Performance Measures for Lean Manufacturing

by

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ABSTRACT

As the Interiors Responsibility Center (IRC) of Boeing implements Lean Manufacturing methods, the organization identified the need to change its manufacturing performance measures to ensure control and improvement of its manufacturing system. This thesis presents a design methodology to derive performance measures consistent with manufacturing system design and performance measurement objectives. Performance measures for lean manufacturing system control are developed for (3) levels of management control within the IRC: the work cell, area management, and factory management levels.

The approach used to derived the performance measures includes: Axiomatic Design, traditional control theory, and Statistical Process Control. A design model of a lean manufacturing system is presented from which the performance measures are derived.

Results from the thesis indicate that the current performance measures in use at the IRC fail to capture the information necessary to control a lean manufacturing system. These measures are not timely and do not contain key system performance information. They are used more for “grading” rather than providing a means to control and improve the manufacturing system. The performance measures derived in this thesis capture information “real-time” within and between work cells where “control” of the system is initiated and executed. The new performance measures provide measures on throughput times, WIP, process quality, product flexibility, delivery reliability, and labor productivity. The new measurement system encourages work cell member involvement in the data collection and analysis of performance information since they are the “controllers” of the system.
ACKNOWLEDGMENTS

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The author thanks his thesis advisors, Professor Charlie Fine and Professor David Cochran for their advice throughout the internship. The use of Axiomatic Design in performance measurement is based on Professor Cochran's Ph.D. work in the design and control of lean production systems.

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1.0 Overview
1.1 Introduction

The “buzzword” in today’s manufacturing environment is “lean manufacturing”. This term was coined by the MIT International Motor Vehicle Program and *The Machine That Changed The World* publication characterizing the performance differences between traditional mass manufacturing systems and the Toyota Production System [3]. When referring to “lean manufacturing”, people are referring to the Toyota Production System. Many U.S. companies have adopted lean manufacturing principles to capitalize on the systems’ performance benefits. Boeing is now another U.S. company implementing lean manufacturing to deliver high quality, low cost aircraft to its customers, with minimum lead time.

The differences between mass production and lean production are significant. *Mass production* involves the production of very high volumes of “standardized” (limited variety) products using single-purpose machines tended by low-skilled labor. The production system includes many buffers (inventory, workers, etc.) to ensure that “disruptions” do not negatively impact machine utilization. The focus of mass production is on reducing direct labor and increasing machine utilization, not reducing throughput time or improving quality, to reduce manufacturing costs.

*Lean production* involves the production of a wide variety of products in low to high volumes using multi-skilled workers and increasingly automated, flexible machines. Lean production continuously seeks improvement. The goal is “more with less”. Less inventory, less workers, less space, and less time [32]. Its focus is on the *absolute* elimination of the 7 *waste* in the production system [26]: overproduction, defects, transportation, waiting, inventory, motion, and processing. The focus of lean production is on: on-time delivery, superior quality, flexibility (product & process), and low cost.

With lean manufacturing, traditional manufacturing performance measures based on mass production systems are inappropriate. Lean manufacturing systems operate with new assumptions and system control variables that are not reflected in traditional
manufacturing performance measures. As the Boeing Interiors Responsibility Center (IRC) transitions to lean manufacturing, it has recognized that its performance measures must change. Since it is human nature to behave in the way one is measured, the choice of performance measures will be critical to ensure behavior consistent with lean manufacturing objectives. The goal of this thesis is to develop performance measures based on the objectives of the lean manufacturing system.

This thesis describes a design methodology to derive performance measures for a manufacturing system. It establishes a lean manufacturing system design model as the basis for generating the system performance measures. Control theory models are also applied to determine performance measures at (3) management control levels within the IRC: work cell management, area management, and factory management.

This thesis intentionally concentrates on non-financial measures: quality, labor productivity, inventory, delivery, throughput times, and flexibility (product). Cost is seen as a "passenger" measure – it results from the activities within the lean manufacturing system.

1.2 Goals & Objectives
The basis for this thesis and continued performance measurement work at the Boeing IRC is summarized in the following problem statement:

The current performance measures used at the work cell through factory management level of the IRC are:

- "Results" focused – Concerned only with average and trend of outcomes.
- Not timely – Delayed feedback makes information less useful for system control.
- Missing key system information on throughput times, process quality, inventory, delivery reliability and product flexibility.
• Used more for “evaluation” (praise/punishment) than for manufacturing system control.

The IRC manufacturing system operates as an “Open Loop” control system. The “controllers” (operators, managers) wait until they receive end result measures before “correcting” the system. By that time, it is too late for corrective action.

The goal of this thesis is to provide a structured methodology and model for deriving performance measures for manufacturing systems and to then use that model to design and implement performance measures at (3) management control levels for a lean manufacturing system. The thesis includes:

• A description of Axiomatic Design and its application to manufacturing performance measure design.
• An Axiomatic Design model of a lean manufacturing system.
• Control theory models for performance measure design and use in the management control hierarchy.
• Recommendations for performance measures at the work cell management, area management, and factory management levels of the Boeing IRC.

1.3 Methodology
This thesis uses Axiomatic Design as the framework for manufacturing system design and performance measure derivation. This design methodology was developed by MIT Professor Nam Suh. The performance measurement derivation model and control theory application was developed in the Ph.D. Thesis of MIT Professor David Cochran. The Axiomatic Design approach is used to design a lean manufacturing system model from which the “system variables” form the basis of the performance measures. This design approach is also coupled with engineering control theory to define: 1) the use of the performance measures in the organization, and 2) the translation of performance measures through a management control hierarchy. Statistical concepts (SPC & variation
measurement) have also been incorporated to allow appropriate interpretation of the performance measures.

This thesis also provides a current literature review on lean manufacturing and performance measurement which provides interesting insights into the measurement issue at the Boeing IRC.

1.4 Managerial Challenges

The critical managerial issues addressed in this thesis include: 1) the importance of designing performance measures with an objective, 2) recognizing fundamental tensions in performance measurement, 3) structuring incentive plans, and 4) identifying and eliminating “constraints” in the system which inhibit continued success.

1.5 Overview

Chapter 2 Provides background material on the Boeing Interiors Responsibility Center (IRC) – its products & processes, organization, lean implementation plan & vision, and current performance measures.

Chapter 3 Reviews current literature on lean manufacturing systems and manufacturing performance measurement.

Chapter 4 Describes the problem-solving approach to performance measurement within the IRC. It describes: 1) the Axiomatic Design methodology and its application in deriving performance measures for manufacturing systems, 2) the control theory models applied to performance measure design, and 3) the statistical concepts (variation measurement and Shewhart control chart) used in the measurement system.
Chapter 5  Documents the results of the project. It describes the Axiomatic Design model of a lean manufacturing system with the derived performance measures. It includes an example of the measures and measurement media applied to a pilot work cell.

Chapter 6  Addresses the managerial issues involved with performance measurement including: 1) aligning performance measures with strategy, 2) the use of measures to influence behavior, and 3) the use of measures at different management levels.

Chapter 7  Provides the thesis assessment, summary, and key learnings.
2.0 Background

2.1 Boeing Interiors Responsibility Center (IRC)

2.1.1 Products & Process

The Boeing Company, now merged with McDonnell Douglas in August 1997, is the world leader in commercial aircraft sales. Its direct competitor is Airbus Industries (a consortium of European aircraft manufacturers). Boeing has recognized the weaknesses of the traditional “batch” manufacturing practices and is now transitioning to “lean manufacturing” practices designed to reduce waste in the manufacturing system.

The Interiors Responsibility Center (IRC) is part of the Boeing Commercial Airplane Group (BCAG) located in Everett, WA. A “responsibility center” contains all the disciplines required to design and manufacture a line of products (process engineering, manufacturing, quality, human resources, financial, product definition, etc.). The IRC has responsibility for manufacturing the following interior products for all five Boeing aircraft models (737, 747, 757, 767, 777):

- Closets, partitions, ceilings, side walls, flight deck panels, stow bins, pursar work stations, door and doorway linings, & floor coverings.

At 1997 airplane production rates, output in terms of “end items” is:

<table>
<thead>
<tr>
<th>Airplane Model</th>
<th>End Items/Airplane</th>
<th>End Items/Month</th>
<th>End Items/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>737</td>
<td>229</td>
<td>2155</td>
<td>25860</td>
</tr>
<tr>
<td>757</td>
<td>351</td>
<td>1404</td>
<td>16848</td>
</tr>
<tr>
<td>767</td>
<td>364</td>
<td>1456</td>
<td>17472</td>
</tr>
<tr>
<td>777</td>
<td>533</td>
<td>3045</td>
<td>36549</td>
</tr>
<tr>
<td>747</td>
<td>738</td>
<td>2952</td>
<td>35424</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td></td>
<td></td>
<td><strong>132153</strong></td>
</tr>
</tbody>
</table>

Production operations include: raw material cutting, press forming, NC routing, water jet cutting, finishing, assembly, and inspection. Unique manufacturing capabilities of the IRC
include: a) silk screening of decorative laminates, b) press forming, c) 3- and 5-Axis NC routing, and d) water jet carpet cutting.

Future directions for the IRC include:

- manufacturing productivity improvements (one operator two machines “pilot”, multiple dies per press)
- new technologies (tab & slot attachment methods, thermoplastic sandwich panels, digital printing)
- enhanced supplier relations (direct shipping).

The IRC Vision Statement is as follows:

To be recognized worldwide as the premier producer of Aircraft Interior Products.

To have the Boeing name associated with superior quality wherever Interiors products are utilized.

To have a reputation of continually exceeding our customers' expectations at an acceptable price.

2.1.2 IRC Organizational Structure

The organizational structure of the IRC is shown in Figure #2-1. There are 31 work cells arranged into 4 commodity areas: Side walls/Ceilings, Stow bins, Silkscreen, and “Balance.” The Area Manager is responsible for multiple work cells within the commodity. All 4 Area Managers report directly to the Factory Manager. As the internship was concluding, a temporary layer of management was added to the organization -- the Manufacturing Superintendents. Each superintendent had responsibility for (2) Areas. The superintendents were formed to help get the new factory manager of the IRC “up to par”.
2.1.3 IRC Lean Manufacturing Transition

The drivers for the IRC’s transition to lean manufacturing include:

- Designation of IRC to become Model Lean Production System for BCAG by end of 1998.
- $8M Use & Occupancy expense savings through a consolidation from (3) buildings at > 2,100,000 sq. ft. to (1) building at 1,600,000 sq. ft.
- Competition from other interiors suppliers – the IRC is cost disadvantaged on some interiors products.
- Cost reduction demands from customers.
- Airplane production rate increases – the IRC will double production in the next two years.
- Results from other mfg. plants that have implemented lean manufacturing (e.g. 30-40% cost reduction; >100% productivity improvement; 30-50% floor space reduction; 40-60% cycle time reduction; 75-90% WIP reduction).
- Work environment improvement through increased employee participation in decision-making, shop floor control, cross-training and problem-solving.

