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AN IMPLEMENTATION METHODOLOGY FOR TRANSITION FROM TRADITIONAL MANUFACTURING TO CELLULAR MANUFACTURING USING AXIOMATIC DESIGN

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ABSTRACT

This paper provides a framework and a road map for people who are ready to transform their traditional production system from process orientation to cellular orientation, based on Axiomatic Design (AD) principles. A feedback mechanism for continuous improvement is also suggested for evaluating and improving the cellular design against pre-selected performance criteria. A complete implementation of the proposed methodology at a local manufacturing company and resulting performance improvements are also provided.

Key words: Axiomatic Design, cellular manufacturing, implementation guide, conversion to cellular manufacturing, and lean manufacturing

1 INTRODUCTION

In today's highly competitive world, customer needs are becoming more important than ever before [Nicholas (1998)]. This new paradigm brought forth the importance of AD principles, which brings the customers needs to the forefront in system reengineering processes.

The ultimate goal of AD is to establish a scientific basis for design and to improve design activities by providing the designer with a theoretical foundation based on logical and rational thought processes and tools [Suh (2001)]. In accomplishing this goal, the AD provides a systematic search process through the design space to minimize the random search process and determine the best design solution among many alternatives.

Many AD applications in designing products, systems, organizations and software have appeared in the literature in the last 10 years. AD theory and principles have been introduced first time by Suh (1990). Kim et. al. (1991) applied AD principles on software design. AD principles have also been used in design of quality systems [Suh (1995)] and general system design [Suh (1995c, 1997a)]. Suh and Cochran (1998) provided a manufacturing system design using AD principles. AD principles have also been applied in designing flexible manufacturing systems [Babic (1999)].

With this work we provide a framework and a road map for people who are ready to transform their traditional production system from process orientation to cellular orientation, based on AD principles. In addition, a feedback mechanism for continuous improvement is also provided for evaluating and improving the cellular design against pre-selected performance criteria (see Figure 1).

Selection of project team, ensuring broad-based participation, analysis of current conversion process, and determining conversion strategy for transition to cellular manufacturing constitute the first stage of our proposed methodology [Silveira (1999)].

The design of the cellular manufacturing system starts following the preliminary stage. At this stage the AD approach to cellular manufacturing is presented to the transition and design team in a systematic and scientifically sound order. These guidelines, which are developed, based on the Independence Axiom, provide necessary steps in transforming an existing process oriented system into a cellular manufacturing system. With this systematic approach the designer will be guided by our methodology for appropriate analysis techniques.

Transition to cellular manufacturing follows after all cellular manufacturing steps are successfully completed. At this stage, the production is achieved through cellular manufacturing system. System is now generating necessary databases and information for comparing the system performance with set target goals on some business metrics. Based on target values and achievements, new target values are established and appropriate system modifications and changes are affected through cellular manufacturing system improvement principles provided in our proposed procedure. These principles are also based on AD Principles. This continuous feedback and improvement principles are also in agreement with the spirit of lean manufacturing and Kaizen activities.

In this paper we provide a complete set of Functional Requirement-Design Parameter (FR-DP) hierarchy for the design of a cellular manufacturing system through AD principles. This corresponds to the second box (Design of Cellular Manufacturing System Based on AD Principles) on Figure 1. The following section provides the proposed FR-DP hierarchy. The design matrices corresponding to the FR-DP pairs are also provided in this section. In Section 3, we present a case study of converting a conventional metal ramp/stairwell manufacturer from process-oriented layout to cellular manufacturing. Finally, in Section 4 we provide conclusions of our work.

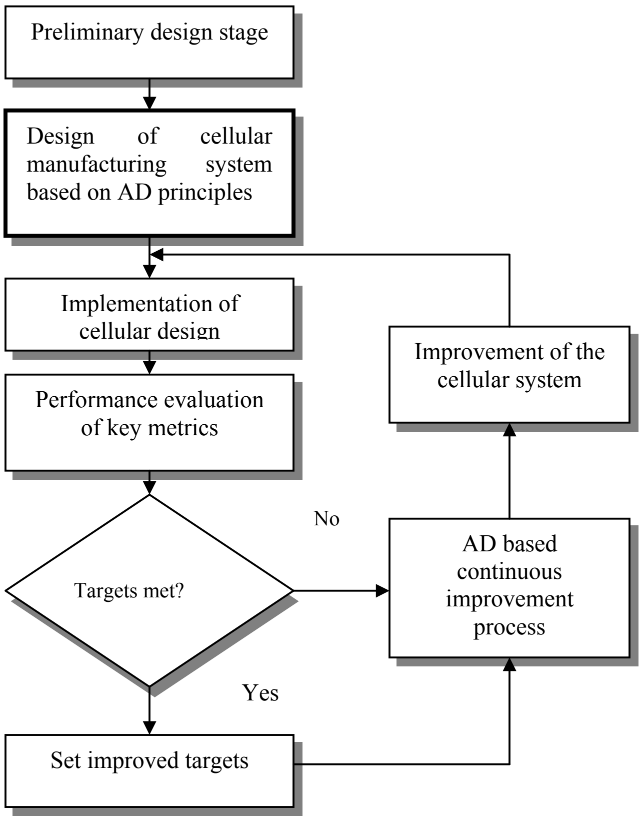

Figure1. Cellular Manufacturing Design Process with Feedback Mechanism Based on AD Principles

