Lean Manufacturing using Axiomatic Design

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Abstract – **The manufacturing system design is the topic of discussion in this paper. Numerous manufacturing system design methodologies have been proposed by researchers but most of them remain procedural which flow from top to down and rough to detail design. But none of the methodologies provide a link between what we want to achieve and how to achieve it. Similarly, various researchers have written in detail about various tools of lean manufacturing but not much literature can be found on a methodology of lean manufacturing design. In the absence of systematic implementation of components of lean manufacturing, the system fails to produce any good results. Using lean manufacturing principles as the basic functional requirements and following axiomatic design theory, a framework proposing the design requirements of the system is developed. The proposed framework is successfully used to implement lean manufacturing system in a manufacturing company.**

Keywords – **Axiomatic Design, Lean Manufacturing, Manufacturing system design.**

I. INTRODUCTION

The present economic meltdown is threatening the existence of many world class manufacturing companies the world over. The manufacturers are left with no option but to lower the prices (hence profits) of products in response to falling customer demand. This once again brings into focus the manufacturing systems like Lean Manufacturing and agile manufacturing to improve effectiveness and efficiency of the manufacturing system. Many companies have tried to implement these concepts with excellent results but many have failed too [Liker 1998]. Often companies try to implement peace meal solutions for lean manufacturing by implementing so called lean tools here and there without understanding prerequisites or objectives of lean tools. This results into incorrect order of implementation of lean tools. The manufacturing system designed in this manner will lack the synergetic effects of a well designed manufacturing system. The improvement of operations doesn't always lead to improvement of the systems [1]

The failure of companies in implementing the well understood lean concepts like kanban and cellular manufacturing highlights the need for manufacturing systems design methodologies [2]. Many system design methodologies have been proposed by various researchers. Manufacturing systems are hierarchical in nature [3].

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The majority of manufacturing system design methods develop a physical hierarchy e.g. plant level, department level, station level [4]. Many system design procedures follow a top down approach in designing a system. The main short coming in all these methods is that it doesn't link design of system with objectives. Shingo describes the mechanisms of Toyota Production system but doesn't provide the frame work showing dependencies of various mechanisms on each other to get the synergetic effect. Monden provides a functional hierarchy, which highlights how different concepts of lean manufacturing build on each other to achieve the objective of low cost manufacturing [5]. But this hierarchy is not related to physical entities but to functions like quality control, lead time, and flexible work force. Many production system design approaches provide a top down procedure for systems design. But system design procedures guide the design process of physical entities but do not provide a clear structure of system objectives which results into local optimization at the cost of overall cost effectiveness [6]. There is plethora of literature on various techniques of cell formation, use of value stream mapping in the analysis of current situation and as a road map for future design of lean manufacturing system, kaizen as a method of achieving lean and simulation as a tool of system design. But there is lack of literature on lean manufacturing system design from systems design perspective.

An axiomatic design methodology was developed by Dr. Nam P. Suh in late 70's. The axiomatic design method provides a link between what we want to achieve and how would we achieve it. This paper presents the use of Axiomatic design for Lean manufacturing system design. An application of axiomatic design for lean manufacturing system design has been illustrated with the help of an industrial case study.

II. AXIOMATIC DESIGN

Axiomatic design defines design as the creation of synthesized solutions in the form of products, processes or systems that satisfy the perceived needs through mapping between functional requirements (FRs) and design parameters (DPs) [7]. The functional requirements represent the goals of the design or what we want to achieve. FRs are defined in the functional domain. FRs are derived from the customer needs from the customer domain. In order to satisfy the functional requirements Design parameters (solutions) are specified in the physical domain. Axiomatic design thus provides a link between what we want to do and why we want to do it. It guides the designer to solve a particular functional requirement by specific means rather than focusing on the means itself. The above discussion can be summarized as shown in Figure 1.