While implementing lean manufacturing principles into the IRC, it is the IRC policy that there will be no layoffs due to lean manufacturing implementation. The IRC will: 1) add less people during rate increases, 2) perform process improvement activities to increase productivity, 3) recall emergent off-load work from outside contractors, and 4) pursue an increased market share of aftermarket (refurbishment) interiors business. IRC
management recognized that the major risk will be in culture change and acceptance of process changes required by lean manufacturing. The IRC plans to mitigate this risk by comprehensive training and communication. The IRC general success factors during lean implementation are:

- Clear management support of the design is needed but must be communicated clearly throughout the IRC - both the lean manufacturing vision and transition plan.

A transitional performance can be achieved by: 1) enough pre-implementation training, and 2) adhering to the lean disciplines such as scheduling logic, single-piece flow, etc.

2.1.4 IRC Work Cell Implementation

The IRC is adopting cellular manufacturing while consolidating operations to (1) building. Thirty-one (31) product focused cells have been designed. Single-piece flow or small lot flow will be used to reduce WIP and throughput time. Critical support labor will be dedicated and collocated to work cells. Work cell implementation, which began in December 1996, is scheduled to be complete by the end of April 1998.

The IRC products were sorted into 31 work cells after grouping them by common process using the following criteria:

- Nomex vs. Non Nomex
- Single Component vs. Multi-Component
- Similar operations
- Equipment Capacity
- Product Type
- Headcount
- Airplane Model
The Four Categories of the IRC work statement are summarized in Table #2-1.

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th># Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Component</td>
<td>Single Nomex sandwich panel end items (sidewalls, ceilings).</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Continuous flow from fabrication through assembly.</td>
<td></td>
</tr>
<tr>
<td>Multiple Component</td>
<td>Multiple Nomex sandwich panel end items (stowbins, closets).</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Requires coordination between fabrication and assembly processes.</td>
<td></td>
</tr>
<tr>
<td>Other: Non-Standard</td>
<td>Nomex sandwich panels that require unique mfg. processes or sequences</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>(tubs and frames)</td>
<td></td>
</tr>
<tr>
<td>Other: Non-Nomex</td>
<td>Product that does not contain paper honeycomb core (nomex) – carpets, silk-</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>screens, thermoplastics</td>
<td></td>
</tr>
</tbody>
</table>

Work cell implementations are scheduled to complete in (12) weeks according to the template in Table #2-2.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Time</th>
<th>Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning</td>
<td>4 weeks</td>
<td>Select team members, finalize layouts, training, build-aheads.</td>
</tr>
<tr>
<td>Facilities Move</td>
<td>4 weeks</td>
<td>Clear existing areas, set-up work cell, define metrics.</td>
</tr>
<tr>
<td>Cell Startup</td>
<td>4 weeks</td>
<td>Start cell operations, on-the-job training, monitor performance, “debug”.</td>
</tr>
</tbody>
</table>

The work cells are being implemented by Cell Implementation Teams with the support of the Core Lean Team as shown in the Figure #2-2.

![Figure #2-2 - Work Cell Implementation Organization](image)
2.1.5 IRC 1998 Lean Vision

In 1998, the IRC will be focused on improving the elements of their Lean Production System shown in Figure #2-3. This “integrated lean vision” was developed by the IRC Management Team during a manufacturing “mission” to Japan during November 1997.

![Diagram showing Lean Mfg. with Business Focus & Planning, Materials Mgmt., Work Teams/Support, Production Process, Factory Layout and Flow, Product Definition & Design, each with specific improvement points.]
2.2 IRC Performance Measures

2.2.1 Current Performance Measures

Rather than describe each performance measure individually in use within the IRC (since they are numerous), Table #2-3 summarizes the measures and highlights: 1) the measures, 2) the management level recipient, and 3) the frequency of reporting. These measures were in effect prior to and during the internship period and were designed before implementation of lean manufacturing in the IRC.

<table>
<thead>
<tr>
<th>Category</th>
<th>Metric</th>
<th>Cell Mgmt.</th>
<th>Area Mgmt.</th>
<th>Factory Mgmt.</th>
<th>Freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivery</td>
<td>Behind Schedule Orders</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Daily</td>
</tr>
<tr>
<td></td>
<td>Order Completions</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Daily</td>
</tr>
<tr>
<td></td>
<td>Workable Aged Orders &amp; Look ahead</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Daily</td>
</tr>
<tr>
<td></td>
<td>Shortage to Factory</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Daily</td>
</tr>
<tr>
<td></td>
<td>Shortage in IRC</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Daily</td>
</tr>
<tr>
<td>Cost</td>
<td>Total Hours Per Part</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Total Production Hours per Part</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Budget vs. Actual</td>
<td></td>
<td></td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Total Hours by Program</td>
<td></td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Misc. Production Hours by Program</td>
<td></td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Overhead Hours</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Overtime Hours</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Headcount</td>
<td></td>
<td></td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Non-Labor Expenditures</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Equipment Utilization</td>
<td></td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td>Quality</td>
<td>Defects by Organization</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Defect Summary</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Defects by Station</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Defects by Problem Code</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Defect per 1000 Station Completions</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Rejection Tags by Organization, Model</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>FAA Audits</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pickups by Organization, Model</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td>Safety</td>
<td>Lost Workday Cases</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Cases/Hours Worked</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Recordable Incidents</td>
<td></td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Incidents/Hrs. Worked</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>Hazardous Waste per 1000 Completions</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Monthly</td>
</tr>
<tr>
<td>Morale</td>
<td>Employee Satisfaction Index</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Yearly</td>
</tr>
</tbody>
</table>
From this table, 59% of the measures were “reviewed” at all (3) management levels. Delivery measures were the most critical to the IRC (and Boeing) and therefore used as the basis for daily production meetings. The delivery measures seemed only important in terms of aggregate output quantities. Delivery was also driven by MRP schedule, not actual assembly demand. Building to MRP schedule without linking cells or assembly resulted in overproduction (excess WIP and Finished Goods inventories). One example was in the Stow bin area where a fabrication cell supplied an assembly cell. Producing to schedule generated 12-15 day’s worth of inventory between the two cells because production was not linked to actual demand from the assembly cell. After instituting a “pull” system experiment in the area, that inventory was reduced to less than 3 day’s worth.

The other measures (quality, cost, safety, morale) were less frequent and did not attract as much management attention. Many measures were ineffective for controlling the system because of the frequency of reporting. The reporting occurred too long after the fact that people couldn’t remember the causes of failure or success.

Quality had the disadvantage of having two reporting systems: one internal to the IRC and one external to Boeing Corporate. This caused “misinterpretation” as to the definition of a defect and how to measure defect totals because of overlapping “defect” categories between the two systems.

Management of the system was management by numbers. These numbers were only viewed in their absolute terms. The numbers were reviewed in only the “average and trend” perspective. There was no measurement of variation or predictability (stability).

Management by numbers also drove “management by fear”. People ensured that their performance numbers were “satisfactory” so as to avoid any “scolding” at the daily production meetings. People also tended to concentrate only on the measures set forth in their performance evaluations. The performance evaluation measures were driven down
from senior management through the management control chain. To ensure satisfactory performance evaluations and receiving “bonuses”, most people paid little attention to measures outside the scope of their performance evaluation measures.

2.2.2 Problem Statement

The basis for this thesis and continued performance measurement work at the Boeing IRC is summarized in the following problem statement:

The current performance measures used at the work cell through factory management level are:

- “Results” focused – Concern only for average and trend of “outcomes.
- Not timely – Delayed feedback makes information less useful for system control.
- Missing key information on throughput times, process quality, inventory, delivery reliability and product flexibility
- Used more for evaluation (praise/punishment) than for manufacturing system control.

The IRC manufacturing system operates as an “Open Loop” control system. The “controllers” (operators, managers) wait until they receive the end result measure before “correcting” the system. The sampling frequency of the current measures is far too infrequent for “real-time” system control.

The need is to design the system and measures to operate as a “Closed Loop” system to achieve the desired results. Closed loop in this case means that the sampling frequency must be less than the time interval for control.
3.0 Literature Review

3.1 Lean Production

3.1.1 Lean Production: Description, Goals, & Essential Elements

Womack et. al. [32] notes that lean production/Toyota Production System (TPS) involves the production of a wide variety of products in low to high volumes using multi-skilled workers and increasingly automated, flexible machines. Lean production does “more with less and less” -- less inventory, less workers, less space, less time, etc. Its focus is on cost reduction through the absolute continual elimination of waste in the production system.

The 7 wastes noted by Suzuki [26] and Cochran [4] are:

- Overproduction - waste through the producing too many goods or producing too early.
- Defects - waste through excess “cost” added to products because of rework or scrap.
- Transportation - waste through moving material throughout the facility or double and triple handling material.
- Waiting (man) - waste from workers waiting for material or machines.
- Inventory - waste through excess “costs” of managing space, material, paperwork, people, and wasted interest charges associated with the extra inventory (semi-finished parts between operations).
- Motion - waste through unnecessary worker movements.
- Processing - waste through unnecessary processing steps.

Lean production systems are comprised of only “value adding” operations -- operations that actually transform materials. Monden’s [20] description of TPS provides a model of the lean production system -- 80% waste elimination, 15% production system, 5% kanban. Lot sizes tend to be small to achieve fast cycle times, flexibility, rapid quality feedback, and level production. The goal of lean production is to deliver the right quantity of the right product with the right quality at the right time to the right location at low cost [3].

Even though the objective is cost reduction, Monden [20] identifies three sub-goals that must be achieved before the primary goal of cost reduction is achieved:

1.) Quantity control - enables the system to adapt to demand fluctuations in quantity and variety.
2.) **Quality control & assurance** - ensures each process supplies only defect-free units to subsequent processes.

3.) **Respect for the worker** - ingrains an improvement culture in the workforce that allows full use of the human resources necessary for attaining cost objectives.

Wheelwright and Bowen [31] identify 5 essential elements of the Toyota Production System which help clarify its purpose:

- TPS strives to have all critical processes “in control and capable” which creates stability and predictability in operations. Achieving such stability requires discipline, documentation, and standard work. Safety, quality, dependable delivery, flexibility, and cost are achieved with processes that are statistically validated and repeatable and that have natural variations that more than meet customer requirements.

- TPS systematically improves its in-control and capable processes by re-examining every activity to improve the value each adds to the product and customer. This relentless elimination of waste satisfies the objectives of lowering costs, increasing productivity and quality, extending the bounds of flexibility, and decreasing lead times. Continuous flow, pull systems, and kaizen attempt to minimize inventory and elaborate “information factors” within the plant and throughout the supply chain.

- TPS highlights production problems as close to their source as possible so that root cause can be identified and eliminated. TPS emphasizes managing the uncertainty and complexity in production.

- TPS connects the production rate directly to upstream suppliers and downstream customers. Takt time is the basic unit for pacing this value chain. Heijunka strives to distribute work intelligently and efficiently thereby ensuring level and balanced production. This requires minimum changeover and setup times to avoid large batch production and rules for order processing and production control. It also requires machines and processes that allow single piece flow.