2 CELLULAR MANUFACTURING SYSTEM DESIGN THROUGH AD PRINCIPLES

In what follows we chose to present our implementation methodology based on the framework provided by Suh (1998).

Step 1. Choose FRs in the Functional Domain

The first step in designing cellular manufacturing system is to define the functional requirements (FRs) of the system at the highest level of its hierarchy in the functional domain [Suh (1998)]. At this stage many functional requirements may be established. Each functional requirement established at this stage may lead to a completely different cellular manufacturing design. Therefore, extreme care should be given to all functional requirements before a single functional requirement is adopted at this highest level. In this work the following has been selected as the highest FR.

FR= Provide a flexible production in line with customer needs

More product variety, in smaller batch sizes with highest quality and more frequent deliveries at lower costs summarize the needs of customers in the 21st century [Steudel and Desruelle (1992)]. These requirements are forcing companies to reevaluate their classical manufacturing systems for more flexibility in response to these customer needs. The flexibility of a manufacturing system is measured by its speed and ability to respond to rapidly changing customer needs.

Step 2. Mapping of FRs in the Physical Domain

At this step, design parameters (DPs), which satisfy the FRs established in the previous step, are selected through a mapping process between the functional domain and the physical domain. In order to make the correct DP selection, the DP set corresponding to the FR set established before, must be exhaustively generated. The following DP has been selected to satisfy the FR provided above.

DP= Cellular Manufacturing System Design

The production system, which can answer customer's needs in an efficient way through elimination of waste, reduction of lead time and improved quality is a cellular manufacturing system designed with lean manufacturing principles in mind.

Step 3. Decompose FR in the Functional Domain-Zigzagging between the domains

If the DPs proposed for satisfying the FRs defined in steps above can not be implemented without further clarification, the AD principles recommends returning to the functional domain for decomposing the FRs into their lower functional requirement set. The following lower functional requirements set is defined for decomposing the FR determined in Step 1 above.

FR1=Classify and group products/ components for simple material flow
FR2=Define production strategy based on product specifications
FR3=Rearrange resources to minimize waste
FR4=Provide means to control production based on customer demand.

Step 4. Find the Corresponding DPx's by Mapping FRx's in the Physical Domain

In satisfying the four FRs defined above, we move to the physical domain from the functional domain. The following DPs are in response to the FRs listed above.

DP1=Procedure for defining product families
DP2=Procedure for selecting production strategy
DP3=Product oriented layout
DP4=Pull production control system

Step 5. Determine the Design Matrix

Once the FR-DP sets are defined in Steps 3 and 4, the corresponding Design Matrix (DM) provides the relationships between the FR and DP elements. It is important to insure that the DM as established satisfies the Independence Axiom (IA) of the AD principles. If the DM matrix is *uncoupled* or *decoupled,* then it satisfies the Independence Axiom of AD principles (see Suh [2001]). The design equation and the DM corresponding to the FR-DP sets are as follows.

$$\begin{bmatrix} FR\,1 \\ FR\,2 \\ FR\,3 \\ FR\,4 \end{bmatrix} = \begin{bmatrix} X & & & \\ X & X & & \\ X & X & X & \\ X & X & X & X \end{bmatrix} * \begin{bmatrix} DP\,1 \\ DP\,2 \\ DP\,3 \\ DP\,4 \end{bmatrix} \quad (1)$$

This design is a decoupled design, and thus, satisfies the IA. In the DM above, a symbol X represents a strong relationship between the corresponding FR-DP pair.

Step 6. Decompose FR1, FR2, FR3 and FR4 by going from the Physical to the Functional Domain again and determine the corresponding DPs (Level3)

Step 6a. FR1- Products/ components branch

The functional requirement FR1 as defined above (classify and group products/components for simple material flow) may be decomposed with DP1 (procedure for defining product families) in mind as:

FR11=Determine high volume products/components to group
FR12=Determine operations and machine types for producing each product family
FR13=Form product families
FR14=Determine final number of machine groups

The corresponding DPs may be stated as:

DP11 Product-Quantity Pareto Analysis
DP12 Machine-Component Incidence Matrix
DP13 Products grouping techniques
DP14 Cost Analysis and economic justification techniques

In this step, product families that will economically be manufactured through cellular manufacturing and their corresponding machine groups are determined by using Pareto analysis followed by product family assignment techniques. This is a very important step in the success of transition form traditional manufacturing to cellular manufacturing [Irani (1999)].

