"Impact of System Design, Organizational Processes and Leadership on Manufacturing System Design and Implementation"

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Abstract

Manufacturing system design methodologies often ignore the importance of enterprise related issues that affect the implementation and improvement efforts. System designers are limited in their scope of influence to the system engineering phases, however these phases are just part of the larger manufacturing system design process that links strategy with system preparation, design, implementation, performance measurement and improvement efforts. Leadership owns the responsibility for aligning organizational interfaces and processes to facilitate change. The paper proposes a set of hypotheses on reasons for poor systemic performance illustrated by a case discussion and finally suggests a broad methodology for future implementations.

1 INTRODUCTION

Manufacturing systems have been designed traditionally in an ad-hoc and non-holistic manner. System design is often not linked to the objectives defined by the firm that are defined through its manufacturing strategy. Further, it is essential to separate the objectives from the means as the converse leads to systems copying 'tools' from successful manufacturing philosophies such as the Toyota Production Systems without an appreciation of the systemic requirements. Most traditional design methods are bottom up where the system is created as an aggregation of existing elements and evaluated in relation to requirements that provide feedback for refinements. The synthesis-analysis-evaluation approach is unsuitable for designing large systems as the complexities of larger systems make the process of analysis, evaluation and improvement difficult. In such cases it is necessary to define requirements as they relate to strategy and customer needs. The design method must consider interactions among elements at different levels as well as provide a structured rigorous approach to design, implementation and operation.

Numerous manufacturing system design concepts have been developed over the last decades [see e.g. Wu 1992, Hopp, Spearman, 1996, Askin, 1993]. Some of these provide a physical hierarchy for the treatment of the system design problems while others adopt a top down procedural approach [Kettner, 1984, Wrnecke, 1993] to physical design. The important shortcoming in both these approaches is the lack of a link between objectives and design. The manufacturing system design decomposition (MSDD) developed at Production System Design Laboratory, MIT proposes the objectives of repetitive discrete part manufacturing systems and relates them to the design solutions by applying axiomatic design [Cochran, 1999]. The process of decomposition thus relates low-level design decisions to high-level system objectives and also highlights the prioritization in the design decision-making sequence. A proposed classification of system designs and methodologies in literature is shown in figure 1. Figure 2 shows the spread in the area of impact across different levels of system design that the methodologies span. Through this paper we wish to illustrate that the ideal methodology for system design would span across all levels of the design pyramid model. Performance measurement helps generate feedback for corrective measures and improvements follow the above stages of engineering the system. To ensure that the information is accurate and aligned towards meeting the objectives of system performance, it is necessary that a) the system is designed such that low-level design decisions are related to higher-level objectives b) system operation and implementation reflects the system design c) performance measurement process highlights problem areas within the system design d) the system is designed to incorporate feedback for change and e) improvements and changes taking place in the system are standardized.

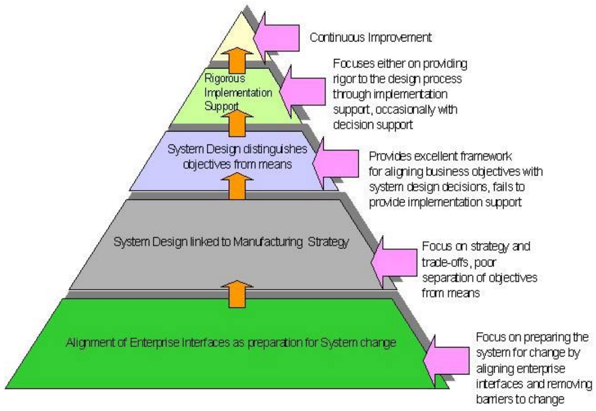


Figure 1: Pyramid classification of design methodologies

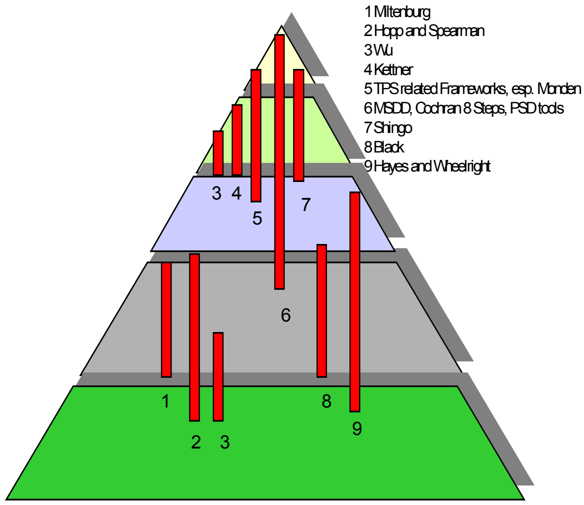


Figure 2: Mapping influence of various literature on system design pyramid.