- TPS requires a workforce (line worker through management) that focuses on learning and continuous improvement. Since problem identification and elimination are critical, all levels in the organization must have a deep understanding of the products and processes.

### 3.1.2 Operational Tools of Lean Production

Successful implementation of TPS requires functional literacy in the following key operational tools of TPS:

- **Cellular Manufacturing**: Machines are arranged in product-flow based cellular arrangements to decrease throughput time and to enable workers to operate multiple machines (multi-skilled workers) inside the cell. The cellular layout allows volume flexibility through varying the number of workers, not through a physical rearrangement of machines. If demand increases/decreases, workers are added/removed in the cell and worker loops are redefined. The key enabler to volume flexibility and continuous improvement is jidoka (autonomous defect detection) and single cycle automatic machines which
allows workers to be separated from machines and to control the timing of machine operation. **Standard work** is mandated to achieve **predictability in cell performance** and to facilitate the elimination of wasted motion.

- **Changeover/Setup Reduction**: "Single Minute" setup (9 minutes 59 seconds or less) is a prerequisite for single piece flow and level production. As setup time increases, it becomes inefficient to produce in small run sizes of product models based on actual customer demand. Since large lot sizes lead to large in-process inventories and hence long lead times, lean manufacturing requires changeover/setup times to be "single minute." Reductions are accomplished with **Single Minute Exchange of Die (SMED)** techniques.

- **Single Piece Flow**: Products are produced and conveyed in a lot size of ideally "one". Single piece flow is facilitated by cellular manufacturing. The cellular arrangement facilitates product flow through the manufacturing system. Improved lead times result because of minimal "lot delay" (queue time due to large in-process inventories) in the system. Single piece flow also reduces having produced defects in large batches. With cells, defects are not advanced to the next operation - the response time to detect a defect is minimized.

- **Pull system** (controlled by kanban): Lean production uses a "pull system" to maintain Just-In-Time production and quantity control in and between processes. A pull system releases material into the system based on withdrawal of finished goods by the customer or downstream processes. Kanbans are used as information signals authorizing the production or withdrawal of product. Information flow is opposite to part flow. The pull system actualizes the goal of producing to **actual** customer demand, instead of to forecast demand as with MRP (Material Requirements Planning). Pull systems work effectively only when single piece flow (in cells) is used to reduce throughput time. Secondly, "pull" only works in conjunction with level production.

- **Level Production**: Production leveling **minimizes the variation in product demand (quantity and variety)** demanded by the final customer on his supplier. It reduces demand fluctuations by producing the same amount of each product per day. Level production achieves shorter run sizes and enables the upstream cell to maintain the minimum amount of inventory necessary. As run size decreases and production is further leveled the discrete parts manufacturing system begins to look like a continuous flow pipeline of products with minimal (not zero) inventory. Leveling is accomplished by averaging demand over some time period and producing at a constant rate during that period. Once the production rate is leveled, specific jobs can be leveled by controlling their sequence in the system. However the prerequisite for a leveled system is that of "single minute" setup.

- **Takt Time**: Takt time (time/unit output) corresponds to the inverse of the production rate (output/time). It is calculated by dividing the available daily operating time by the average daily demand. Takt time provide the "rhythm" at which the manufacturing system must produce a unit of output.

- **Poka-yoke (mistake proofing)**: Poka-yoke methods/devices ensure defects are prevented. This eliminates the need for inspections which act solely as
defect identifiers. Poka-yoke devices can take many forms (fixtures, sensors, templates, etc.). The goal is to design poka-yoke devices to prevent every possible defect from occurring.

3.2 Performance Measurement

3.2.1 Functions & Tensions in Management Accounting Systems

Management accounting information can be designed to serve several functions. Eight functions categorized by MIT Prof. Charles Fine [6] include:

1. Product Costing
2. Influence Behavior
3. Operations Control & Improvement
4. Influence Worldview
5. Performance Evaluation
6. External Reporting/Inventory Evaluation
7. Project Evaluation/Capital Budgeting
8. Communication & Translation.

Having a clear objective is required so the measurement system can be designed to accomplish its task and provide the necessary information. The question to be asked when measuring something is ‘Why do you want to know?’ Do I need this information to ‘punish/praise’ the production operators? Do I need the information to control the system? Do I need to report accurate inventory figures? However, fundamental tensions will exist between conflicting objectives: information for decision-making vs. control; performance evaluation vs. operations control & improvement.

Neely et. al. [21] regard performance measurement as the quantification of the effectiveness and/or efficiency of an activity over a given time period. The suitability of performance measures should be viewed in terms of their organizational and behavioral impact as the old adage states – You get what you measure! Senge [24] notes that a system responds to how it is measured. When measures adversely affect a system it results in “creative tension” which affects a person when he attempts to do the right thing at the expense of his measures. Therefore the choice of appropriate measures consistent with desired behaviors and organizational goals is crucial to performance measurement.
Improper measures encourage dysfunctional behavior, distorted judgment, sub-optimization, and manipulation.

The effectiveness of the performance measurement system is the quality of information it provides. Successful decision making depends on timely, reliable, accurate, relevant information. Hiromoto [11] states that the Japanese use management accounting systems to support and reinforce their manufacturing strategies. The systems are used more to motivate employees to act in accordance with long-term manufacturing strategies rather than providing precise data to senior management.

3.2.2 Problems with Traditional Performance Measurement

Traditional accounting measures which focus solely on costs can lead management to focus on the wrong targets. Cost information provides little or no information on the sources of waste or drivers of cost. Kaplan [13] notes that poorly designed or outdated accounting systems can distort the realities of manufacturing performance. The most widely criticized practice is the allocation of overhead based on direct labor. Direct labor now accounts for only 10-20% of full product costs while overhead accounts for 30-40% [13]. This leads to extremely high overhead burdens. A slight change in direct labor can have a massive impact on a product’s cost structure. This allocation method focuses attention on direct labor content while ignoring overhead.

Maskell’s [18] view of traditional performance measurement systems is that information is: irrelevant (too late, financial, not related to strategy), distorted (overhead allocations), and inflexible (over time or by location). Maskell notes that:

   The fundamental flaw in the use of management accounting for operational performance measurement is the assumption that financial reports are valid and relevant to the control of daily business operations. This assumption is wrong…the day-to-day control of manufacturing operations is handled better with non-financial measures [18].
Fry [7] found that performance measures in the United States were:

- Based on financial criteria supplied by management accounting systems -- standard cost accounting systems based on full absorption of overhead were used in 80% of the companies in his study.
- Derived from cost accounting systems of the early 1900s -- assumptions of which are no longer valid in current manufacturing systems.

Kaplan [14] notes that the prevailing theme has been to capture non-financial measures of manufacturing performance in terms of quality, delivery, productivity, inventory, flexibility and time.

3.2.3 Performance Measure Criteria & Use

Maskell [18] claims that ideally the measures would have the following attributes:

- Timely - Fast feedback is important to make proper decisions and to learn.
- Non-financial - Financial measures are not applicable to daily operations.
- Simple and easy to understand - For people to use them, people must understand them. Use direct measures for most important parts of business.
- Consistent with manufacturing strategy - Provide consistent focus on what is to be pursued so measures are consistent with desired action.
- Complementary - No sub-optimization at expense of other measures.
- Promote continuous improvement - Not just reducing variance from target.
- Flexible - Over time and by area.

Thor [28] proposes a “family of measures” approach. A family of measures is:

- well communicated
- complete (has enough measures)
- consistent with reward, recognition and management style
- linked to appropriate level of plan and in that level's “language”
- customer driven

Performance measures should incorporate statistical concepts. Tribus [29] states that “all systems exhibit variability - knowing how to tell if the variation is a signal that something is wrong or is simply part of the expected variation distinguishes a good manager from the
inept. Managers must learn to think statistically. Learning to remove variation in the process is the first step to improving the process. Increased education and training in such fundamentals of the interpretation of variation is imperative to proper analysis decision making.

Hall et. al. [10] state that how measures are used are just as important as what measures are used. In a problem-solving network, the measurement system should contribute to corrective action with a minimum assignment of blame. Company culture should encourage the use of measurement results as motivational tools rather than instruments of punishment. The measures should motivate personnel to find and eliminate waste and inefficiencies and provide means to anticipate problems rather than simply reacting to them (i.e. SPC). An important result of making information visible and available is to objectify it. Rather than assigning blame, supervision and workers together analyze the situation for ways to improve it.

Greif [8] contrasts “results” measures versus “process” measures. Results measures are the “outcomes” of some action (i.e. a score). Process measures, however, measure the effectiveness of the process yielding the outcome. Process measures would be similar to those measures used after a game by a sports coach to develop conclusions about the team’s strengths and weaknesses. Table #3-1 illustrates process versus results measures with a simple football game analogy.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Dallas Cowboys</th>
<th>Chicago Bears</th>
</tr>
</thead>
<tbody>
<tr>
<td>RESULT - Final Score</td>
<td>14</td>
<td>42</td>
</tr>
</tbody>
</table>

**PROCESS**

<table>
<thead>
<tr>
<th>Measure</th>
<th>Dallas Cowboys</th>
<th>Chicago Bears</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD/Attempts</td>
<td>66%</td>
<td>33%</td>
</tr>
<tr>
<td>Pass Completion %</td>
<td>15%</td>
<td>85%</td>
</tr>
<tr>
<td>Missed Tackle %</td>
<td>70%</td>
<td>18%</td>
</tr>
<tr>
<td>Penalties</td>
<td>8 for 160 yd.</td>
<td>3 for 15 yd.</td>
</tr>
</tbody>
</table>
Results measures tell an organization where it stands in its efforts to achieve goals, but not how it got there or what it should do differently. Performance measures thus should include process measures as well as results measures.

3.2.4 Performance Measures & the Management Control Hierarchy
All levels within an organization need information on: goals and objectives, short-term feedback on progress relative to those goals, and a means to track long-term performance. Information needs, however, will differ in terms of detail, frequency, and type of measure depending on the responsibility level and decision making authority of the user. In general, as responsibility level increases, resolution of information decreases.

<table>
<thead>
<tr>
<th>Management Control Level</th>
<th>Decision Type</th>
<th>Decision Time Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factory Management</td>
<td>Strategic Decisions</td>
<td>Monthly/Yearly</td>
</tr>
<tr>
<td>Middle Management</td>
<td>Tactical and Operational Decisions</td>
<td>Weekly/Monthly</td>
</tr>
<tr>
<td>Cell Management</td>
<td>Operational Decisions</td>
<td>Real time/Weekly</td>
</tr>
</tbody>
</table>

Thor's [28] view of the management hierarchy and decision time frame is shown in Table #3-2. Factory and middle management needs to know:

- performance to plan
- whether problems are being addressed
- what are reasonable targets and improvement rates relative to financial considerations.

Cell management (including cell members) are responsible for process optimization and resource deployment. Cell management needs to know:

- if operations are being performed correctly
- what are the most frequent problems in order to diagnose and eliminate problems (cause & effect relationships)
- assignable causes of variation.