The first step of this branch is to establish the high volume products through Product-Quantity (Pareto) analysis. The next step is to group similar products (in terms of their process requirements) into product families. There are several algorithmic procedures to accomplish this task. Most of them use the Machine-Component Incidence Matrix. These algorithms swap rows and the columns of this matrix until suitable block-diagonal sub-matrices or near block-diagonal sub-matrices are obtained. The products that fall into the same sub-matrix are candidates to be allocated to a potential cell. Once these potential cell allocations are complete, the next and the final step of this branch is to decide on how many of these cells to implement based on economic justification principles. The designers perform cost benefit analyses on each potential cell formation. In this process, each candidate cell's contribution to the company's bottom line in terms of productivity, lead time and profitability together with return on investment are calculated. Those cells that satisfy the company internal rate of return are recommended for formation.

The design matrix for the above set of FRs and DPs are

$$\begin{bmatrix} FR\ 11 \\ FR\ 12 \\ FR\ 13 \\ FR\ 14 \end{bmatrix} = \begin{bmatrix} X & & & \\ X & X & & \\ 0 & X & X & \\ 0 & X & X & X \end{bmatrix} * \begin{bmatrix} DP\ 11 \\ DP\ 12 \\ DP\ 13 \\ DP\ 14 \end{bmatrix} \quad (2)$$

Once again, this is a decoupled design satisfying IA of AD.

Step 6b. FR2- Production strategy branch

The functional requirement FR2 as defined above (Define production strategy based on product specifications) may be decomposed with DP2 (procedure for selecting production strategy) in mind as:

FR21=Determine the master process
FR22=Select most appropriate process elements
FR23=Determine required training/education needs
FR24=Motivate labor participations

The corresponding DPs may be stated as:

DP21=Master Process selection
DP22=Production resources selection procedure
DP23=Multi-purpose labor training programs
DP24=Gain sharing program

At this stage, production resources are determined following the establishment of the master process based on product specifications. Once the resource selection is complete, the education and training requirements of the workers can be established. For ensuring the full participation of workers in the education and training activities followed by transition to cellular manufacturing, appropriate gain sharing programs must be established and announced to the workers for strong buy in.

The design equation and matrices are as follows:

$$\begin{bmatrix} FR\ 21 \\ FR\ 22 \\ FR\ 23 \\ FR\ 24 \end{bmatrix} = \begin{bmatrix} X & & & \\ X & X & & \\ 0 & X & X & \\ 0 & X & X & X \end{bmatrix} * \begin{bmatrix} DP\ 21 \\ DP\ 22 \\ DP\ 23 \\ DP\ 24 \end{bmatrix} \quad (3)$$

This is a decoupled design satisfying IA of AD.

Step 6c. FR3- Resource rearrangement branch

The functional requirement FR3 as defined above (Rearrange resources to minimize waste) may be decomposed with DP3 (Product oriented layout) in mind as:

FR31=Minimize material handling
FR32=Eliminate wasted motion of operators
FR33=Minimize waste due to imbalance in the system

The corresponding DPs may be stated as:

DP31= Material flow oriented layout
DP32 =Arrangement of stations to facilitate operator tasks
DP33 =Balanced resources in response to Takt time

At this stage lean manufacturing principles are the guiding principles of this design step. In this step, the focus is the waste elimination. Therefore, in rearranging the resources waste due to motion, material handling and imbalances between resources is minimized [Cochran (2000)]. Without this step the designed cell will not provide the expected performance.

The design equation and matrices are as follows:

$$\begin{bmatrix} FR\,31 \\ FR\,32 \\ FR\,33 \end{bmatrix} = \begin{bmatrix} X & & \\ X & X & \\ X & X & X \end{bmatrix} * \begin{bmatrix} DP\,31 \\ DP\,32 \\ DP\,33 \end{bmatrix} \quad (4)$$

Once again, this is a decoupled design satisfying IA of AD.