Poor system performance could be a function of the design process and methodology, a set of enterprise issues such as poor leadership and ill-designed organizational processes, or misalignment of manufacturing with other parts of the enterprise. The following hypotheses on system design and performance are proposed.

Hypothesis 1 Production systems that have poor operational performance owe it to poor design or implementation.

Hypothesis 2 Poor design is often a result of improper control and feedback from poorly designed organizational processes especially of performance measurement and accounting.

Hypothesis 3 Poor organizational processes are often supported by environmental conditions that prevent the easy detection of problems in system performance through extraneous effects.

Hypothesis 4 Poor organizational leadership does not change and rather supports/sets poor organizational processes that are misaligned with objectives.

This paper will discuss these hypotheses through a case illustration and ultimately propose a combination of approaches being researched and developed at PSD, MIT in the form of a serial yet iterative approach to system design.

2 CASE STUDY ILLUSTRATION

In June of 1999, PSD, MIT teamed up with engineers and production managers at Mexican facilities owned and operated by a giant automobile components supplier, to re-design their production system. The plants manufacture fluid connectors used in automobile air-conditioning systems. The design sought embodied fundamental "lean" concepts, while respecting current company constraints.

2.1 Project Motivation and Goals

The fluid line connector manufacturing operations at these plants was plagued by several problems. The major issues that required attention were: limited floor space for new products and expansion, high throughput time, quality problems, and wasteful processing methods. These problems were deeply rooted in the design of their manufacturing system, which has a departmental, mass production approach to manufacturing. At the start, the project constraints were outlined as lack of resources for any major investments in product, process or equipment to achieve the project goals. More specifically, these goals were:

- Simplify product and information flow
- Reduce throughput time by eliminating lot delay
- Eliminate the waste of transport and storage
- Prevent occurrence of defects by integrating quality control into the station design
- Separate the workers from the machines to effectively utilize direct labor
- Reduce the time and complexity of machine setup by designing the machines to system takt time (rather than high speed to reduce labor cost) and by eliminating adjustment need during setup.

2.2 Pre-Project State of Manufacturing System

A wall separates the assembly and fabrication sections of the plant (Figure 3). On the fabrication side there are two distinct paths parts follow depending on their material type. Tubes are formed, washed, then go to rotary braze machines, and finally, to assembly. On the assembly side, the tubes get bent and then sent to the final assembly lines, to be assembled into the fluid connectors. Manufacturing operations can be classified into one of the following: processing, inspection, storage, or transport [Shingo, 1989]. Processing is often the only value adding operation (defined as changing the form or function of a part to a state that the final customer is willing to pay for). The act of inspection while ensuring quality adds no value. Table 1 offers a summary of the manufacturing system attributes.

2.3 System Design Process and Phases

The methodology chosen for the systen design change and implementation process was a combination of the MSDD and the eight steps to Lean [Cochran, 1998] as they addressed most levels of the pyramid and project goals. The design process followed the three broad phases of conceptual design, followed by preliminary design and detailed design.

Step 0. Determine who the customers are
Step 1. Define linked cell system
Step 2. Form cells based on takt time
Step 3. Reduce setup times - Single minute changeovers