3.2.5 Specific Measures for Lean Production
Womack, Jones, and Roos [32] describes plant level lean manufacturing measures in the automotive industry as: productivity (assembly hours per car), quality (assembly defects per car), layout (plant floorspace per car), inventory (WIP and Finished Goods), size of repair area, job rotation, suggestions per employee, absenteeism rates, training hrs. per employee.

Examples of other “lean measures” include:

- **Throughput Time** - the average time for a product to go from raw material to finished goods.
- **Inventory** - Raw material, WIP, and Finished Goods. High levels of WIP lead to long throughput times which create negative results such as uneven loading, speculative demand forecasts, and schedule inflexibility.
- **Part travel distance** - reflects a product’s use of space as well as potential inventory levels and labor requirements.
- **Flexibility** - often referred to as the ability of an organization to change from one product to the next (product flexibility), or the ability to adapt to changes in volume (volume flexibility), or the extent the workforce is cross-trained (workforce flexibility).

Fry [7] found that Japanese performance measurement systems measure the following:

- **Corporate Level** – Market share and growth; Less on profit and ROI
- **Plant Level** - Combination of financial and non-financial: quality, labor productivity, schedule adherence, WIP, total cost, cost improvement.
- **Shop Floor Level** – Physical measures: defects, output, WIP.

Fry [7] noted that the use of physical measures on the shop floor were easily understood by employees and were readily available which provided “real time” feedback regarding performance. The primary criteria used to measure shop floor performance was consistent with the most important market factor as indicated by top management - QUALITY.

Hall [9] notes the measurement changes as one moves from traditional to lean production:

- **Attention shifts from defect identification to defect prevention**
- **Measures include total costs, not solely direct labor costs**
- **Progress tracking is performed in lean manufacturing characteristics such as:** housekeeping, setup times, batch sizes, equipment downtime, employee suggestions, first-inspection pass rates, space occupied, part travel distance, etc.
3.2.6 Summary

Many studies have been done on performance measurement and there is not always consensus among researchers. Past literature suggests creating performance measures based on satisfying a set of general criteria. The literature review found this criteria to be inconsistent. Arguments have been presented for: financial vs. non-financial measures; ratios (indices) vs. direct measures; team supportive vs. competitive measures; and standard vs. flexible measures. Not much work has focused on a structured approach for deriving manufacturing performance measures from a manufacturing system design and performance control perspective. This thesis addresses this problem and presents an engineering design approach for performance measure development.
4.0 Methodology for Performance Measure Development

4.1 Axiomatic Design

4.1.1 Axiomatic Design Theory

Axiomatic Design is a design methodology for developing solutions in the form of products, processes or systems that satisfy customer needs through a logical mapping framework. The methodology was developed in the late 1970's by MIT Professor Dr. Nam P. Suh. Suh [25] named the approach “Axiomatic Design” because it is based upon axioms which are fundamental truths that are observed to be valid and for which there are no counterexamples or exceptions. Axiomatic Design is based on two axioms: 1) The Independence Axiom, and 2) The Information Axiom. The design approach provides a “scientific basis for design” with the goal of independently satisfying the Functional Requirements (to eliminate coupling) by the proper selection of Design Parameters which serve to implement the physical aspects of the design.

<table>
<thead>
<tr>
<th>Axiom 1 - The Independence Axiom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintain the independence of Functional Requirements.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Axiom 2 - The Information Axiom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimize the information content.</td>
</tr>
</tbody>
</table>

There are four key concepts in Axiomatic Design:

- Four Design Domains
- Design Decomposition
- Independence Axiom & Coupling
- Information Axiom
4.1.1.1 Four Design Domains

The Axiomatic Design process is portrayed in Figure #4-1. As shown, the design process involves mapping through (4) design domains. Each translation or transition to a new domain is a refinement of the design. The design process begins by translating expressed Customer Wants in the customer domain into Functional Requirements (FRs) in the functional domain. FRs represent what you want the system to do – the objectives. Design Parameters (DPs) are generated in the physical domain that satisfy the FRs. DPs represent how you accomplish the objective – the physical embodiment. In systems design, the DPs are mapped to System Variables (SVs) that would satisfy the DPs. The SVs are actions or decisions used to control the system [3].

Design is the continuous interplay and synthesized solution between the mapping of what we want to achieve (FRs) in the functional domain and how we want to achieve it (DPs) in the physical domain. Suh [25] states that the mapping process is nonunique – more than one set of DPs can be generated that satisfy the FRs.

4.1.1.2 Design Decomposition

Axiomatic Design involves a process of hierarchical decomposition which allows the designer to examine small parts of a larger problem. Constraints govern the design space
and must be obeyed. After compiling the list of Customer Wants, they must be sorted in a manner to facilitate design. Suh [25] notes that the most critical step in the design process is defining the problem – the customer wants must be reduced to a representative set of FRs as the first and most critical stage of the design process. Without a proper set of FRs, a good design is not likely to result.

Two important facts about design and the design process are:

1) FRs, DPs and SVs have hierarchies and can be decomposed
2) FRs at the ith level cannot be decomposed to the next level without first developing a corresponding DP that satisfies that ith FR. The process of decomposing and moving back and forth between the design domains is "zigzagging".

In order to have an uncoupled and non-redundant design, the decomposition trees for FRs, DPs, and SVs must be identical in form. This means exactly one DP satisfies each FR and exactly one SV satisfies each DP. A numbering system can be used to relate and document the FRs, DPs, and SVs as shown in Figure #4-2. The numbering system would assign the highest level FRs numbers of 1.0. When we decompose to the second level, we add a period to these numbers and begin numbering the sub-FRs of each high level FR (FR1.1, FR1.2, DP1.1, DP1.2, SV1.1, SV1.2).

![Design Decomposition Numbering System](image)

The “zigzag” decomposition process is shown in Figure #4-3. The axioms must be followed during “zigzagging” to provide a good design solution. The reason behind the zigzag method is: a) it allows the designer to assess “coupling” at each level and b) the selection of a DP affects the selection of FRs at the next level.
4.1.1.3 The Independence Axiom & Coupling

The mapping between FRs and DPs and DPs and SVs can be described mathematically as a vector. The Design Matrix [DM] describes the relationship between FRs and DPs and DPs and SVs. A design equation should be written for each transition between domains and at each decomposition level.

\[
\{\text{FRs}\} = [A] \bullet \{\text{DPs}\} \\
\{\text{DPs}\} = [B] \bullet \{\text{SVs}\}
\]

Each element in [DM] is defined as: \( A_{ij} = \delta \text{FR}_i/\delta \text{DP}_j \), or \( B_{ij} = \delta \text{DP}_i/\delta \text{SV}_j \) which is constant in linear design.

To satisfy the Independence Axiom, the [DM] must be a diagonal or triangular. A design with a diagonal matrix is an "uncoupled" design and is ideal. A design with a triangular matrix is a "decoupled" design and is acceptable, but not ideal. The decoupled designs satisfy the Independence Axiom provided the DPs are set in a specific sequence. All other forms of [DM] are "coupled" designs and are unacceptable. See Figure #4-4 for matrix types.
4.1.1.4 The Information Axiom

Information content in Axiomatic Design is defined in terms of the probability of successfully achieving FRs by a given design. Information is defined as:

\[ I = \sum_{i=1}^{n} \log_2(1/p_i) \]

where \( p_i \) is the probability of DP\(_j\) satisfying FR\(_i\). Log can either be base 2 or base e. With a total of \( n \) FRs, the total information content of a design is the sum of each probability. This axiom states that the best design is the design with the smallest \( I \) -- the least amount of information to satisfy the FRs.

4.1.2 Performance Measure Derivation from Axiomatic Design

Figure #4–5 illustrates: 1) the derivation of performance measures from the Axiomatic Design framework and 2) the process for Manufacturing System Design (MSD) and Manufacturing System Control (MSC) as described by Cochran [3]. To design a system to accomplish its objectives, the system performance measures must be part of the MSD process because the system will respond to how it is measured. The FRs are needed to determine the DPs of the MSD but also in determining the measurable parameters on which to assess system performance. Thus, **FRs should be stated in measurable parameters** [4]. Systems Variables (SV), derived from the DPs, constitute the parameters that control the manufacturing system. (e.g. lot size, WIP quantity, kanban delivery). These SVs form the basis for calculation of the performance measures. The designer
should validate that the SVs are capable of providing the component elements for the performance measures.

![Diagram showing the relationship between customer wants, functional requirements, design parameters, system variables, and performance measures.](image)

*Figure #4-5 - Performance Measure Derivation from Axiomatic Design [3]*

### 4.2 Control Theory

#### 4.2.1 Traditional Control Theory

The key to systems control is to obtain and assess performance information on a "real-time" basis. "Real-time" being defined as knowing the problem condition that occurs in time to react to the problem situation before it re-occurs [3]. The control and operation of a system requires: 1) timely feedback of performance information, and 2) established decision-making and reaction processes.
The fundamental principle of control theory is to determine the "error" between a desired result and the actual result and take corrective action to eliminate the error. *Thus to control something, one must measure it.* The four components of the control model are: 1) measurement, 2) comparison, 3) the controller, and 4) the controlled process. Figure #4-6 illustrates the standard control theory model.

![Diagram of Control Theory Model]

*Figure #4-6 - Traditional Control Theory Model*

Actual output is measured and then compared against the desired result. The "error" is the difference between the actual result and the desired result. This "error" is communicated to the controller which determines the necessary corrective action. The corrective action is initiated and then executed at the controlled process. The key point is that the controller takes action with the "error" to control the process. This "operation specific" model can be extended to include system control (multiple operations).

Control of the system can be accomplished by:

1. *Open Loop Control* - Selecting an input and waiting for the result without interference until the result occurs, or
2. *Closed Loop Control* - Selecting an input, observing "errors", and modifying the process to attempt to achieve the desired result within the bounds of a given sampling frequency.

The critical feature of closed loop control is that of the controller. Corrective actions are determined from "errors" and initiated to bring the actual output in line with the desired result. The "errors" highlight two critical points: 1) how to redesign the system to function in the future, and 2) how to control the system to operate as it should. *The*
controllers need to be close to the system, have decision-making authority, and have timely feedback of performance information.

Applying the control theory model to MSC, a control level is determined by the physical span of control and by the degree in which human intervention is required in the control model components [3]. This thesis will focus on the performance control level where people are the "controllers". They will determine and initiate the appropriate solution based on the "error" signal.