Step 6d. FR4- Production control branch

The functional requirement FR4 as defined above (Provide means to control production based on customer demand) may be decomposed with DP4 (Pull production control system) in mind as:

FR41=Ensure Smooth and steady production in assembly line
FR42=Provide material/information flow
FR43=Provide continuous feedback information flow

The corresponding DPs may be stated as:

DP41=Leveled /Mixed production
DP42=Card System (Kanban)
DP43=Information/Report System and visual management tools

Satisfying customers by right amount and just-in-time can only be accomplished through pull system [Hopp and Spearman (1996)]. However, just-in-time systems require a steady pull on all products in the family. To insure a steady pull, a leveled/mixed production schedule must be established. This leads us into developing the appropriate Heijunka schedule and the necessary visual management tools including Kanban system for successful implementation.

The design equation and matrices are as follows:

$$\begin{bmatrix} FR\,41 \\ FR\,42 \\ FR\,43 \end{bmatrix} = \begin{bmatrix} X & & \\ X & X & \\ X & X & X \end{bmatrix} * \begin{bmatrix} DP\,41 \\ DP\,42 \\ DP\,43 \end{bmatrix} \quad (5)$$

This is a decoupled design satisfying IA of AD.

Step 7. Fourth Level Decomposition

Step7b. FR2- Production strategy branch

The functional requirement FR22 as defined above (Select most appropriate process elements) may be decomposed with DP22 (Production resources selection procedure) in mind as:

FR221=Time production in concert with customer pull rate
FR222=Ensure the selection of right machines
FR223=Ensure most efficient material movement
FR224=Ensure labor flexibility in the cell
FR225=Minimize indirect labor needs

The corresponding DPs may be stated as:

DP221=Determined Takt time for each family (Takt time=Available Time /Demand)
DP222=Selection of machines according to DA2
DP223=Selection of Material Handling System (MHS) based on DA2
DP224=Appointing multi-skilled worker to the cell
DP225=Establishment of self directed work teams

At this stage, the cell needs to operate for satisfying customer demand without producing excessive work-in-process inventories and finished goods. In controlling these two measures the cell must operate at the calculated Takt time. Once the Takt time is at hand, the number of machines and staffing can easily be determined for effective operations. Based on selected machines, it becomes feasible to decide on the right material handling equipment. Having the required machines and the material handling equipment, the designer can now select the right personnel for the line.

The design equation and matrices are as follows:

$$\begin{bmatrix} FR\,221 \\ FR\,222 \\ FR\,223 \\ FR\,224 \\ FR\,225 \end{bmatrix} = \begin{bmatrix} X & & & & \\ X & X & & & \\ X & X & X & & \\ X & X & 0 & X & \\ 0 & 0 & X & X & X \end{bmatrix} * \begin{bmatrix} DP\,221 \\ DP\,222 \\ DP\,223 \\ DP\,224 \\ DP\,225 \end{bmatrix} \quad (6)$$

This is a decoupled design satisfying IA of AD.

The functional requirement FR23 as defined above (Determine required training/education needs) may be decomposed with DP23 (Multi-purpose labor training programs) in mind as:

FR231=Develop waste elimination focus
FR232=Develop multi-skilled workers

The corresponding DPs may be stated as:

DP231=Lean Manufacturing training and education program
DP232=Cross-training program

At this stage, internal and/or external resources are recruited to establish the required lean manufacturing training. In addition, labor certification programs are also established for developing multi skilled workers who can operate all equipment in the cell.

The design equation and matrices are as follows:

$$\begin{bmatrix} FR\,231 \\ FR\,232 \end{bmatrix} = \begin{bmatrix} X & \\ X & X \end{bmatrix} * \begin{bmatrix} DP\,231 \\ DP\,232 \end{bmatrix} \quad (7)$$

This is a decoupled design satisfying IA of AD.

The functional requirement FR24 as defined above (Motivate labor participations) may be decomposed with DP24 (Gain sharing program) in mind as:

FR241=Ensure workers participation for 5S activities
FR242=Ensure worker participation for other lean manufacturing applications

The corresponding DPs may be stated as:

DP241=5S Reward system
DP242=Kaizen teams/ multi-skill certification and reward system

One of the major reasons for failure in the lean journey is the lack of institutionalization of 5S activities. Inadequate 5S applications always lead into bigger problems during this transition. One way to insure the success of lean transition is to ensure the workers participation in 5S activities. This may be accomplished by preparing appropriate 5S score sheet. With this score sheet, cells with higher scores are awarded additional benefits and the winning teams are announced company-wide. In addition, appropriate reward system must also be established to recognize the workers who earn new certification for additional operations in the cell. Kaizen teams are established to insure the worker participation in lean manufacturing activities. With the established gain sharing programs workers are motivated to participate in these activities.

The design equation and matrices are as follows:

$$\begin{bmatrix} FR\,241 \\ FR\,242 \end{bmatrix} = \begin{bmatrix} X & \\ X & X \end{bmatrix} * \begin{bmatrix} DP\,241 \\ DP\,242 \end{bmatrix} \qquad (8)$$

This is a decoupled design satisfying IA of AD.