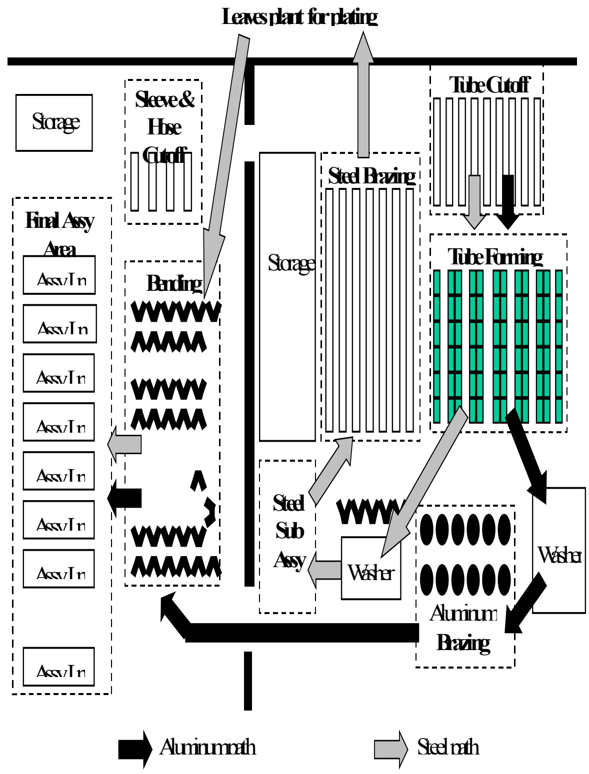


Figure 3: Overview of Fabrication system [Estrada, Shukla et al, 2000]

Features	Manufacturing System
Production	~7,000,000 parts/year
Floor Space	163,140 sq. ft
Direct Labor proportion	0.83
Man Hours/part	0.31
Fab Scrap Expenses/Part	~8 cents/part
Fab WIP	Variable~64,000
Fab Throughput Time	Variable~1 day
Assembly Scrap Expenses/part	~2 cents/part
Assembly WIP	Variable~1800
Assembly Throughput Time	Variable~1 day

Table 1: Scorecard for manufacturing system attributes

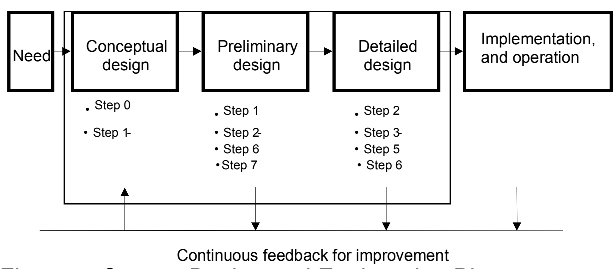


Figure 4: System Design and Engineering Phases

Step 4. Improve quality and output predictability
Step 5. Level manufacturing in assembly cells
Step 6. Link cells with a pull system
Step 7. Link suppliers with plant pull system
Step 8. Integrate product development

The eight steps do not necessarily follow the design hierarchy inherent in the design phases. A mapping of the steps with the phases is presented in Figure 4.

Conceptual Design Phase

Identifying the customers in Step 0 gives a basis for product family formation as well as for initial value stream mapping. The rationale for forming families in this manner is that if all products going to a single customer constitute a family, then the system shown in Figure 5 can be achieved. In this system, the flow of parts and information is in its simplest form. However, in the case being studied, more than one connector made up a single automobile's air conditioning unit. Thus, connectors going to a single customer are not necessarily similar in material, geometry or size, and hence undergo different manufacturing processing routes. Forming product families based on customers would have led to an increased level of complexity at the subsystem level of design. Therefore, families were instead formed on the basis of processing, using the following criteria in the same order of priority.

- Material make up (all steel, all aluminum or hybrid)
- Number of crimps (0, 2, 4, 6 or 8), related to number of connector tubes making up the end product
- Braze type (none, saddle, charge valve, P-nut, stem adaptor, or other.)
- Hose diameter (5/16", 1/2", 5/8" or 3/4")