4.2.2 Management Control Hierarchy Model

Black [1] defines a manufacturing system as a complex arrangement of physical objects (tools, equipment, people) characterized by measurable parameters (See Figure #4-7). The feedback of measurable parameters is required to control the inputs and physical objects of the manufacturing system and to mitigate external/internal disturbances affecting the system. Internal measures are fed back to operators of the manufacturing system for control. External measures are fed back to operators, management, and engineering so performance of the system relative to external customer wants can be evaluated. External disturbances affect inputs. Internal disturbances affect the manufacturing system directly [3].
The production system supports the daily operational functions of the manufacturing system. People of the production system design the manufacturing system and the performance measures.
Figure #4-8 illustrates a modified version of an Enterprise Control Model (adapted from Cochran [3]) which shows the domains of the manufacturing system and production system relative to a control hierarchy. The pyramid shape indicates the physical span of control. The cell domain is the physical domain of a logically grouped stations. An area represents the physical domain of multiple cells. The plant domain includes the production system's design and operational support activities of the plant's manufacturing system (factory management). The enterprise domain models the interactions between plants.

![Control Theory Model Applied to Manufacturing System & Production System](image)

Figure #4-9 - Control Theory Model Applied to Manufacturing System & Production System

Figure #4-9 illustrates the control theory model as applied to the use of performance measures to control the manufacturing system and to continuously improve the production system as developed by Cochran [3]. The upper loop represents the control model applied to the production system where the performance measures are compared to the strategy, business plan, historical results, and best-in-class information. Management acts to redesign and improve the manufacturing system. The lower loop shows the control model applied to the manufacturing system (described previously). The performance measures are fed back to the corresponding domain in the control hierarchy.
4.2.3 Thesis Model Basis: Linkage of Axiomatic Design & Control Theory

In summary, Figure #4-10 illustrates the linkage between the performance measure design process via Axiomatic Design and the control theory model for use of measures to control a manufacturing system.

Figure #4-10 - Linkage between Axiomatic Design & Control Theory [3]
4.3 Statistical Applications

4.3.1 Quantifying Variation

One of the main goals in manufacturing is the reduction of variation in time, quality, etc.. Decisions should be made on the interpretation of variation and the patterns of variation. The goal of MSD should be to eliminate variation as a result of the design. Therefore to make appropriate decisions, variation must be measured and incorporated into the decision-making process.

To measure variation, one needs an accumulated history of measures – a distribution. To quantify the variation for a distribution, “location” and “spread” measures can be used. The mean or average is suitable as a measure of “location”, while the standard deviation is suitable as a measure of “spread”. One can be misled by measuring only the mean because it is sensitive to outliers in the distribution and it can be “equalized” by equally offsetting high and low values. One may conclude the distribution is performing satisfactorily at an “average” level but without accounting for any “spread” of data, one does not know the reliability (consistency) of the data. The standard deviation indicates how far from the mean all other values lie. This measures accounts for all values in the distribution. The standard deviation is sensitive to outliers but it captures the variation in the data. (Formulas for the mean and standard deviation can be found in Wheeler [30]).

4.3.2 Statistical Process Control - Shewhart Control Charts

Distributions are only an accumulated history of data. They do not provide a method for distinguishing between the types of variation in a process. For the mean and standard deviation to be useful, the process has to be stable or predictable. Deming [5] defines a stable process as:

- A process whose only source of variation is through “common causes”. No “assignable causes” of variation are present.

  Common Cause: variation inherent in the system – none to occur “at random”.

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Special Cause: Variation due to a distinct event that is unpredictable and unstable over time. The cause of variation may be determined.

A stable process:

- Allows one to predict within control limits how the process should vary in future.
- Has a definable identify and capability.
- Provides the basis for process improvement.

Hence the need arises for: 1) an information system to distinguish between the (2) types of variation (common vs. special), and 2) a management system to identify what action to take with each type of variation. Deming [5] states that management by numeric goal is an attempt to manage without knowledge of what to do.

The Shewhart Control Chart is the tool that provides: 1) the detection of assignable causes of variation, 2) the control limits, and 3) a common language. The control chart becomes a powerful tool for continual process improvement only as those involved with the process learn how to use the chart to identify and remove assignable causes of variation.] (Wheeler [30] provides reference for Shewhart control chart construction).

Small Variation is the Goal – Zero Variation is Impossible
5.0 Results

5.1 Axiomatic Design Model of a Lean Manufacturing System

5.1.1 Design Derivation & Decomposition

This section derives an Axiomatic Design model of a lean manufacturing system. It includes a manufacturing systems design and control derivation to be used as the basis for the performance measures. Table #5-1 depicts the lean mfg. system design model.

Customer Wants:

As summarized by Schonberger [23], the external customer demands the following four items: Superior Quality, On-Time Delivery (reliability and responsiveness), Flexibility (quantity and variety), and Low Cost. Internal “customer” wants include cost reduction through the continuous elimination of the (7) wastes of manufacturing identified by Suzaki [26]: overproduction, waiting, transportation, processing, unnecessary inventory, unnecessary motion, and defective products.

Customer Wants Translation to Functional Requirements:

The author’s translation of the Customer Wants to Functional Requirements involve stating only (2) major FRs of lean manufacturing from which sub functional requirements can be grouped:

FR 1.0 On-Time Delivery

FR 2.0 Predictable Output Rate
<table>
<thead>
<tr>
<th>FR</th>
<th>Functional Requirements</th>
<th>DP</th>
<th>Design Parameters</th>
<th>SV</th>
<th>System Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>On Time Delivery</td>
<td>1.0</td>
<td>Produce to Actual Demand</td>
<td>1.0</td>
<td>Actual Demand</td>
</tr>
<tr>
<td>1.1</td>
<td>Produce at Customer Demand Rate</td>
<td>1.1</td>
<td>Balance System to Takt Time</td>
<td>1.1</td>
<td>Takt Time</td>
</tr>
<tr>
<td>1.2</td>
<td>Produce the Right Mix of Product</td>
<td>1.2</td>
<td>Leveled Production System</td>
<td>1.2</td>
<td>Changeover/ Setup Time</td>
</tr>
<tr>
<td>1.3</td>
<td>Produce Quantity Demanded</td>
<td>1.3</td>
<td>Machine stops when right quantity made</td>
<td>1.3</td>
<td>Kanban Quantity</td>
</tr>
<tr>
<td>1.4</td>
<td>Produce at Time Demanded</td>
<td>1.4</td>
<td>Replace part removed by next process</td>
<td>1.4</td>
<td>Kanban Delivery</td>
</tr>
<tr>
<td>1.5</td>
<td>Produce within Lead Time</td>
<td>1.5</td>
<td>Lead Time Reduction Methods</td>
<td>1.5</td>
<td>Conveyance/ Lot Prcd. Policies</td>
</tr>
<tr>
<td>1.5.1</td>
<td>Eliminate Lot Delay</td>
<td>1.5.1</td>
<td>Lot Size Reduction (1 pc. Flow)</td>
<td>1.5.1</td>
<td>Lot Size</td>
</tr>
<tr>
<td>1.5.2</td>
<td>Minimize Transportation</td>
<td>1.5.2</td>
<td>Cellular Layout</td>
<td>1.5.2</td>
<td>Transfer Distance</td>
</tr>
</tbody>
</table>

| 2.0 | Predictable Output Rate | 2.0 | Predictable Resources Inputs | 2.0 | Standardized Work Methods |
| 2.1 | Predictable Time Output | 2.1 | Predictable Production Resources | 2.1 | Standard Work |
| 2.1.1 | Start to # Operators Required | 2.1.1 | Sum of Manual Time/Takt Time | 2.1.1 | Manual Operation Time |
| 2.1.2 | Establish Work Sequence within Takt Time | 2.1.2 | Standard Work (Man-Machine Integration) | 2.1.2 | Mutual Relief Movement |
| 2.1.3 | Maintain Constant Min. Oper. WIP Level | 2.1.3 | Kanban & Operating WIP Limits | 2.1.3 | Total WIP (Kanban + Op WIP) |
| 2.1.4 | Maximize Equipment Availability | 2.1.4 | Total Productive Maintenance (TPM) | 2.1.4 | TPM schedule |
| 2.1.5 | Workforce Flexibility | 2.1.5 | Multi-Skilled Worker | 2.1.5 | # of jobs a worker can perform |
| 2.1.6 | Maximize Worker Utility | 2.1.6 | Balancing Line | 2.1.6 | Number of workers in cell |
| 2.2 | Predictable Quality Output | 2.2 | Produce without defects | 2.2 | Defect Prevention |
| 2.2.1 | Produce "zero" defects | 2.2.1 | Machine Stops when defect detected | 2.2.1 | Mistake Proofing Devices |
FR - DP - SV Decomposition

The design decomposition in Table #5-1 contains the detail of the lean manufacturing system model. This section highlights some key points of the model and documents the Design Matrices.

From Table #5-1, one must produce the right quantity of the right product at the customer demand rate within the required lead time to satisfy the obligation of “on time delivery”. To achieve these objectives, the system incorporates DPs such as lead time reduction methods and leveled and balanced production systems. The corresponding SVs therefore are takt time, changeover times, kanban quantity and delivery, and lot sizes.

To achieve a predictable output rate, the system needs to: produce at a predictable time output rate with predictable quality and have flexible, efficient, and available resources. The DPs for this major FR include standard work, established WIP controls, productive maintenance programs, line balancing, cross training programs, and defect free processes. The SVs governing this FR domain focus on standard work control variables and defect prevention devices.

Design Matrices

A design matrix [DM] can be developed based on the FRs - DPs - SVs of the design in Table #5-1. According to the Axiomatic Design methodology a [DM] must be generated at each level of the design to assess coupling within the design. The design equations corresponding to the design in Table #5-1 are:

\[
\begin{bmatrix}
    FR1.0 \\
    FR2.0
\end{bmatrix} =
\begin{bmatrix}
    X0 & [DP1.0] \\
    0X & [DP2.0]
\end{bmatrix}
\]

\[
[DP1.0] =
\begin{bmatrix}
    X0 & [SV1.0] \\
    0X & [SV2.0]
\end{bmatrix}
\]
\[
\begin{align*}
\{FR1.1\} &= \begin{bmatrix} X & 0 \end{bmatrix} \begin{bmatrix} DP1.1 \end{bmatrix} \\
\{FR1.2\} &= \begin{bmatrix} 0 & X \end{bmatrix} \begin{bmatrix} DP1.2 \end{bmatrix} \\
\{FR1.3\} &= \begin{bmatrix} 0 & X \end{bmatrix} \begin{bmatrix} DP1.3 \end{bmatrix} \\
\{FR1.4\} &= \begin{bmatrix} 0 & 0 \end{bmatrix} \begin{bmatrix} DP1.4 \end{bmatrix} \\
\{FR1.5\} &= \begin{bmatrix} 0 & 0 \end{bmatrix} \begin{bmatrix} DP1.5 \end{bmatrix}
\end{align*}
\]

\[
\begin{align*}
\{FR2.1\} &= \begin{bmatrix} X \end{bmatrix} \begin{bmatrix} DP2.1 \end{bmatrix} \\
\{FR2.2\} &= \begin{bmatrix} 0 \end{bmatrix} \begin{bmatrix} DP2.2 \end{bmatrix}
\end{align*}
\]

\[
\begin{align*}
\{FR1.5.1\} &= \begin{bmatrix} X \end{bmatrix} \begin{bmatrix} DP1.5.1 \end{bmatrix} \\
\{FR1.5.2\} &= \begin{bmatrix} 0 \end{bmatrix} \begin{bmatrix} DP1.5.2 \end{bmatrix}
\end{align*}
\]