Step7c. FR3= Resource rearrangement branch

The functional requirement FR32 as defined above (Eliminate wasted motion of operators) may be decomposed with DP32 (Arrangement of stations to facilitate operator tasks) in mind as:

FR321=Minimize operator movements between stations
FR322=Minimize operator time during setup
FR323=Minimize operators wasted time in processing

The corresponding DPs may be stated as:

DP321=Machine layout/ labor allocation to minimize walking distance
DP322=Standard tools/ equipments for each cell/station
DP323=Ergonomic interfaces between workers and equipment

In rearranging the resources of the cell, the ultimate goal is to minimize no-value added time of operators. This comes from operator movements between stations and operator's time spent on equipment setup. In addition, stations designed without serious consideration to human factors and ergonomics plays a significant role in these losses due to strenuous working conditions and potential work slow down.

The design equation and matrices are as follows:

$$\begin{bmatrix} FR\ 321 \\ FR\ 322 \\ FR\ 323 \end{bmatrix} = \begin{bmatrix} X & & \\ 0 & X & \\ 0 & 0 & X \end{bmatrix} * \begin{bmatrix} DP\ 321 \\ DP\ 322 \\ DP\ 323 \end{bmatrix} \qquad (9)$$

This is an uncoupled design satisfying IA of AD.

The functional requirement FR33 as defined above (Minimize waste due to imbalance in the system) may be decomposed with DP33 (Balanced resources in response to Takt time) in mind as:

FR331=Ensure that each machine Cycle Time ≤ Takt Time
FR332=Ensure that each operator Cycle Time ≤ Takt Time
FR333=Ensure that Transportation Cycle Time ≤ Takt Time

The corresponding DPs may be stated as:

DP331=Appropriate work assignment for each machine
DP332=Optimal task assignment
DP333=Speed adjustment of material handling system or arrangement of appropriate MHS

An ideally balanced cell should utilize all workers, resources and material handling systems to their fullest capacity. In accomplishing this task, the cell designer must insure that each machine's cycle time, operator cycle time and the material handling cycle times are as near to the Takt time as possible. This will insure a smooth mixed/leveled production satisfying customer demand in most efficient way.

The design equation and matrices are as follows:

$$\begin{bmatrix} FR\ 331 \\ FR\ 332 \\ FR\ 333 \end{bmatrix} = \begin{bmatrix} X & & \\ 0 & X & \\ 0 & 0 & X \end{bmatrix} * \begin{bmatrix} DP\ 331 \\ DP\ 332 \\ DP\ 333 \end{bmatrix} \qquad (10)$$

This is an uncoupled design satisfying IA of AD.

Step 7d. FR4= Production control branch

The functional requirement FR41 as defined above (Ensure smooth and steady production in assembly line) may be decomposed with DP41 (Leveled /Mixed production) in mind as:

FR411=Acquire information on desired product mix/volume
FR412=Ensure small batch production
FR413=Develop Smooth Assembly Sequence

The corresponding DPs may be stated as:

DP411=Continuous information flow from customers (periodic forecast)
DP412=Minimized setup times (SMED)
DP413=Selected Method for Assembly Sequence

An effective production plan depends on accurate forecast from the customers. Given accurate forecasts from the customers, the planners estimate the assembly Takt time required to satisfy customer demand. The difference between the available time on the assembly line and production time needed to assemble the forecasted demand will determine the amount of time that can be allocated to setup and changeover activities on the line. Therefore, to increase the possibility of number of setups (and thus reduce batch sizes towards one-piece flow), reduction of set up efforts are initiated using SMED principles. Once the reduced setup and changeover time matrix is on hand, the planners can then calculate the maximum number of setups that can be afforded on the line. Naturally, the larger the time available for setup, the smaller the batch sizes the line can afford. This available setup time is apportioned between different products by using appropriate allocation procedures. Subsequently, the sequencing of different products through the assembly line is initiated. This is accomplished through mixed/level scheduling process. Through this mixed/leveled schedule the smooth production schedule that satisfies customers' demand just-in-time emerges. The schedule that will result will dictate the schedule for the newly designed cell.

The design equation and matrices are as follows:

$$\begin{bmatrix} FR\ 411 \\ FR\ 412 \\ FR\ 413 \end{bmatrix} = \begin{bmatrix} X & & \\ X & X & \\ X & X & X \end{bmatrix} * \begin{bmatrix} DP\ 411 \\ DP\ 412 \\ DP\ 413 \end{bmatrix} \quad (11)$$

This is a decoupled design satisfying IA of AD.