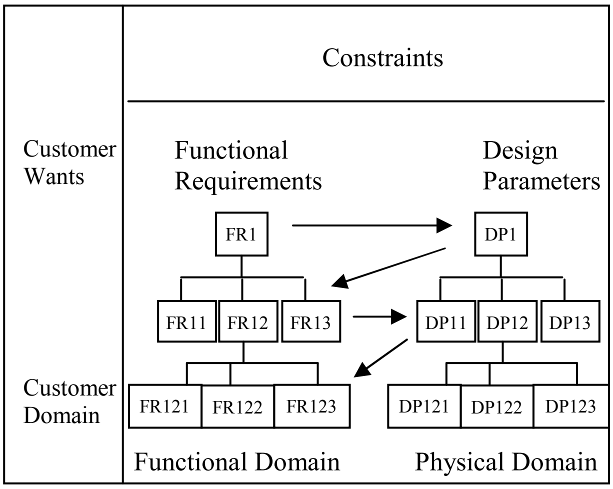

Figure 1 Axiomatic Design Approach [8]

Axiomatic design is a process of determining DPs to satisfy the FRs. Two axioms are used in order to select the best possible physical design:

1. Independence Axiom: The Design parameter chosen to satisfy a particular functional requirement should not affect the other functional requirements. [5]. If no DP affect more than one requirement the design is said to be uncoupled design. It helps in independent implementation of functional requirement.
   Mathematically the relationship between FRs and DPs are expressed as,
   (FR)= | A | (DP)
   Where FR is functional requirement Vector
   DP is the design Parameter Vector
   | A | is the design matrix that characterizes the design.
   Each A_{ij} of | A | relates the ith FR to jth DP.
   In order to satisfy independence axiom, the design matrix must be either diagonal or triangular matrix representing uncoupled or decoupled designs respectively.

2. Information Axiom: Minimize the information content of the design. In other words simpler designs are better than the complex designs.

Mapping & Decomposition: The axiomatic design approach involves mapping through four design domains. In the customer domain the customer wants are defined. The customer wants are translated into Functional requirements in the Functional domain. FRs are then mapped to Design Parameters in the physical domain. The Design Parameters are the physical solutions through which the functional requirements are met. Finally DPs are mapped to Prcess variables in the Process Domain. Only mapping between functional domain and physical domain are needed for manufacturing system design.

The process of decomposition establishes a design hierarchy based upon the selection of DPs to satisfy the FRs at increasingly refined levels of details. To advance to the next level of detail in decomposition requires the fulfillment of the Independence Axiom. Once a set of DPs has been determined at one level of decomposition, the next step is to decide if further decomposition to another level of FRs and DPs is necessary. The Mapping & Decomposition process is illustrated in Fig 1. If a DP affect more than one FR or a FR requires two DPs, this kind of design is called partially coupled or decoupled design. An uncoupled design is the best design, in which one DP affects only one FR. But partially coupled designs also satisfy the requirement of independence axiom if DPs are implemented in particular order. The DP which affect most of the FRs is implemented first followed by the DP which affect second most number of FRs and so on. The consequence of the uncoupled or decoupled design is that it implicitly prepares the sequence in which various DPs (lean tools) must be implemented avoiding the iteration process to achieve the benefit of FR. The above discussion can be summarized by figure 2.

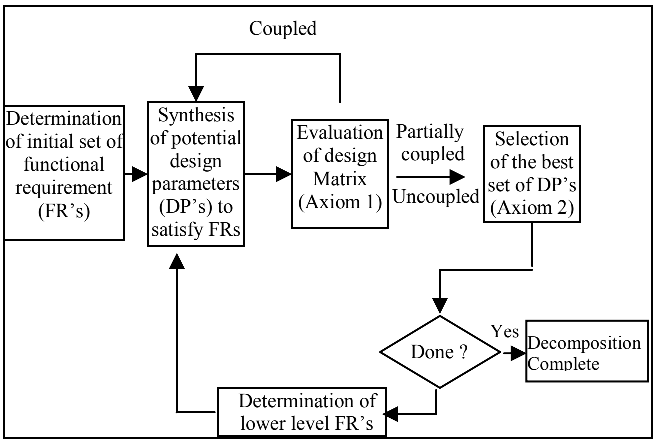

Figure 2 Simplified Axiomatic Design Decomposition Process [9]

III. DEVELOPMENT OF LEAN MANUFACTURING SYSTEM USING AXIOMATIC DESIGN APPROACH

The first functional requirement of the company was
FR1: Manufacturing system capable of meeting customer demand in cost effective way
DP1 : Lean Manufacturing system
Keeping in view of constraint of minimum investment in new machinery, Lean Manufacturing system was selected as the Design parameter to satisfy FR1. The justification was to eliminate waste and increase production to the level of demand.
Second level of FRs and DPs
The requirements of lean manufacturing system are
FR11: Create a predictable output (for Zero inventory)
FR12: Create continuous flow (customer order lead time reduction)
FR13: Just in Time
The corresponding DPs are,
DP11: Standardized work
DP12: Connect processes with same volume requirements

DP13: Create a pull system

The decoupled design equation for this matrix may be written as

$$\begin{Bmatrix} FR12 \\ FR11 \\ FR11 \end{Bmatrix} = \begin{pmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{pmatrix} \bullet \begin{Bmatrix} DP12 \\ DP11 \\ DP13 \end{Bmatrix}$$

DP11 standardize work can not be done until the manufacturing line has been redesigned. So, DP12 should be implemented before DP11. It gives the sequence of implementation.