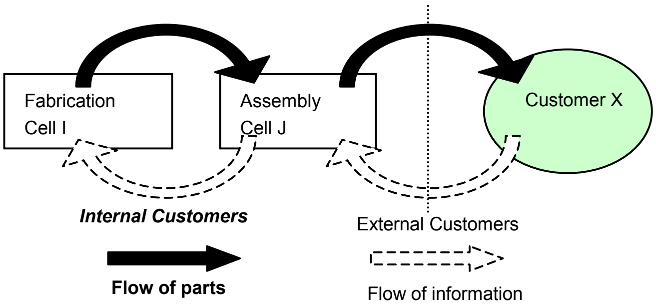
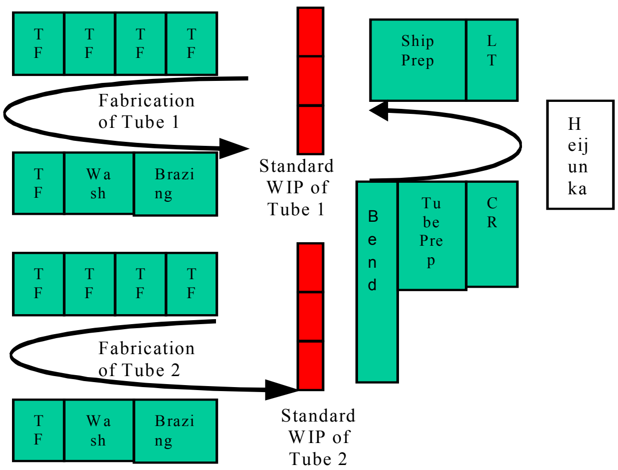


Figure 5: Simplified flow- customer based families

For step 1 we needed to define a linked cellular system. The linked cellular subsystem design model has been shown in literature to meet the subsystem requirements of reduction of throughput time, reduction of transport and storage delay, and increased worker utilization through single-piece flow and multi-functional workers [see also Shukla, Estrada, Cochran, 2000]. In linked cellular manufacturing systems cells formed in assembly and fabrication run products from the same family and are linked through material and information flow.

Preliminary/Ideal Design Phase



TF=Tube forming; CR=Crimp, LT=Leak Test

Figure 6: Ideal model for linked sub-system

This phase was essentially an extension of the principles set forth in the previous phase. In order to implement the conceptual model it was crucial that cells were defined and based on the customer demand time also known as Takt time, the available production time by the demanded quantity in that period. Also the pull system linking the cells and a process for integrating suppliers both internal (material handlers) and external (raw material) was needed to implement Steps 1,2, 6 and 7. The linkage of the cells design was further achieved through the provision for Standard WIP (SWIP) or decoupler between assembly and fabrication and the final assembly Heijunka helps level and pace the cells based on customer demand. This structure helps provide the framework for integrating supply and distribution at a later stage (Figure 6).

Detailed Design Phase

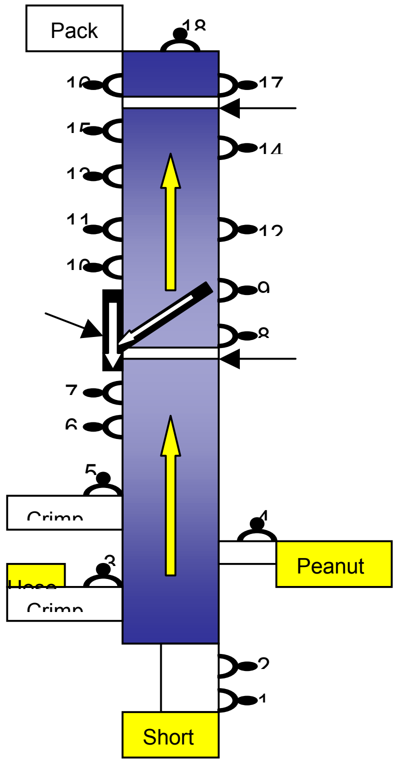


Figure 7: Assembly line layout prior to conversion

The assembly operations, in this system were performed on conveyor-belt-driven moving assembly lines. Several problems that caused line stoppages for varying amounts of time were observed to be a direct consequence of the moving assembly line design [Estrada, Shukla et al, 2000]. Conveyors create the need for final inspection, since a part can pass through a station unprocessed. There is a lack of flexibility in the production rate as the lines are designed for a fixed speed and physical isolation is a problem. Lines are never truly balanced and workers operating at different cycle times cause increased WIP and throughput time leading to unpredictability. Linear conveyors prevent inspectors from fixing the problem themselves; output quality is variable and unpredictable leading to addition scheduling costs, floor space and expediting costs.

The layout of the assembly line is as shown in Figure 7. However, the constraints of leak testing equipment implied that each piece of the latter had to be shared between two cells. Moreover, a single crimping machine would have to make both the crimps in the assembly. Thus equipment off each line would help produce two assembly cells placed in a U-shape to share the leak testing equipment in the layout shown in Figure 8.