The functional requirement FR42 as defined above (Provide material/information flow) may be decomposed with DP42 (Card System (Kanban)) in mind as:

FR421=Ensure information /material flow between cells and assembly
FR422=Ensure information /material flow within each cell
FR423=Ensure information /material flow between the supplier and manufacturer

The corresponding DPs may be stated as:

DP421=Move Card System (In-plant Kanban)
DP422=Production Kanban System (production Kanban-non lot, signal Kanban-lot)
DP423=Move Card System (Supplier Kanban system)

The ultimate goal of cellular manufacturing (and lean manufacturing) is to convert the make-to-stock production system (push production) to make-to-order production system (pull production). In pull production material is pulled through the system starting from the customer end all the way to the suppliers end [Sipper and Bulfin (1997)]. Therefore, appropriate pull systems need to be established for assembly, within-cell material movement, between-cell material movement and supplier material movement in the plant. Depending upon the proximity of these different plant components, appropriate pull mechanisms need to be selected. In case of distances between components (e.g., between cells and between the plant and the suppliers), signal cards (Kanbans) may need to be established.

The design equation and matrices are as follows:

$$\begin{bmatrix} FR\ 421 \\ FR\ 422 \\ FR\ 423 \end{bmatrix} = \begin{bmatrix} X & & \\ X & X & \\ 0 & X & X \end{bmatrix} * \begin{bmatrix} DP\ 421 \\ DP\ 422 \\ DP\ 423 \end{bmatrix} \quad (12)$$

This is a decoupled design satisfying IA of AD.

The functional requirement FR43 as defined above (Provide continuous feedback information flow) may be decomposed with DP43 (Information/Report System and visual management tools) in mind as:

FR431=Provide efficient means to collect data
FR432=Ensure freshness of data

The corresponding DPs may be stated as:

DP431=Data acquisition system
DP432=Data acquisition schedule

Visual management tools are an important part of a lean manufacturing implementation. They play a significant role in the success of the lean journey. Therefore, well developed visual management and feedback system will help significantly in improving the newly designed cells and become an important part of the feedback mechanism as proposed in Figure 1. These visual tools are simple, yet significant information tools that help workers to assess the system performance and conditions at a glance. Some visual management tools include reports on production performance, quality performance and TPM related visual tools including OEE measures, to name a few. There are many specific visual tools available in each category listed above. The design team must select an appropriate set of visual management tools and their update frequencies to support the cellular manufacturing activities. Additional visual management tools may be added to the system during the feedback cycle.

The design equation and matrices are as follows:

$$\begin{bmatrix} FR\ 431 \\ FR\ 432 \end{bmatrix} = \begin{bmatrix} X & \\ X & X \end{bmatrix} * \begin{bmatrix} DP\ 431 \\ DP\ 432 \end{bmatrix} \quad (13)$$

This is a decoupled design satisfying IA of AD.

Step 8. Fifth Level Decomposition

Step 8d. FR4= Production Control Branch

The functional requirement FR421 as defined above (Ensure information /material flow between cells and assembly) may be decomposed with DP421 (Move Card System (In-plant Kanban)) in mind as:

FR4211=Transport consistent quantities
FR4212=Ensure timely deliveries

The corresponding DPs may be stated as:

DP4211= Standard container size from cells to assembly line
DP4212=Optimal number of Move Kanban

Inadequate lot sizing and/or inadequate number of Kanbans lead into suboptimal cell performance between the cells and the assembly line or between the cells. Excessive amount of cards and larger batch sizes lead into inflated WIP and increased lead time without impacting the throughput. On the other hand, insufficient cards and smaller than optimal batch sizes, lead into lost productivity and starvation of some of the cells within the plant. Therefore, appropriate procedures for Kanban calculations and container size determination must be implemented at this stage. Some analytical techniques exist for estimating these two parameters.

The design equation and matrices are as follows:

$$\begin{bmatrix} FR\ 4211 \\ FR\ 4212 \end{bmatrix} = \begin{bmatrix} X & \\ X & X \end{bmatrix} * \begin{bmatrix} DP\ 4211 \\ DP\ 4212 \end{bmatrix} \quad (14)$$

This is a decoupled design satisfying IA of AD.

The functional requirement FR422 as defined above (Ensure information /material flow within each cell) may be decomposed with DP422 (Production Kanban System (production Kanban-non lot, signal Kanban-lot)) in mind as:

FR4221= Transport consistent quantities within the cell
FR4222= Ensure timely deliveries between cell operations

The corresponding DPs may be stated as:

DP4221=Standard container size within the cell
DP4222=Optimal number of Production Kanban

Inadequate lot sizing and/or inadequate number of Kanbans lead into suboptimal cell performance. Excessive amount of cards and larger batch sizes lead into inflated WIP and increased lead time without impacting the cell throughput. On the other hand, insufficient cards and smaller than optimal batch sizes, lead into lost productivity and starvation of some of the equipment within the cell. Therefore, appropriate procedures for Kanban calculations and container size determination must be implemented at this stage. Some analytical techniques exist for estimating these two parameters.