Third Level of FRs and DPs:

The design solutions need to be decomposed further.

FR12 will be decomposed further to see the functional requirements to achieve continuous flow.

FR12 Continuous Flow

FR121: Jidoka: More than one machine per operator
FR122: Man power flexibility
FR123: Eliminate or reduce inventory between Operations/Machines

FR11 Create Predictable output

FR111: Identify Production rate
FR112: Determine the number of Operators
FR113: Determine sequence each worker will work within takt time

FR13 Create pull system

FR131: Control Start/ Stop of machine as per demand
FR132: Make consistent quantity.

By zig zagging between the Functional domain and Physical domain, the DPs of third level were identified.

DP12: Connect process with same volume requirements

DP121: Multi Functional Workers
DP122: U shaped layout of machines
DP123: Single piece flow

FR121 require cross training of employees for multi tasking on machines. Man power flexibility means that depending on the demand number of operators can be increased or decreased. To enable this, the work stations or machines should be arranged in U layout so that work can be redistributed between operators easily. To eliminate inventory between operations, single piece flow system need to be implemented.

The correct sequence of implementation of DPs will be DP121, DP122 & DP123. Because, the workers need to be trained before they start working on cell manufacturing in U shape layout. The single piece flow can not be implemented unless the machines are arranged in a cellular layout. The design matrix of FRs referring to FR12 and DPs referring to DP12 is as following

$$\begin{Bmatrix} FR121 \\ FR122 \\ FR123 \end{Bmatrix} = \begin{pmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & 0 & X \end{pmatrix} \bullet \begin{Bmatrix} DP121 \\ DP122 \\ DP123 \end{Bmatrix}$$

The design parameters to satisfy the FR111, FR112 & FR113 are,

DP111: Determine takt time
DP112: Manual time required to produce one part divided by takt time
DP113: Create standardized operation routine worksheet.

Using the method used above and the principles of lean manufacturing the design is decomposed to the level after which no further decomposition is possible. Due to shortage of space the full decomposition can not be explained in this paper. The fully decomposed Design solution looks as shown in figure 3

