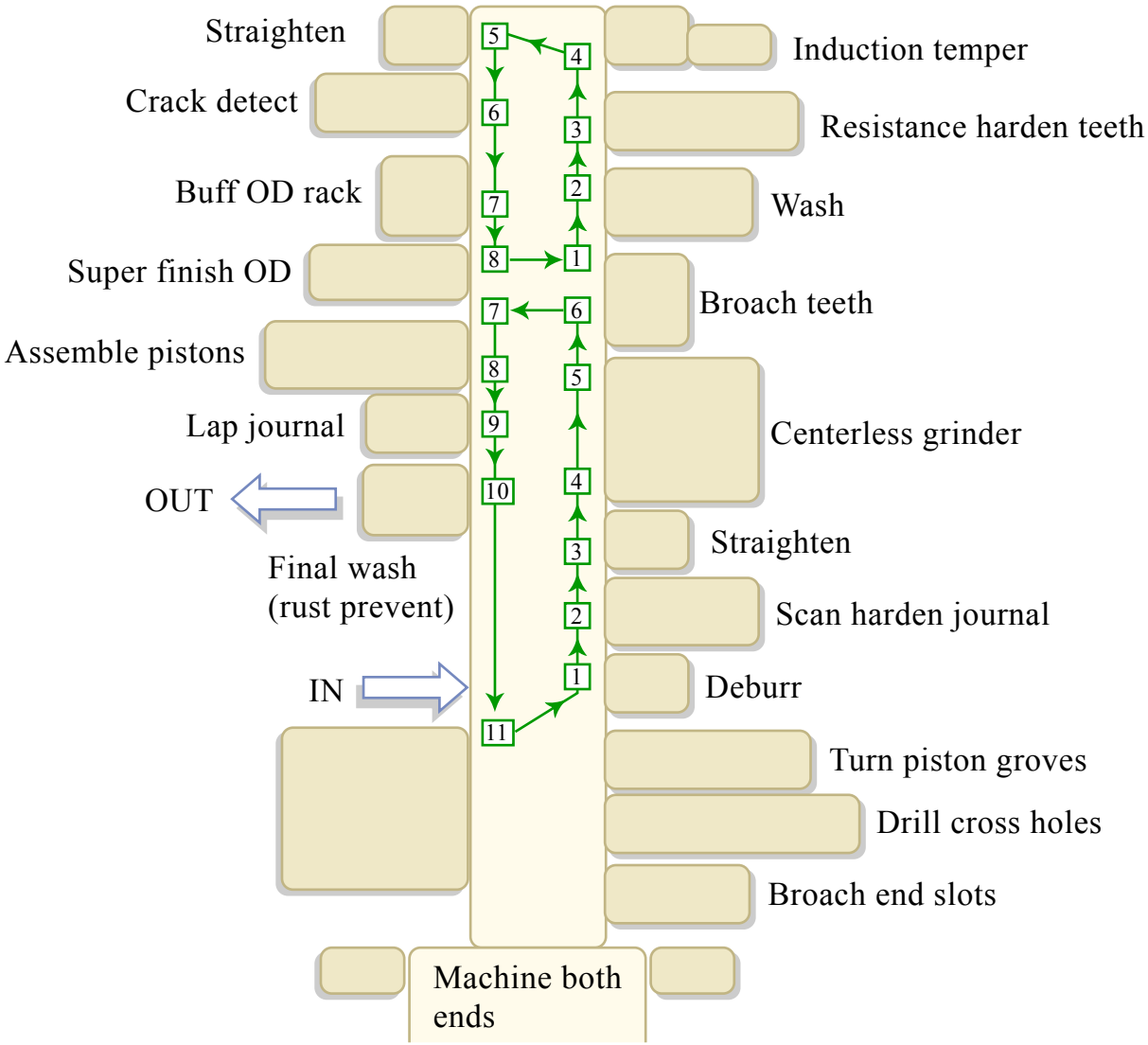


Figure by MIT OCW.

Axiomatic Design Steps

Step 8. Fifth Level Decomposition

Step 8-a. FR11 – Sales Revenue Branch

Functional requirement FR1114 (Decrease variation of the delivery time) and DP1114 (Predictable production output) must be decomposed.