The design equation and matrices are as follows:

$$\begin{bmatrix} FR\ 4221 \\ FR\ 4222 \end{bmatrix} = \begin{bmatrix} X & \\ X & X \end{bmatrix} * \begin{bmatrix} DP\ 4221 \\ DP\ 4222 \end{bmatrix} \qquad (15)$$

This is a decoupled design satisfying IA of AD.

The functional requirement FR423 as defined above (Ensure information /material flow between the supplier and manufacturer) may be decomposed with DP423 (Move Card System (Supplier Kanban system)) in mind as:

FR4231= Transport consistent quantities from the supplier
FR4232= Ensure timely deliveries from the supplier

The corresponding DPs may be stated as:

DP4231=Standard container size from the supplier
DP4232=Optimal number of supplier Kanbans

Supplier reliability becomes a very important issue in JIT manufacturing. Once the system operates in pull environment, it is natural to expect the suppliers to also become JIT suppliers. Inadequate lot sizes and/or inadequate deliveries from the suppliers lead into suboptimal plant performance. Excessive amount of deliveries and large shipments lead into inflated raw material stocks and increased lead time without impacting the plant throughput. On the other hand, infrequent and or unreliable deliveries and smaller than requested batch sizes, lead into lost productivity and starvation of some of the equipment within the plant. Therefore, appropriate procedures for supplier Kanban calculations and supplier container size determination must be implemented at this stage. Some analytical techniques exist for estimating these two parameters.

The design equation and matrices are as follows:

$$\begin{bmatrix} FR\ 4231 \\ FR\ 4232 \end{bmatrix} = \begin{bmatrix} X & \\ X & X \end{bmatrix} * \begin{bmatrix} DP\ 4231 \\ DP\ 4232 \end{bmatrix} \qquad (16)$$

This is a decoupled design satisfying IA of AD.

3 Implementation and Some Results

The proposed Cellular Design Process is implemented at a company manufacturing aluminum walkways, bridges, stairs and ramps in Keystone Heights, Florida.

Our study involved their ramp rails landings and stairs manufacturing. We implemented proposed AD principles in transforming this system from the existing classical manufacturing layout to a cellular manufacturing system.

At the start of our implementation the facility layout was organized based on process layout principles. A simplified version of the old layout is given in Figure 2.

Following the preliminary stage of project team selection, plans have been devised for company-wide participation in the transition to lean and cellular manufacturing. Around this time, six 3-day lean manufacturing and TPM workshops were provided to 80% of the factory personnel. Subsequently, the next task was to define the product families. Based on the machine-component incidence matrix the team decided that stairs, ramp rails, and landings were ideal candidates for cellular manufacturing. Ensuing economic analysis and justification showed that each cell was economically feasible and desirable. Due to large sizes of the incoming aluminum raw material stock, it was also economically more acceptable to cut incoming stock to smaller sizes later to be resized at each cell by using the 22” saw at the entrance to the facility. It was also determined that this facility will operate as a supermarket for the newly designed cells.

After determining the desired Takt time for each cell, the team proceeded with the selection of the process elements. It is at this stage the team concluded that each cell should have its own saw, which is much smaller than the large saw that cater to all cells. Furthermore proper allocation of welding machines have also been established for each cell and several new power outlets needed to be installed to service these welding machines. In order to maintain a smooth product flow, each cell received the appropriate number of punches, milling machines and buffing equipment.

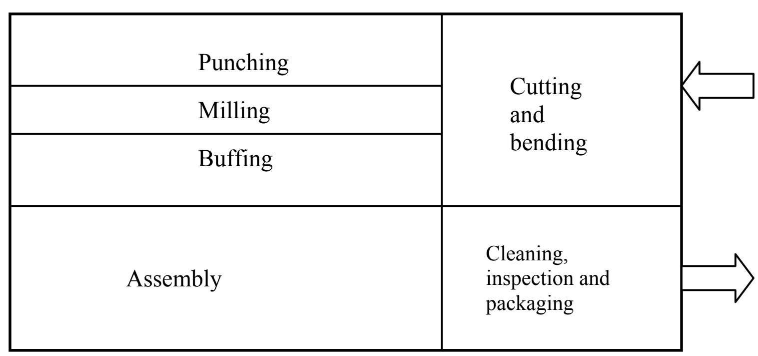

Figure 2. Old Layout before Transformation

The educational and training needs of the workers, supervisors and team leaders were established around this time. This was followed by a series of lean manufacturing and TPM workshops for supervisors, team leaders and majority of the workforce. These team leaders started all out announcement of lean journey, cellular manufacturing and the importance of 5S activities plant-wide.