2.4 Pilot- Implementation and Operation

Piloting the new sub-system design was the first step in the implementation and operation phase, which followed the design process. Formation of product families in the conceptual phase provided a framework for choosing the pilot. The Al-2 crimp models were the simplest and most representative/generic product type. An entire assembly line was dedicated to the manufacture of the largest volume product system-wide. Based on 16 hours of available working time from 2 shifts, daily demand of 4200 and an assumed uptime factor of 0.85, the takt time was 12 seconds for a single cell working two shifts.

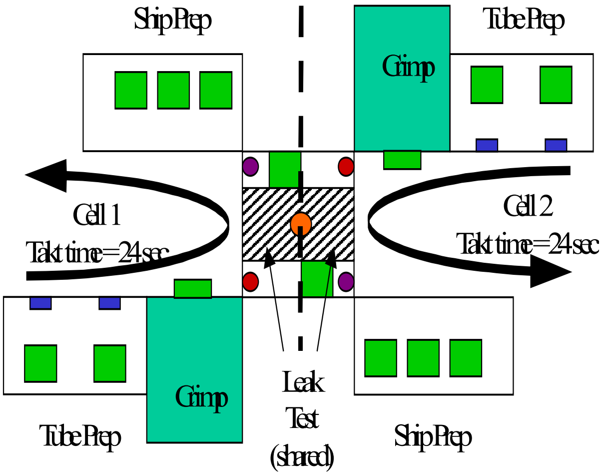


Figure 8: Layout of two cells used to replace a line

Cells running on low takt times of 12 seconds experience similar problems of balancing similar to those on assembly lines. Thus, it was chosen to implement two cells running on a takt time of 24 seconds. Multi-functional and moving workers in cells provides greater flexibility in formation of work loops as the order of operations need not necessarily follow the product's assembly sequence. This added flexibility provides several options for defining standard work loops that are always subject to improvement. The number of workers needed to run the cell was decided by dividing the sum of operating times determined from assembly line standards (67.9 seconds) by the takt time. This calculation suggested that three workers would be needed with about 23 seconds of work in each loop.

Important Challenges in Testing Phase

- Operators experience learning curve working in cells and hence initially it was difficult to meet takt time. Instead of mastering a single task earlier they now became efficient over time at completing their work loops and learning all operations.
- The change in approach from individual responsibility for a single operation on the line to collective responsibility for improving work loops was an interesting challenge for the workers. They responded with effective communication aimed at improving their work loops, stations and identifying non-essential processing steps.
- The temptation of workers to over-produce after completing work loops ahead of time was regulated through material handling. A single material handler replenished both cells by offering 50 parts every 20 minutes for production.
- Absenteeism became apparent as underproduction in a particular time interval thus providing feedback for improving worker habits.

Comparison of Results

The comparison between mass assembly lines and cells on some of the quantifiable terms is shown in Table 2. Most striking are 78% reductions in floor space and 45% reduction in man-hours required for production.

Measurable	Assembly Line	2 Cells
Floor Space	1500 sq. ft.	320 sq. ft.
Direct Workers	18	12 (2 cells, 2 shifts)
Cycle Time	6.2 sec	24 sec
Man-hours required	~170	96
Avg defects/month	226	2.5
% Absenteeism	4	0
Throughput time	Variable (~20 min)	72 secs
WIP	Variable (~150)	6 (3/cell)
Incoming Material	High and variable	50 pcs/20 min
Conveyor	90 ft	None

Table 2: Comparison of mass assembly line with cells

Apart from the measures listed above the other non-quantifiable benefits were

- Increased ability to balance work content
- Improvement in worker's attitudes, increased team work and enthusiasm as well as interest in improving work methods; drop in absenteeism
- Volume flexibility by adding or removing workers
- Predictable output that exposes problems caused by upstream processes or operation in cells

2.5 Plan for system wide roll out

The interim plan for system conversion focused on all the assembly operations before forming and linking fabrication cells since fabrication cells required greater investment on equipment design and acquisition. It also required the leadership and finance functions to be first convinced of the benefits from conversion; realized benefits would help justify new expenditure. The order of implementation of assembly cells followed the product family framework with design and implementation of cells for 2-crimp Al products followed by Al 4-crimp, Hybrid 4-crimp, Al 6+ crimp and Hybrid 6+crimp families and sub families. The leadership (plant and functional) was expected to guide the rest of the process.