\[
\begin{align*}
\{FR2.1.1\} &= \begin{bmatrix} X & 0 \end{bmatrix} \begin{bmatrix} DP2.1.1 \end{bmatrix} \\
\{FR2.1.2\} &= \begin{bmatrix} 0 & X \end{bmatrix} \begin{bmatrix} DP2.1.2 \end{bmatrix} \\
\{FR2.1.3\} &= \begin{bmatrix} 0 & X \end{bmatrix} \begin{bmatrix} DP2.1.3 \end{bmatrix} \\
\{FR2.1.4\} &= \begin{bmatrix} 0 & 0 \end{bmatrix} \begin{bmatrix} DP2.1.4 \end{bmatrix} \\
\{FR2.1.5\} &= \begin{bmatrix} 0 & 0 \end{bmatrix} \begin{bmatrix} DP2.1.5 \end{bmatrix} \\
\{FR2.1.6\} &= \begin{bmatrix} 0 & 0 \end{bmatrix} \begin{bmatrix} DP2.1.6 \end{bmatrix}
\end{align*}
\]

\[
\begin{align*}
\{DP2.1.1\} &= \begin{bmatrix} X & 0 \end{bmatrix} \begin{bmatrix} SV2.1.1 \end{bmatrix} \\
\{DP2.1.2\} &= \begin{bmatrix} 0 & X \end{bmatrix} \begin{bmatrix} SV2.1.2 \end{bmatrix} \\
\{DP2.1.3\} &= \begin{bmatrix} 0 & X \end{bmatrix} \begin{bmatrix} SV2.1.3 \end{bmatrix} \\
\{DP2.1.4\} &= \begin{bmatrix} 0 & 0 \end{bmatrix} \begin{bmatrix} SV2.1.4 \end{bmatrix} \\
\{DP2.1.5\} &= \begin{bmatrix} 0 & 0 \end{bmatrix} \begin{bmatrix} SV2.1.5 \end{bmatrix} \\
\{DP2.1.6\} &= \begin{bmatrix} 0 & 0 \end{bmatrix} \begin{bmatrix} SV2.1.6 \end{bmatrix}
\end{align*}
\]

\[
\begin{align*}
\{FR2.2.1\} &= \begin{bmatrix} X \end{bmatrix} \begin{bmatrix} DP2.2 \end{bmatrix} \\
\{DP2.2.1\} &= \begin{bmatrix} X \end{bmatrix} \begin{bmatrix} SV2.2.1 \end{bmatrix}
\end{align*}
\]

From the (12) design equations, all but (1) are uncoupled designs. The [DM]s are all diagonal except for the “decoupled” design equation which has a triangular matrix. This is acceptable, although not ideal under Axiomatic Design. The reason for coupling here is that the functional requirement “produce at time needed” is accomplished by both delivering in the required lead time and by producing at the time demanded by the kanban signal. Two DPs satisfy the FR, therefore we have coupling.

5.1.2 Derivation of Performance Measures from Axiomatic Design Model
Table #5-2 summarizes the performance measures derived from the Axiomatic Design model of the lean manufacturing system. The FRs in the model were stated as measurable parameters. Therefore, in determining the performance measures, a validation was made to ensure the measures not only captured the FR but also that the measures’ calculations were based on the SVs in the model.

### Table #5-2 - Performance Measures derived from Lean Mfg. Design Model

<table>
<thead>
<tr>
<th>FR Requirements</th>
<th>PM Performance Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 On Time Delivery</td>
<td>1.0 % On Time Delivery</td>
</tr>
<tr>
<td>1.1 Produce at Customer Demand Rate</td>
<td>1.1 Adherence to Target</td>
</tr>
<tr>
<td>1.2 Product the Right Mix of Product</td>
<td>1.2 Changeover Time</td>
</tr>
<tr>
<td>1.3 Produce Quantity Demanded</td>
<td>1.3 Fill Rate %</td>
</tr>
<tr>
<td>1.4 Produce at Time Demanded</td>
<td>1.4 % Successful Starts</td>
</tr>
<tr>
<td>1.5 Produce within Lead Time</td>
<td>1.5 Throughput Time</td>
</tr>
<tr>
<td>1.5.1 Eliminate Lot Delay</td>
<td>1.5.1 Lot Size</td>
</tr>
<tr>
<td>1.5.2 Minimize Transportation</td>
<td>1.5.2 Part Travel Distance</td>
</tr>
</tbody>
</table>

### 2.0 Predictable Output Rate

<table>
<thead>
<tr>
<th>2.1 Predictable Time Output</th>
<th>2.0 System Output Capability (Cpk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1.1 Staff to # Operators Required</td>
<td>2.1.1 # Workers Over/(under) target</td>
</tr>
<tr>
<td>2.1.2 Establish Work Sequence within Takt Time</td>
<td>2.1.2 % Standard Work</td>
</tr>
<tr>
<td>2.1.3 Maintain Constant Min. Oper. WIP Level</td>
<td>2.1.3 WIP</td>
</tr>
<tr>
<td>2.1.4 Maximize Equipment Availability</td>
<td>2.1.4 Equipment Uptime %</td>
</tr>
<tr>
<td>2.1.5 Workforce Flexibility</td>
<td>2.1.5 # workers fully cross-trained</td>
</tr>
<tr>
<td>2.1.6 Maximize Worker Utility</td>
<td>2.1.6 Labor productivity</td>
</tr>
<tr>
<td>2.2 Predictable Quality Output</td>
<td>2.2 First Time Through Perfect</td>
</tr>
<tr>
<td>2.2.1 Produce &quot;zero&quot; defects</td>
<td>2.2.1 # Defects</td>
</tr>
</tbody>
</table>

The measures derived in Table #5-2 are based on the following assumptions:
• A work cell has been established
• “Flow” has been established within the work cell
• Takt Time is known
• Work sequence within Takt Time & manpower for work cell are known
• Minimum operating WIP level to maintain flow has been defined

Performance Measure Description

• **On Time Delivery % (delivery reliability)** – Provides information on cumulative delivery reliability performance (per week/per month). This should be measured as a function of actual “pull” dates and customer kanban quantity (per ship set, per daily required quantity, etc.). “On time” is defined as an order that is complete (right quantity of right product) and delivered at the time needed. This measure complements the “Adherence to Target” measure. The work cell could be meeting target output quantity, but it may not necessarily be the “right product”.

• **Adherence to Target (linearity)** – Work cell production targets are set based on takt time, which is the customer demand rate. Each work cell must meet those targets on a daily basis. In a repetitive flow environment, “linearity” is important — producing at the daily target level consistently (predictably). This measure shows the deviation (+/-) from target. Its outcome is dependent on the cell’s management of process quality, WIP, and work sequence to takt time.

• **Changeover Time** – Captures the required changeover time at machines/stations. Changeovers impact capacity and the sequence of which parts are processed. One can compare the average changeover times to takt time to see how much input is being lost. Changeover times must be stable to establish proper sequence control and planning. Although not a perfect measure of build to sequence, this measure indicates if mixed model production is feasible.

• **Fill Rate %** – Provides measure of satisfying kanban quantity demand. Measures if kanban order is complete in quantity and “right product”. Indicates the portion of complete orders to total orders produced.

• **% Successful Starts** – Measures the number of successful starts to kanban signal versus the total “pull” signals. Indicator of any delays in not starting parts when authorized by kanban.

• **Throughput Time (responsiveness)** – Measures the average time a part spends as WIP through the system. Ideally each part should be time stamped to record actual throughout times from start of process to completion. Mathematically, throughput time is a function of WIP and Takt time [Little’s Law: Throughput Time = (WIP) X (Takt Time)]. With lean mfg., no expediting is allowed in the cell. Parts are just introduced into the normal flow.
• **Lot Size** - Indicates the average lot size used through work cell. Ideally, the lot size should be “one” with single-piece flow. Average lot size provide an indicator of the time wasted in the work cell as “queue time”.

• **Part Travel Distance** - Provides measure of “transportation waste” within the system. With lean mfg. system, transportation must be at a minimum as all operations should be contained within a work cell.

• **System Output Capability** - Application of the Cpk (process capability) index from SPC to the work cell output rate. The “engineering limits” will be those established by the customer. A Cpk > 1.0 for output capability indicates the six sigma spread falls completely within the “engineering limits”. Wheeler [30] provides the formula for Cpk.

• **Output Rate (minutes/part)** - This measures establishes the rate at which the work cell can consistently produce output. This measure can be compared to Takt Time to verify if demand can be satisfied.

• **Number of Workers Over (under) Target** - Work cells are staffed according to “Sum of Operator Loop Cycle Time/Takt Time” formula. This measure indicates deviation form planned cell manpower levels in term of absolute headcount.

• **% Standard Work** - Documents the portion of the total work cell’s operations have documented and maintained Standard Work.

• **Average WIP** - Provides aggregate information on cell WIP performance to allowable operating WIP limits. WIP in the cell is a function of defined operator work “loops” (not necessarily work stations), manual/automatic operations, and kanban limits. Operating a cell above established limits drives longer throughput times, increases exposure to quality issues, and demonstrates “pull” not occurring within the cell. Operating below established limits will lead to starvation (“bubbles”) in the cell.

• **Equipment Uptime** - Indicates the portion of total working time that the equipment is available (in proper working condition). In lean mfg. systems, machines must be available on demand to avoid flow disruption. Availability is assumed by standard work.

• **% Operators Fully Cross-Trained** - Indicates what portion of total work cell personnel are capable of performing every operation within the work cell. The multi-skilled worker is an essential part of work cell capability and flexibility.

• **Labor Productivity** (output/operator) – focuses on meeting daily output targets with the planned cell staffing. This measure focuses the cell on maximizing worker utility within the cell.

• **First Time Through Perfect (FTTP)** – This is a measure of process quality. Percent of daily completed parts that are processed through the cell with zero defects/rework.

• **# Defects** – Provides frequency information for defects/rework. This information is used to construct a Pareto chart to identify high leverage improvement areas.
5.2 IRC Performance Measures for Lean Manufacturing System Control

5.2.1 IRC Objectives & Guiding Criteria
The performance measures derived from the lean manufacturing system model were
designed to perform two functions: 1) systems control & improvement, and 2) influence
behavior consistent with lean manufacturing principles. SPC was also incorporated into
the measurement system to determine the appropriate action to be taken in response to
variation and to determine process predictability.

The general criteria developed by the working project teams for the performance measures
that were to be “married” with the measures developed in Section 5.1.2 (Table #5-2)
were:

- Simple, Easy to Use & Interpret
- VITAL FEW
- Timely
- Flexible (by area over time)
- Consistent with Takt-Flow-Pull – the three principles most emphasized at
  Boeing through the Shingijutsu Consultants.