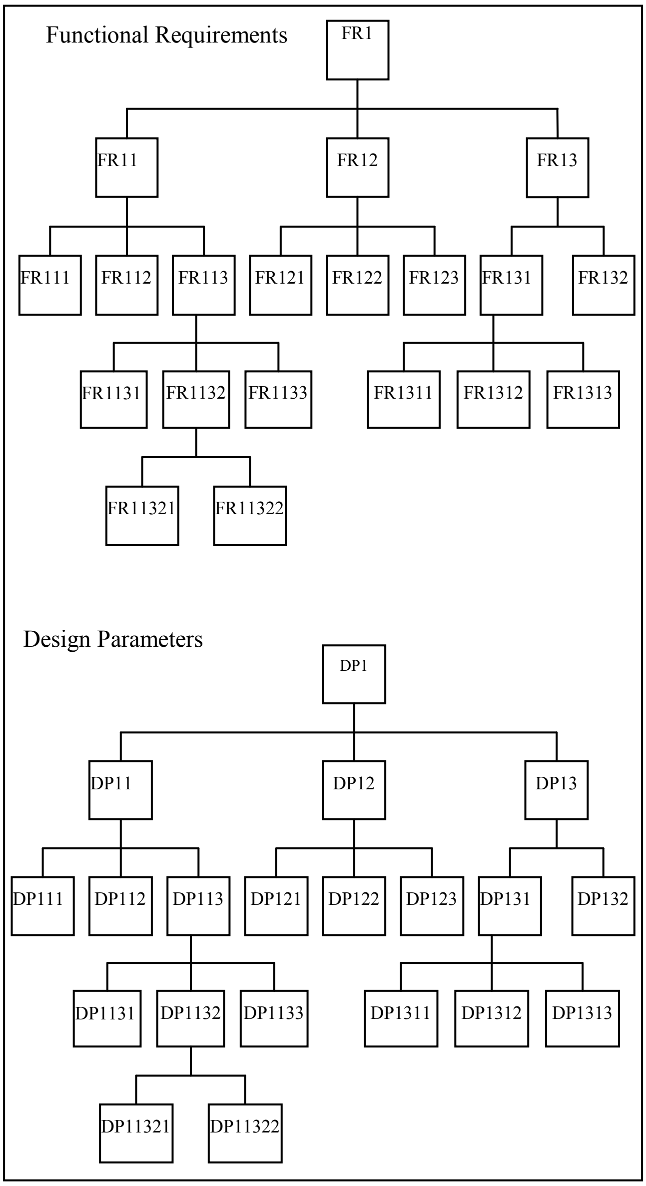

Figure 3 Decomposition of FRs & DPs

The tree structure shown in the table 1 shows all the FRs and corresponding DPs decomposed to the lowest level.

IV. CASE STUDY

The FRs in the decomposition developed in the previous section of the paper, indicate the requirements of a lean manufacturing system and the DPs suggest what need to be done to fulfill those requirements. Using this decomposition as the reference the manufacturing system of a leading The case study is about the implementation of 'plastic injection molded auto-parts' manufacturer of India was redesigned.

It is a fast growing medium sized company, with a turnover of $8 million and 200 employees on its pay rolls. The company supplies plastic injection molded components as well as assemblies to leading auto manufacturers and consumer goods manufacturers of India. Apart from other products the company manufactures air cleaner for 'TVS victor' motor bike. The company was experiencing problems in meeting the customer demand for the product 'Victor Air Cleaner' which was growing steadily. The product consisted of injection moulded Air Cleaner body and injection moulded cover assembled together with number of bought out parts.

The company was already running 3 shifts/day. The demand could not justify in investing in two more injection moulding machines and air cleaner case and cover moulds. So, the goal of the company was to meet the customer demand in cost effective way without considerable investment in machines and injection moulds. As a first step, the manufacturing system of the company was analysed using the value stream mapping technique, various tools of methods study and work measurement. The current state value stream map was as shown in the figure 4.

Table 1 Tree structure of FRs and DPs

Detailed Tree structure showing all the FRs and Corresponding DPs			
FR1	Manufacturing system capable of meeting customer demand in cost effective way	DP1	Lean Manufacturing system
FR11	Create a predictable output	DP11	Standardise work
FR111	Identify production rate	DP111	Determine takt time
FR112	Determine number of operators	DP112	Manual time/Takt time
FR113	Determine sequence each worker will work within takt time	DP113	Create standardized operation routine worksheet
FR1131	Reduce manual operation time	DP1131	Eliminate operations without added value
FR1132	Reduce Worker's movement	DP1132	Eliminate wasted movement
FR1133	Reduce Machining cycle time	DP1133	Eliminate non value added machining time
FR11321	Reduce Walking time	DP11321	Move machines/stations closer
FR11322	Reduce Material Handling time	DP11322	Place material at point of use
FR12	Create Continuous Flow	DP12	Connect process with same volume requirements
FR121	Jidoka: Separate machines from workers	DP121	Multi functional workers
FR122	Man power flexibility	DP122	U shaped layout
FR123	Reduce inventory between stations	DP123	Units from one operation to the next one by one
FR13	Produce what is needed and when is needed	DP13	Pull system
FR131	Control start time of Machine	DP131	Kanban Delivery
FR132	Make consistent quality	DP132	Kanban Quantity
FR1311	Authorise production of standard container	DP1311	Production ordering kanban
FR1312	Authorise preceding cell to replenish demanding cell	DP1312	Withdrawal Card (Internal Move card)
FR1313	Authorise supplier cell to replenish customer plant's cell	DP1313	Withdrawal Card (Supplier Move card)

The value stream map shows the process flow, information flow, material movement and cycle times. The present system was compared to the proposed system developed by axiomatic design. The in complacencies were identified and changes to be done were identified. The DPs which can't be decomposed to another level represent the definite tasks which need to be completed if not already done. So, DP123, DP122, DP121, DP11321, DP11322, DP1132, DP1131, DP132, DP1311, DP1312, DP1313 were selected to be implemented. The sequence of implementation was decided from the design matrix.

The table 2 below gives details of how the respective DPs were implemented.