2.6 Post Pilot System change and Implementation

Three cells were implemented and a fourth designed. Of the four cells, two produced single models, while the other two were used for re-inspection of models run on the assembly lines (customer requirements for some models mandated 200% inspection). However, the cells were run at 25% lower takt times. The result of running at such low takt times is an increase in the number of workers required. The cells had 9 direct workers in each, increasing the floor space required by 50%. The problem of poor balancing expressed itself with instances of some operators having twice the work content of their co-workers. The designed 'cells' were essentially a U-shaped miniaturization of the line.

The product families were ignored, and the goal instead became one of converting each assembly line to cells, regardless of which products were being run on the line. In creating the new plan, the project leaders in different plants worked independently of each other. Moreover, their focus on the conversion process was split along departmental lines, as in the previous system. Performance evaluation and responsibility continued to be divided along departmental lines, providing strong incentives for project leaders to pursue goals and activities different and often in conflict with each other, to ensure individual targets were met over system goals.

3 REASONS FOR PROJECT SLOWDOWN

The success of the pilot and subsequent failure of the project helps prove the hypotheses postulated earlier on system design and implementation.

Hypothesis 1 *Production systems that have poor operational performance owe it to poor design or implementation*. The pilot project succeeded as the design combined an axiomatic decomposition framework that helped separate objectives from means with a rigorous systems engineering approach. However, the subsequent altering of the plan for system conversion led to complexities in information and product flow at the system level as well as poor operational performance at the cell level. Poorly designed cells thus did not replicate pilot benefits, as they were mere modifications to the line to physically resemble pilot cells.

Hypothesis 2 *Poor design is often a result of improper control and feedback from poorly designed organizational processes.* Accounting processes are typically geared towards minimizing the unit labor cost of a part or maximizing machine utilization. Both these practices lead to mass production systems with departmental layouts and are a continuation of the days when labor was the major component of part costs. Departments often measure their performance separately from system goals and compensate individual's on their performance rather than that of the system. There was no feedback loop from performance measures to highlight large WIP or throughput time when cells were operated as U-shaped lines. Moreover, benchmarking with past performance of the system lead to complacency toward efforts for improvement. This apparent lack of critical feedback aimed at pointing sub-system design flaws thus further perpetuated poor system design, mental models and practices.

Hypothesis 3 *Poor organizational processes are often supported by environmental conditions, which prevent the easy detection of problems in system performance through extraneous effects.* The fact that the plants belonged to a leading automotive components supplier based in the US with global operations, enabled the accounting department in these plants to compare their operational and distribution costs with those of American plants. Given the proximity to the US and the substantially lower Mexican wages, traditional accounting practices reflecting labor costs as the chief production cost indicated superior performance at these plants despite their flawed designs and operationally inferior performance. Thus lower personnel costs buffered the impact and camouflaged the problems of poor system design and processes. It encouraged the use of traditional accounting practices since they projected factory performance as superior.

Hypothesis 4 *Poor organizational leadership does not change and rather supports/sets poor organizational processes that are misaligned with objectives*. The leadership was more interested in impressive bottom-line figures reflecting their performance in a good light. Despite the possibility of potential benefits far exceeding the current returns from reduced labor costs, the leadership was not proactive in identifying change as the important step towards superior system performance in the future. Moreover, in order to avoid conflict between departments and risk a precipitous situation, the leadership failed to commit to the implementation plan. The failure in changing traditional measurement practices, promoting departmentalization and overlooking poor operational performance all point to poor leadership as a principal cause of system failure, thus illustrating the set of hypotheses.