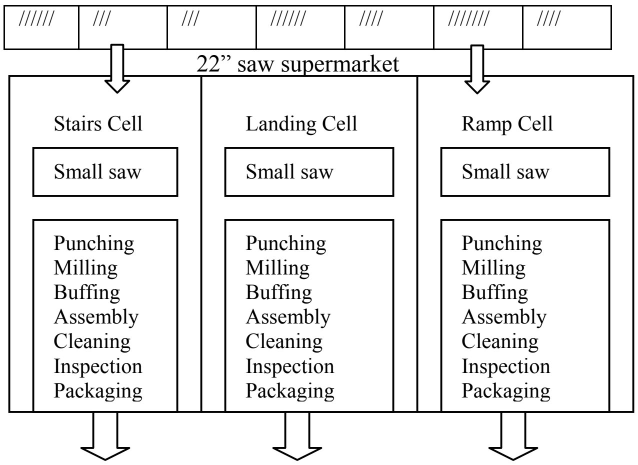

Figure 3. New Cellular Layout after the Transformation

For maintaining the 5S discipline, 5S evaluation worksheets were developed and routinely implemented as a prelude for the gain sharing program. Once the standard work in each cell was defined, proper metrics were developed for continuous improvement monitoring. Based on these metrics, appropriate gain sharing program was developed. This gain sharing program was widely publicized throughout the plant and a copy of this program was made available to all plant personnel.
With the participation of cell teams final acquisition and arrangement of resources in each cell was determined. Staffing of the cell was finalized based on the current cell Takt time requirements. Tasks were assigned to workers to minimize idle times. Figure 3 provides the new layout of the facility based on three newly formed cells.

Based on firm demand and forecasted sales, production volume and eventually mixed leveled assembly plans were established for each cell. Based on these leveled production plan optimal container sizes and number of containers have been established for each cell. For Kanban implementation, new carts have been built to transport batches between stations and also act as Kanban signals. Similarly, the Kanban operations between the cells and the 22" saw supermarket were established through transportation carts built in-house. Once again, the sizes of each cart were determined through proper analytical tools.

Before the start of the implementation of cellular manufacturing, material suppliers were not very reliable and usually promised once a week deliveries. Usually the lowest cost suppliers had won the bids without paying attention to their performance both on delivery frequencies and reliability. Through new vendor certification and rating system, all potential suppliers were evaluated. Several visits and conferences were held with current and potential vendors. The need for just-in-time deliveries and reliability were emphasized in those meetings. After proper negotiations, final vendors selected promised daily deliveries with smaller batch sizes responding to company's supplier Kanban signals.

In order to maintain the overall equipment effectiveness, total quality control and just-in-time production, appropriate information feedback system and visual management tools were developed. Through posting of this information at suitable places in each cell, workers were transformed into self monitoring and continuous improvement teams. With the availability of gain sharing system details, they were able to evaluate the impact of improvements to their pocketbooks.

The first stage of lean transformation started in May 2000. The following table provides the comparative measurements of important business metrics as of May 2000 and as of September 2001, for the Ramp Rail Cell.

Metric	Before Cellular	After Cellular
Raw matl. stock (days of inv.)	11	3.5
Lead Time (days)	18	7
Scrap Rate (percentage)	3	1.6
Throughput (units pairs)	50	70
Overtime (hours/week)	300	60
WIP (days inventory)	6	2.5

Table 1. Comparison of business metrics

4 CONCLUSIONS

In this paper we provide a complete and concise methodology for transforming a process oriented manufacturing facility into a cellular manufacturing system. The methodology is based on Axiomatic Design principles. The proposed process is implemented at a company that manufactures aluminum ramp rails, landings and stairwells. The results show that the proposed methodology is sound, easy to follow and implementable. Implementation of the proposed methodology at an automotive hose manufacturing plant is under way.

During the implementation we have learned some lessons that need to be shared for future users of this methodology.

- Insure excellent 5S training
- Insure lean training plant-wide
- Insure 100% commitment from top management
- Communicate the benefits of the transformation with workers early on.
- Provide them with information on gain sharing program as early as possible
- Focus on OEE early on in the program
- Focus on SMED early on in the program
- Implement gain sharing program as early as possible
- Set clear goals for each cell and each Kaizen improvement teams.
- Train team leaders with the basics of teamwork and leadership
- Be patient with the pull system implementations. Usually success follows a few failed attempts.

Details of the feedback mechanism for continuous improvement of the cellular system under the guidelines of AD principles will be presented at our subsequent publications.

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