ISBN: 978-988-17012-5-1

Table 2 Details of action taken

Design Parameter	Tasks	Actions
DP123	Units from one operation to the next one by one	Cell was formed to facilitate single piece flow as shown in figure 5
DP122	U shaped layout	Not required as cell requires only two operators
DP121	Multi functional workers	All workers given training on operating automatic injection moulding machines and assembly tasks
DP11321	Move machines/stations closer	The Injection moulding machines and assembly work stations moved closer
DP11322	Place material at point of use	Special trolleys designed to contain shift's requirement of parts used in assembly. One trolley positioned in cell and other in store for replenishment.
DP1132	Eliminate wasted movement	Injection moulding and assembly brought together to eliminate material movement and men movement between assembly and moulding. Material handlers appointed to move material rather than being moved by assembly operators
DP1131	Eliminate operations without added value	Assembly operation was analysed using method study. A fixture was designed to complete a particular assembly task. Packing of air cleaners discontinued as it wasn't found to be adding any value to air cleaner.
DP1311	Production ordering kanan	
DP1312	Withdrawal Card (Internal Move card)	Kanban system designed and implemented
DP1313	Withdrawal Card (Supplier Move card)	

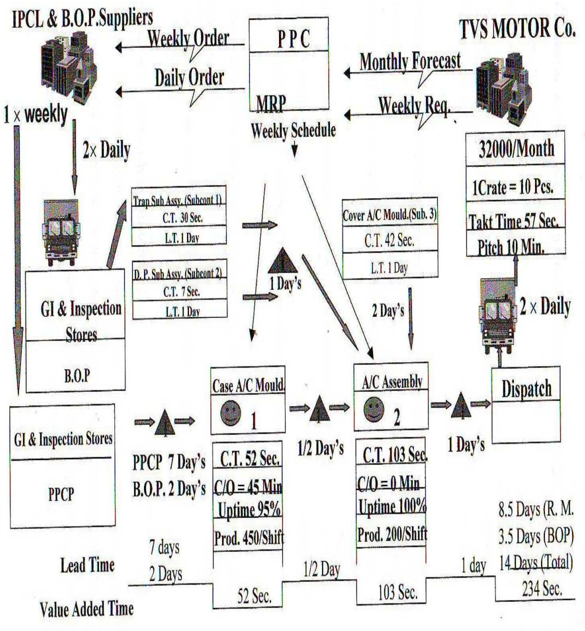

Figure 4 Value Stream Mapping of current state

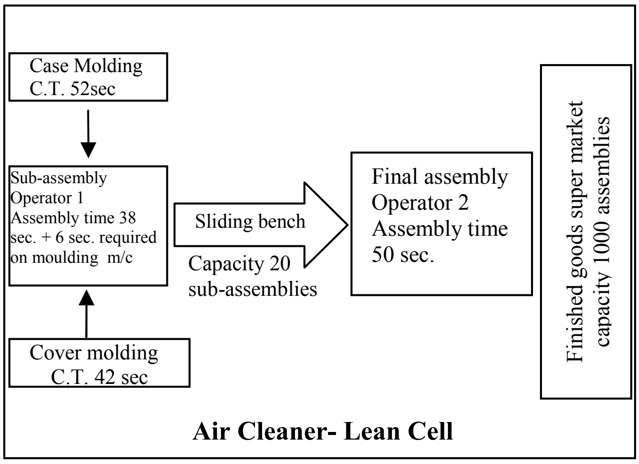

Figure 5 Design of Lean Cell

V RESULTS

The following results were achieved after implementing lean manufacturing system,

- Production increases from 200 assemblies/operator/shift to 250 assemblies, therefore a productivity rise of 25% due to elimination of various waste activities.
- Finished goods inventory reduces by half.
- Bought out parts inventory reduces by half.
- Negligible work-in-process inventory.
- Space saving of approximately 20 m^2 due to cell formation and inventory reduction.
- Better production control due to kanban.
- Defect free production due to single piece flow.

The company's objective of meeting the customer demand was fulfilled without investing in new machinery.

VI. CONCLUSIONS

Axiomatic design approach for manufacturing system design has been discussed. A framework of lean manufacturing system was developed, which correlates the tools of lean manufacturing (what) to why. The better understanding resulting from this helps in the systematic and effective implementation of lean manufacturing. The decoupling requirement of design matrix also suggests the sequence of implementation.

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