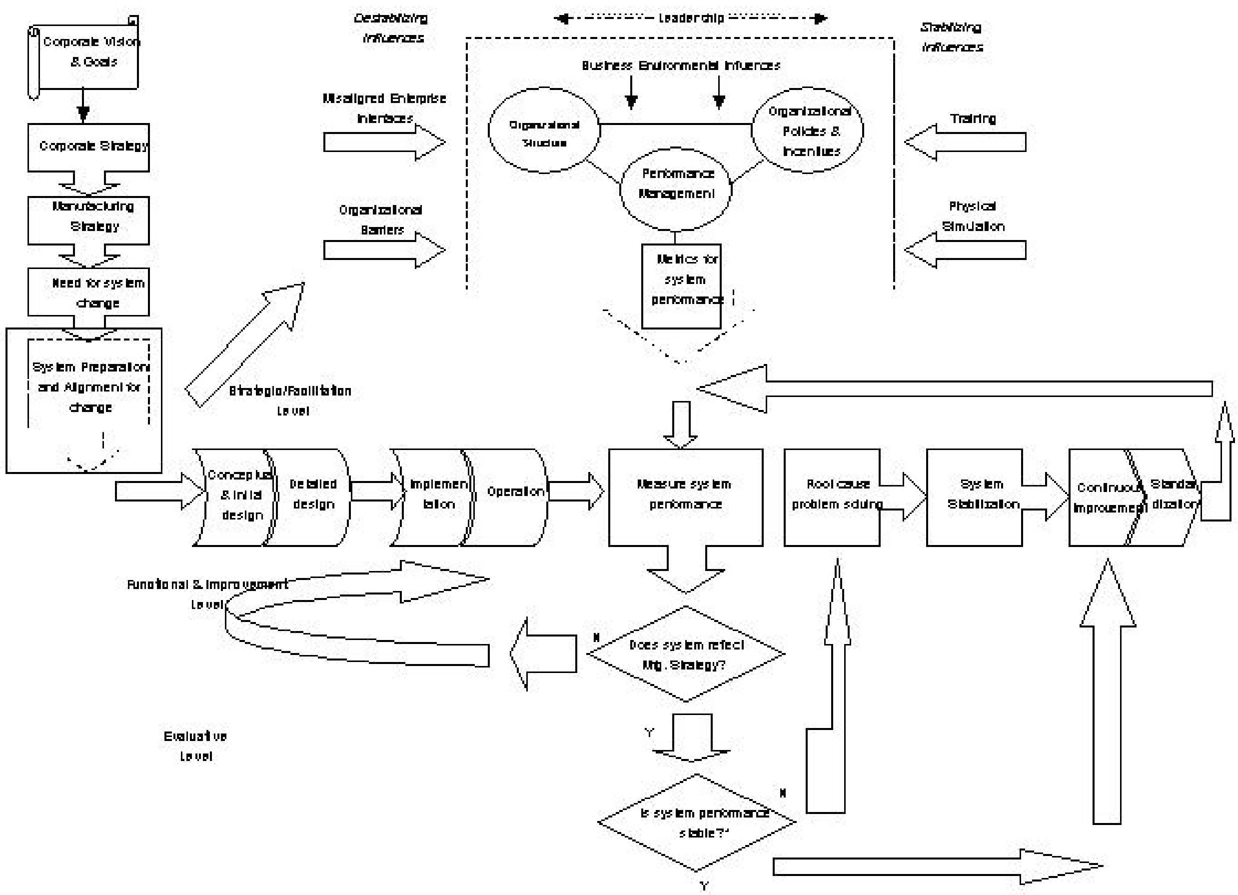


Figure 9: Manufacturing System Design and Improvement Process

A proposed general framework for the process of manufacturing system design and implementation is shown in Figure 9. It further illustrates the role of leadership, organization and outside influences on system design. The process highlights the three important levels through which the process of change advances. At the strategic-facilitation level, manufacturing strategy is derived from corporate strategy and highlights the importance of systemic change. For successful implementation it is critical to prepare the system for change by removing organizational barriers, alignment of organizational interfaces and incentives towards such a change. The responsibility for this critical step rests with the leadership who need to use the stabilizing influences of training and/or physical process simulation to illustrate the proposed value stream and its desired impact.

The proposed system design process combines the system engineering process in the design-implementation-improvement level. After implementation, performance evaluation determines if the design meets objectives (Functional Requirements) of the manufacturing strategy. An additional iteration through the system engineering process may be needed to identify and correct design flaws. Evaluation using the manufacturing system design decomposition developed for the system determines whether the system is stable. In order to stabilize the system it may be necessary to do prioritized root cause problem solving so as to achieve the functional requirements across the decomposition. In a stable system it is possible to perform improvements on a continuous basis and standardize the best practices in the system. The system iterates between the evaluation and functional levels on continuous basis during the operation.