5.2.2 IRC Performance Measures at the (3) Management Control Levels
Table #5-3 summarizes the results of applying the control theory model (Section 4.2.2),
the IRC general criteria (Section 5.3.1) and the performance measures (Section 5.1.2) for
each management level.
Table #5-3 - IRC Performance Measures at the (3) Management Levels

<table>
<thead>
<tr>
<th>Category</th>
<th>Cell</th>
<th>General Supervisor</th>
<th>Factory Mgr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivery</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linearity</td>
<td>Adherence to Target</td>
<td>Actual Output/Target Output</td>
<td></td>
</tr>
<tr>
<td>Responsiveness</td>
<td>Throughput Time</td>
<td>Avg. Throughput Time/Target Throughput Time</td>
<td>Lead Time (Flow Time)</td>
</tr>
<tr>
<td>Reliability</td>
<td>On Time Delivery %</td>
<td>On Time Delivery %</td>
<td>On Time Delivery %</td>
</tr>
<tr>
<td>Tardiness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quality</td>
<td>First Time Through Perfect (FTTP) %</td>
<td>FTTP %</td>
<td># Defects</td>
</tr>
<tr>
<td></td>
<td># Defects &amp; Rework Time</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inventory</td>
<td>Average WIP</td>
<td>Avg. WIP/Target WIP</td>
<td>Inventory Level or Turns</td>
</tr>
<tr>
<td>Productivity</td>
<td>Labor Productivity (Output/Mechanic)</td>
<td>Actual Labor Productivity/Target Productivity</td>
<td>Actual Headcount</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Changeover Time (at Press)*</td>
<td>Changeover Time Capability</td>
<td></td>
</tr>
</tbody>
</table>

* Appropriate for Fab cells and Single component cells

Figure #5-1 illustrates the performance measures at the work cell level in terms of process versus results measures. At the work cell level, more measures are “process” focused as they are used for system control, whereas at the factory management level, the measures are “results” focused, where they are used for evaluating performance to plan.
The previous IRC performance measures were missing key system information (inventory, throughput times, etc.). The new measurement system was designed to include all relevant information for system control – a balanced approach. The analogy is that of an airplane cockpit as described by Brown [2]. Airplane pilots spend the majority of time monitoring several key measures and controlling the plane so that it arrives safely at its destination. Pilots have timely and good data and they understand the relationship between different measures. Pilots do not just care about one measure. They care about many measures of the flight (airspeed, fuel level, altitude, bearing, etc.). THE RELIANCE ON ONE INDICATOR CAN BE FATAL!!

Table #5-4 illustrates the reporting frequency of each work cell measure as well as the appropriate type of control chart for the measure (IX + MR = Individual Record and Moving Range; X + R = “X-bar” and Range):
Table #5-4 - Work Cell Performance Measure Frequency & Control Chart Type

<table>
<thead>
<tr>
<th>Metric Category</th>
<th>Metric</th>
<th>Frequency per Day</th>
<th>SPC Chart</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Delivery</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linearity</td>
<td>Adherence to Target</td>
<td>Hourly, Daily</td>
<td>IX + MR</td>
</tr>
<tr>
<td>Responsiveness</td>
<td>Throughput Time</td>
<td>Daily</td>
<td>X + R</td>
</tr>
<tr>
<td>Reliability</td>
<td>On Time Delivery %</td>
<td>Daily</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tardiness</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Quality</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>First Time Through Perfect (FTTP) %</td>
<td>Daily</td>
<td>IX + MR</td>
</tr>
<tr>
<td></td>
<td># Defects &amp; Rework Time</td>
<td>Daily</td>
<td></td>
</tr>
<tr>
<td><strong>Inventory</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total WIP</td>
<td>Daily</td>
<td>X + R</td>
</tr>
<tr>
<td><strong>Productivity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Labor Productivity (Output/Mechanic)</td>
<td>Daily</td>
<td>IX + MR</td>
</tr>
<tr>
<td><strong>Flexibility</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Changeover Time</td>
<td>Daily</td>
<td>IX + MR</td>
</tr>
</tbody>
</table>

5.2.3 Pilot Work Cells

Within the IRC three types of work cells existed: single component, multi-component fabrication, and multi-component assembly. The differences were characterized in Section 2.1.4. Since all work cells were not implemented, the project work focused on established and “mature” work cells. It was also decided to capture at least one work cell of each type. Therefore, the work cells used as “pilots” for this project were:

4SC - Single component cell - 747/737 Ceiling Panel Work Cell
4MC - Multi-component fabrication work cell - Crushed Core Components
7MS - Multi-Component assembly work cell - 737X Stow Bin assembly.

The majority of work was performed within 4SC and carried forward to other cells. 4MC and 7MS were just beginning to implement during the last 2 months of the project. Other work cells had also started on their own even though they were not designated as pilot
work cells because they thought the information was useful compared to the previous measures.

Performance measures were similar across single component and multi-component fabrication work cells. The difference with multi-component assembly cells was that the measures were applied along the critical path for the assembly of stow bins. Assembly cells consisted of "mini-cells" that fed the main assembly line. Measures could have been set-up for each mini-cell (and may be in future) but the team began with measures focused along the critical path.

5.3 Measurement Media

5.3.1 Work Cell Measurement System

The measurement media used for the work cell performance measures was a 4' X 8' white board with markers that was located within each work cell. A sketch of the board is shown in Figure #5-2. The white board was formatted to contain daily measures and cumulative weekly performance data. The reverse side of the white board contained monthly and quarterly performance information. The white board was a simple media to record an analyze performance. Its format could be changed readily to accommodate modifications.

<table>
<thead>
<tr>
<th>Cell Prod. Schedule</th>
<th>Hourly Output Targets (Takt)</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Station WIP</td>
<td>WIP vs. Time Graph</td>
</tr>
<tr>
<td></td>
<td>Average WIP</td>
<td>On Time Delivery % and Tardiness graph</td>
</tr>
<tr>
<td></td>
<td>Deviation from Target (Takt) vs. Time Graph</td>
<td>First Time Through Perfect (FTTP) Data by Operation</td>
</tr>
</tbody>
</table>

*Figure #5-2 - Work Cell Performance Measurement Board*
The author attempted to involve the work cell members in data collecting and analysis with the hope of creating ownership of the data into the cell. The measures were designed for operations control and improvement. If the "controllers" (cell members) were not going to use the data, then the system was useless. Schonberger [23] shares the same view. He states that data recording comes first -- the tools are cheap and simple (markers and white board). It is important to make the recording an integral part of an operator's job to record performance. The person who records is inclined to analyze. The analyzer is then inclined to think about solutions.

All measures were recorded in a graphical format to interpret patterns in variation of performance. SPC charts were designed to be used by work cell engineers. A critical feature of the system was to allow the work cell engineer to do more analysis of the data while allowing work cell members to control the operation of the system. The work cell manager was responsible for reviewing the cell performance information daily at the morning work cell meetings and ensuring problems with the system were being corrected.

5.3.2 Area Management & Factory Management

Once all work cells were functioning with the new cell measurement systems, a report could be generated for the IRC Area Managers which would show deviation from targets and actual performance levels in the performance measure for each work cell under their span of control (See Figure #5-3). Similarly for the factory manager, a report could be generated with aggregate numbers of cell or area measures. This method, however, is still management by the numbers. The reports only show numbers, not the patterns of performance of the system. The intention was to force the Area Managers and Factory Manager to visit the shop floor and "see" the performance in the work cells. The white board with the daily, weekly, and monthly performance in graphical format & control charts would identify work cell performance reliability and sources of variation. The reports were solely to be used to identify which work cells may need assistance.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell 1</td>
<td>-10%</td>
<td>+200%</td>
<td>25%</td>
<td>100%</td>
<td>+60%</td>
<td>-4%</td>
</tr>
<tr>
<td>Cell 2</td>
<td>-15%</td>
<td>0%</td>
<td>90%</td>
<td>100%</td>
<td>0%</td>
<td>-20%</td>
</tr>
<tr>
<td>Cell 3</td>
<td>+15%</td>
<td>+60%</td>
<td>80%</td>
<td>85%</td>
<td>+20%</td>
<td>+20%</td>
</tr>
<tr>
<td>Cell 4</td>
<td>-40%</td>
<td>+150%</td>
<td>75%</td>
<td>79%</td>
<td>+80%</td>
<td>+50%</td>
</tr>
<tr>
<td>Cell 5</td>
<td>-68%</td>
<td>+120%</td>
<td>60%</td>
<td>66%</td>
<td>-50%</td>
<td>-10%</td>
</tr>
<tr>
<td>Cell 6</td>
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<td>33%</td>
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<td>-25%</td>
</tr>
<tr>
<td>Cell 7</td>
<td>-80%</td>
<td>+110%</td>
<td>50%</td>
<td>20%</td>
<td>-10%</td>
<td>-70%</td>
</tr>
<tr>
<td>Cell 8</td>
<td>-20%</td>
<td>+30%</td>
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<td>0%</td>
<td>+30%</td>
</tr>
<tr>
<td>Cell 9</td>
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<td>100%</td>
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<td>+26%</td>
</tr>
<tr>
<td>Cell 10</td>
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<td>0%</td>
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<tr>
<td>Cell 11</td>
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<td>-10%</td>
<td>100%</td>
<td>75%</td>
<td>0%</td>
<td>+60%</td>
</tr>
<tr>
<td>Cell 12</td>
<td>-20%</td>
<td>+50%</td>
<td>60%</td>
<td>70%</td>
<td>+80%</td>
<td>-20%</td>
</tr>
</tbody>
</table>

*Figure #5-3 - Area Manager Performance Measure Report*

### 5.4 IRC Work Cell Example

#### 5.4.1 Work Cell 4SC - Description

The 4SC work cell was a single component work cell that produced ceiling panels for the 737 and 747 airplanes. The average takt time in the cell was 20 minutes per ceiling panel, therefore its daily production target was on average approximately 23-25 panels per day. The operations were as shown in Figure #5-4.

*Figure #5-4 - Work Cell 4SC Representative Layout*
The press and NC router operations were separate from the work cell and were organized as functional departments. The remaining operations were all part of the work cell configuration. The work cell required 7-9 mechanics. Customers (final assembly) demanded "ship sets" of panels (22/set or 66/set depending on model). Per each airplane model's ship set, there were 4-12 different part numbers.

5.4.2 4SC Performance Measures
This section illustrates the application of the new performance measures to the 4SC work cell with sample data and a discussion of any pertinent issues. The data presented is shown for a month's time frame and was formatted to be representative of the scenarios that were encountered.

**WIP**

![WIP vs. Time Graph](image)

*Figure #5-5 - 4SC WIP Profile*

Figure #5-5 illustrates the WIP profile for 4SC. Given the defined work sequences for the operators, established SWIP (standard WIP), and established kanban limits, 4SC could have operated at a minimum WIP level of 17 parts. From the data, the cell operated severely over the minimum operating WIP level. Reasons for this "overage" were: no
enforcement of "1-pc. Flow" discipline; no adherence to kanban limits on transportation carts, no "pull" from assembly through the cell.