FR1114 may be decomposed as follows:

FR11141 = Respond quickly to production problems

FR11142 = Produce with a predictable quality output

FR11143 = Produce with a predictable time output

The corresponding DPs are:

DP11141 = Visual control system to provide rapid response

DP11142 = Production with no defects and the ability to identify root cause

DP11143 = Predictable production resources

The design equation and matrices are as follows:

$$\begin{Bmatrix} FR11141 \\ FR11142 \\ FR11143 \end{Bmatrix} = \begin{bmatrix} X00 \\ XX0 \\ XXX \end{bmatrix} \begin{Bmatrix} DP11141 \\ DP11142 \\ DP11143 \end{Bmatrix} \quad (14)$$

Axiomatic Design Steps

Step 8. Fifth Level Decomposition

Step 8-b. FR12 – Manufacturing Cost Branch

FR 1223 (Reduce costs of manual operations (mach. load/unload, assembly, inspect.)) may be decomposed with DP122 (Effective use of the workforce) in mind as

FR12231 = Reduce tasks that tie the operator to the machine

FR12232 = Enable worker to operate more than one machine or station

FR12233 = Plan the resources to produce with different production volumes

The corresponding DPs are:

DP12231 = Machines & stations designed to run autonomously

DP12232 = Work-loops implemented in a cell layout

DP12233 = Standardized work-loops designed for different volumes

The design equation and matrices are as follows:

$$\begin{Bmatrix} FR12231 \\ FR12232 \\ FR12233 \end{Bmatrix} = \begin{bmatrix} X00 \\ XX0 \\ XXX \end{bmatrix} \begin{Bmatrix} DP12231 \\ DP12232 \\ DP12233 \end{Bmatrix} \quad (15)$$

Axiomatic Design Steps

Step 9. Sixth Level Decomposition: **FR11 – Sales Revenue Branch**

Functional requirement FR11131 (Produce at the customer demand cycle time (or takt time) and DP11131 (Linked-cell manufacturing system balanced to customer demand) may be decomposed as follows:

FR111311 = Define customers, parts, and volumes for each sub-system or cell within production

FR111312 = Design sub-system for a range of volume fluctuation

DP111311 = Configuration of sub-systems to enable flow at the ideal range of cycle times

DP111312 = Cell or sub-system designed to meet the minimum takt time

The design equation and matrices are as follows:

$$\begin{Bmatrix} FR111311 \\ FR111312 \end{Bmatrix} = \begin{bmatrix} X0 \\ XX \end{bmatrix} \begin{Bmatrix} DP11131 \\ DP11132 \end{Bmatrix} \quad (16)$$

Axiomatic Design Steps

FR11132 (produce the mix of each part type demanded per time interval) and DP11132 (Level production) may be decomposed as follows:

FR111321 = Produce in small run sizes
FR111322 = Convey in small and consistent quantities
FR111323 = Produce and supply only the parts needed

The corresponding DPs are:

DP111321 = Short setup time
DP111322 = Standard containers that hold small amounts of parts
DP111323 = Information system to produce only the parts needed (Pull system)

The design equation and matrices are as follows:

$$\begin{Bmatrix} FR111321 \\ FR111322 \\ FR111323 \end{Bmatrix} = \begin{bmatrix} X00 \\ XX0 \\ XXX \end{bmatrix} \begin{Bmatrix} DP111321 \\ DP111322 \\ DP111323 \end{Bmatrix} \quad (17)$$

This design is a decoupled design and thus, satisfies the Independence Axiom.

Axiomatic Design Steps

FR11133 (be responsive to the downstream customer's demand time interval) must be decomposed with DP11133 (reduced response time across the production system) in mind. FR11133 may be decomposed as

FR111331 = Reduce sub-system replenishment time to less than the customer demand interval.

FR111332 = Ensure that sufficient parts are available to satisfy the customer demand interval.

The corresponding DPs are

DP111331 = Elimination of wastes that cause excess lead-time

DP111332 = Standard work-in-process (swip) quantity of parts

The design equation and matrices are as follows:

$$\begin{Bmatrix} FR111331 \\ FR111332 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP111331 \\ DP111332 \end{Bmatrix} \qquad (18)$$

This design is a decoupled design and thus, satisfies the Independence Axiom.

Axiomatic Design Steps

FR11142 (produce with a predictable quality of output) must be decomposed with DP11142 (production with no defects and with the ability to identify root cause) in mind.

FR111421 = Ensure capable processes.
FR111422 = Decrease sources of variation due to multiple flow paths.
FR111423 = Prevent making defects throughout.
FR111424 = Do not advance defects to the next operation.

The corresponding DPs are:

DP111421 = Capable machines, equipment, tools, and fixtures
DP111422 = Single path through manufacturing system and external supplier (no parallel processing)
DP111423 = Use of standards and devices to prevent defects
DP111424 = Use of successive checks to detect defects if they do occur

The design equation and matrices are as follows:

$$\begin{Bmatrix} FR111421 \\ FR111422 \\ FR111423 \\ FR111424 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP111421 \\ DP111422 \\ DP111423 \\ DP111424 \end{Bmatrix} \quad (19)$$

Axiomatic Design Steps

Step 10. Seventh-Level Decomposition: FR11 – Sales Revenue Branch

FR111312 (design sub-system for a range of volume fluctuations) must be decomposed with DP111312 (sub-system designed to meet the minimum TAKT time) in mind.