4 METHODOLOGY FOR FUTURE PROJECTS

In the solution space the authors suggest the following phases and steps that in conjunction with the MSDD and the system performance evaluation tools developed at PSD, MIT could have anticipated the problems in the aftermath of the pilot and taken preventive action before project implementation. A significant portion of the steps mapped in Figure 10 focus on the strategic phase, in particular on system preparation and alignment, an important phase missed in the case project.

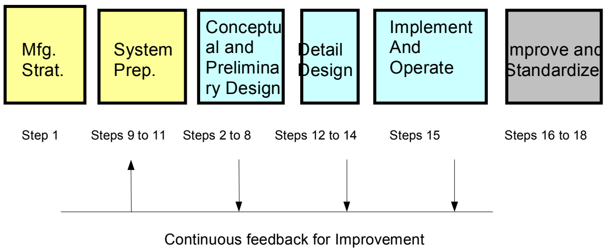


Figure 10. Steps mapped to Mfg. System design process

Strategic and Facilitation Level

- Identify external customer and create a customer-focused capacity and investment planning process.
- Align product development and business planning processes.
- Physical Simulation (using Lego models) to be used as an organizational learning tool to demonstrate the impact of working within a stable system.
- Derive key metrics for operating management's performance and compensation based on their success in establishing a stable manufacturing system and improving it.
- Identify the significant interfaces between manufacturing and the rest of the enterprise as well as organizational elements that can prevent putting the system in place.
- Develop a Lego model of the future value stream and train people to design the standardized work.
- Teach the merits of a pull replenishment system design for stable performance.

Systems Engineering Steps

- Create a common mental model of the manufacturing system objectives, derived axiomatically from the strategy in the form of the manufacturing system design decomposition.
- Develop and examine the current state value stream map to determine the weaknesses in current design especially with material and information flow.
- Develop the future state map linking suppliers.
- Define the external customer in a way that allows flexibility in balancing work loops and maintains a one-to-one relationship between a supplying and customer process
- Form volume flexible cells based on takt Time with adequate provision for variation.
- Design cells for zero changeover time.
- Operate the linked system with leveling and pacing.

Continuous Improvement and Standardization

- Systematically reduce SWIP between cells to reduce variation, improve reliability and mistake-proof processes.
- Reduce the run size.
- Constantly improve the work.

These steps not only cover all levels of the system design pyramid presented earlier but also extend to all sections of the system design process in the previous figure. Apart from being comprehensive, they also offer physical simulation solutions as an important element of system preparation. It is likely that the projected benefits of system conversion as presented in Table 3, could have been achieved if adequate attention had been paid to preparing system for change.

Features	Current	Assembly Conversion
Floor Space	163140 sq. ft.	112124 sq. ft.
Direct lab. Ratio	1	0.65
Indirect lab. Ratio	1	1
Man-hours Ratio	1	0.61
Scrap Expense Ratio	1	0.33
Assembly WIP	Variable~1800	81
Assembly Throughput time	Variable~1 day	11-12 min

Table 3: Comparison of past and proposed systems

5 CONCLUSIONS

The case study highlights some of the shortcomings in the available literature on system design methodologies. Almost no comprehensive system design methodology exist that combine elements of strategy with a rigorous system engineering approach to design and implementation, nor addresses enterprise issues that affect manufacturing performance. The steps and phases to design suggested in this paper in conjunction with the MSDD, as well as additional tools developed at PSD, MIT for system evaluation, is an attempt to address all the levels of the system design pyramid. The case study establishes how rigor in system design is a necessary but not sufficient condition for superior operational performance and leadership must help align the incentives of the system as well as demonstrate through training and physical simulation the benefits of change. It also illustrates value of having a performance evaluation system that is consistent with manufacturing strategy and stabilizes the system before standardizing improvements. Most importantly the case study serves to prove the authors hypothesis on the causes of poor systemic performance and emphasizes the importance of preparing the system for change.

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