FR1113121 = Select appropriate manufacturing process.
FR1113122 = Design manufacturing process cycle time at each station to meet minimum TAKT time.
FR1113123 = Design station fixtures to enable minimum TAKT time.

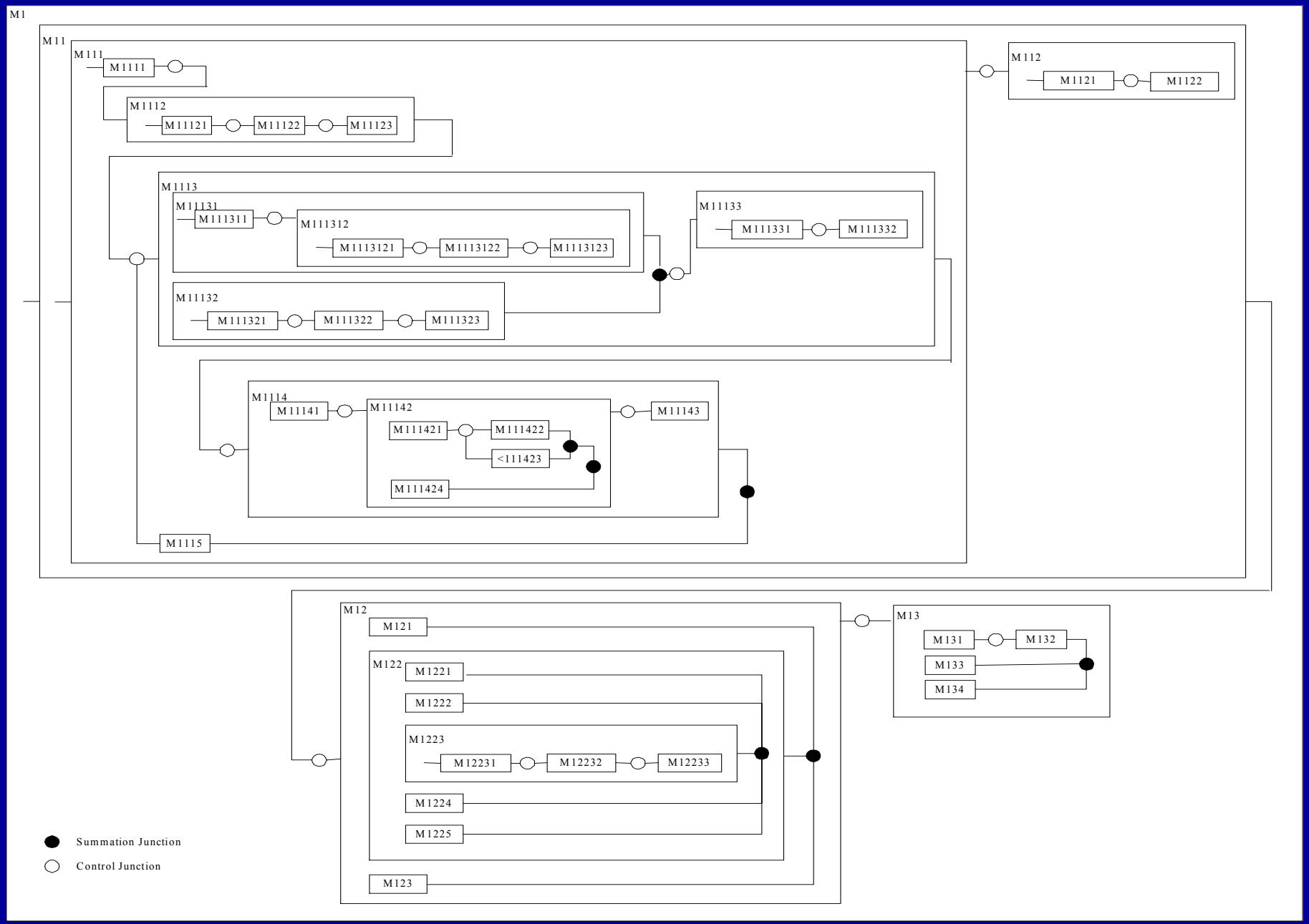
The corresponding DPs are:

DP1113121 = Physics of the manufacturing process
DP1113122 = Manufacturing process work content defined to be less than the minimum TAKT time
DP1113123 = Fixture design to provide quick load/unload (within required tolerance)

The design equation and matrices are

$$\begin{Bmatrix} FR1113121 \\ FR1113122 \\ FR1113123 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP1113121 \\ DP1113122 \\ DP1113123 \end{Bmatrix} \quad (20)$$

Flow Chart of the Manufacturing System Design



Use of the Flow Chart of the Manufacturing System Design

1. *Diagnosis*
2. *Engineering changes*
3. *Job assignment and management*
4. *Distributed systems*
5. *Software development*