WIP could be used as a surrogate measure of throughput time for the work cell. Assuming a 20 minute takt time and an average WIP level of 60 parts, the average throughput time at the beginning of the month was 20 hours. As the cell manager enforced the kanban rules and "1-pc. Flow" discipline, the WIP level was reduced to about 36 parts. Further enforced discipline and the reestablishment of "pull" from assembly reduced WIP to approximately 23 parts. At this level, throughput time was estimated to be 8 hours. Thus, a dramatic reduction in WIP plus a corresponding reduction in throughput time. WIP levels by station were assessed 3X during the day to ensure discipline and to assess constraints in the process. As physical controls and discipline was ingrained, the sampling interval could be reduced; however it must noted that WIP control is very important in lean manufacturing – not only in a reduced aggregate quantity but also in its placement within the work cell to maintain continuous flow.

**Throughput Time**

To measure throughput time, each individual part had to be time stamped at the beginning of the process at again at the end of assembly to gather a distribution. Within the IRC, there was no formal system to do this. Within the work cell, the team tried to sample (1) part a day to validate throughput time that was "estimated" from the WIP levels. The suspicion was that the actual throughput times were higher than those estimated by the WIP calculation because of operation cycle times being greater than takt times. The actual data on throughput time was sparse and its collection method unreliable; hence it will be not presented for discussion.
First Time Through Perfect & Defects

![First Time Through Perfect vs. Time](image)

*Figure #5-6 - 4SC First Time Through Perfect Profile*

To capture process quality in the work cell, the team developed a simple method to capture "fallout" in the process. This data was important because poor quality issues caused: interruption in continuous flow, added rework, additional WIP, and reduced output. The team constructed a card that was attached to the "traveler" with each part. The FTTP card identified the majority of potential defects generated in the process. When a mechanic detected a "defect", he simply marked a box next to the corresponding defect. Calculation of "first time through perfect" yields was straightforward. The number of defects was extracted from the FTTP cards and categorized. The data in Figure #5-6 shows that the FTTP % increased over the month from 70% level to the 95% level.

FTTP was a great "real-time" process quality measure that forced the work cell to prevent defects from reoccurring. The data allowed the cell to take action daily as compared to the old system which reported the data on a monthly basis. The problems encountered with this system were: 1) a failure to obtain all FTTP cards for the given days output and 2) a psychological effect where 100% FTTP was obtained even though defects and rework had occurred. This was caused by having the displayed measurement board
attracting a lot of attention and having the work cell members not want to report any problems because of pride and because of “grading”.

Changeover Time
The enabler for product flexibility within the work cell is to have “zero” (< 10 minute) changeover time at the press and router operations. The press operation was the major constraint as it set the production sequence for the cell and had the most variable and longest changeovers. One changeover team was responsible for the entire press department. Scheduling and sequencing changeovers was difficult and ensuring equipment and manpower were available was also a concern. It was demonstrated one time within the IRC that a die change at the press could be accomplished in 10 minutes. However, that was a one-time affair. Die changes seemed to never happen in under 30 minutes. The work cell stored “off-line” inventory for their responsible part families because > 3 die changeovers could not happen in a shift. The 4SC press operator collected data on the changeovers. The data was sparse (only 12 data points over 3 months), but the results show that on average changeovers were 48.5 minutes with a range of 100 minutes.

Adherence to Target

![Deviation From Target](image)

*Figure #5-7 -4SC Deviation from Target Profile*
Given the customer demand rate for the work cell, daily production output targets were set. The “adherence to target” measure was used to capture the deviation from the output target. Linearity (extremely small deviations form daily targets) is a necessity as the work cell tries to produce at a stable output rate. From Figure #5-7, 4SC was not very successful in achieving “linearity”. Its output rate may be predictable but not within the “engineering limits” that were required for proper control of the system. Most “spikes” in the data came from weekend output that was all “charged” to one manufacturing day when in actuality there were three days of output. Output targets were established hourly and posted in the work cell. This allowed the cell to compare the actual output at any given time during the day to the target. Adjustments and corrective actions could be implemented early in the day if an “error” existed. This was an attempt to alleviate the excess weekend overtime that was required to make up for the negative deviations that accumulated during the regular work week.

On Time Delivery

![On time Delivery % vs. Time](image)

*Figure #5-8 - 4SC On Time Delivery Performance Profile*

The delivery reliability measure was the strictest measure of all. This measure changed the mindset of the work cell to be focused on true customer needs. Previous measures of production output did not capture if the work cell produced the “right product” – it was
just an aggregate output measure. The "On Time Deliver %" was a measure designed to capture true delivery reliability of the system. For 4SC, the customer demanded "ship sets" of ceiling panels. If the customer needed 22 panels in a ship set (19 part A, 2 part B, 1 part C) then 4SC had to deliver that complete ship set at the required time. This completely changed the mindset of 4SC who had been previously focused on just meeting quantitative output numbers. To be considered 100% on time, the order had to correct and complete (the right quantity of the right product) AND had to be delivered on the required due date. If the ship set was shy just one part, the order was not on time. If the ship set was complete, but delivered a day late, it was not on time. This measure truly influenced behavior and was meant to drive strict adherence to customer demand. 4SC delivery performance improved over the course of time (Figure #5-8) as the work cell adjusted its scheduling and inventory control practices.

In addition to "On Time Delivery %" as a cumulative measure for ship sets delivered per month, 4SC was also tracking the "tardiness" of each order. Tardiness was defined as being "of those orders that were late, how late were they". At the beginning of the project, orders were on average in the 4-5 day range with a std. deviation of 1 day. As the project concluded, tardiness was driven to the 2-3 day range with a standard deviation .8 day. From the customer's perspective, a late order is a late order. 4SC did show improvement that was not reflected in the On Time Delivery % measure.
Labor Productivity

![Labor Productivity vs. Time](image)

*Figure #5-9 4SC Labor Productivity Profile*

Labor productivity was a "sensitive" measure for the work cell. It certainly provoked conversations among the work cell members about the performance of each individual member as performance was framed in a "output/mechanic" measure. The work cell also became driven to correct quality issues and part shortage issues as these factors impacted output and flow through the work cell. This measure was certainly skewed by the aforementioned quality and shortage problems and was thus difficult to use as a stable measure at the current time. Figure #5-9 displays the data for 4SC.

**Summary**

The 4SC work cell was a great "learning lab" for these measures. It pointed out that just grouping stations into a "U-shaped" cell is not the equivalent of operating a lean manufacturing system. The data recording was driven down to the operators -- the controllers of the system. The measures captured key system information that was missing from previous measures. The data was collected and used "real-time" to correct errors. Some measures lacked integrity in the data collection process and a more robust process will have to be established. The challenge for the IRC is to drive the reason for the measures -- system control and improvement, not "grading". As soon as 4SC recognized the exposure their measures were attracting, the more "perfect" the measures became.
5.5 Implementation Process

The author’s recommendation for performance measures implementation is the continued use of “lead user” work cells per each work cell type (single component, multi-component, etc.) to share new enhancements with operational work cells. Ideally, the performance measures should be implemented during the cell start-up phase identified in the IRC work cell implementation plan. However, many work cells have already been implemented and are operational. There is no other “best time”, especially if management continues to use the old metrics to monitor work cell performance. Perhaps once the IRC establishes its plan for becoming the “model” lean manufacturing center for Boeing, there will be a task that will specify “changing performance measures” for the entire organization simultaneously. Having two measurement systems posed a conflict in work cell behavior.

A major mistake during implementation of the pilot measures was in the assumption that all people within the IRC (cell members & management) understood lean manufacturing principles. This was false. Much time was expended teaching relationships between the performance measures (i.e. WIP impact on throughput times, changeover time impact on build sequence and WIP, etc.) and trying to “sell” the new performance measures to the work cells. The author’s recommendation is to teach the measures one at a time to all people in the work cells. Then each work cell can establish the data collection process and presentation format for each measure. Once all measures have been discussed, the complete work cell measurement board can be officially “turned on”. Once all work cells are functioning, an Information Systems program could be developed to aggregate all work cell data for factory reporting (if such a cost was to be undertaken). The IRC must evaluate the trade-offs between such an extensive IT system versus the proposed “white board” and Microsoft Excel/Access based system. The risk of completely automating the system and taking the cell members out of the data collection and reporting loop may transform this from a control system to “just another tracking system”.

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6.0 Managerial Issues

6.1 Performance Measures as a Means to Change the Organization

6.1.1 Use of Measures for System Control & Improvement

The performance measures will be used differently depending on the management control level – work cell vs. area management vs. factory management. In the work cell, the measures are used for "real-time" control and improvement of the manufacturing system by the operators and work cell managers. At the area management level, the measures are still used for control although on a daily basis, not "real-time". Area managers must analyze the measures to validate if the behaviors being driven by the measures are acceptable. At the factory management level (production system design level), the measures indicate if the manufacturing system is functioning according to plan or if a redesign of the system is required. The factory management level also compares the measure to best-in-class measures and historical measures to evaluate performance improvement and set appropriate targets.

From these uses, the differentiating factor in the uses of the performance measures is in the timeliness required for using the performance measures at each management level. This correlates back to the "process vs. results" measure contrast. At the work cell level, the measures are "process" measures where the cell needs to perform operations correctly. At the middle management level, the measures are a combination of process and result measures. Finally, at the factory management level the measures are "result" measures as they are used only to compare performance to plan or the best-in-class performers.

6.1.2 Use of Measures to Influence Behavior

The performance measures were designed to alter the behavior and thinking of management and the operators by focusing attention on other facets of manufacturing performance other than "schedule" which was optimized at the expense of other measures (inventory, quality, throughput time). The desired behaviors are:
- On time delivery of customer demanded quantities
- Predictable processes
- Meet TAKT time - Single Piece FLOW – PULL from customer
- Reduce lead time

The issue with influencing the desired behaviors is that it was inconsistent with the behaviors driven from Boeing senior management down through the organization. Schedule performance outweighed any other measure. Use of the performance measures by the work cells was sporadic because they were not supported by management from the top-down and because performance evaluation criteria was inconsistent with the new performance measures.

6.1.3 Use of Measures in Influencing World-View

"World-view" can be described by how employees think of their role in the organization. The new performance measures modify the "world-view" of the employees. The employees at the work cell level are now given the responsibility of "controllers" to act on performance information in the cell to achieve the desired results. The employees also take part in the data collection and analysis to synthesize solutions that will lead to more predictable performance in the work cell. This has been a change in the Boeing culture where it has been the engineers who has previously collected data, conducted analyses, and recommended solutions. At the upper management levels, the measures were again designed around the basics of lean manufacturing (Takt-Flow-Pull) and system predictability to influence managers to take a proactive role in redesigning the system if performance was unsatisfactory. This again changed the Boeing culture from a "reactive" management role to a more proactive management role.

6.1.4 Use of Measures in Performance Evaluation

Since individuals/groups will tend to concentrate on the areas where their performance clearly affects their rewards, it is important for the reward structure to be tied to the
performance measurement system and aligned with the performance evaluation criteria. There is still an unsettled debate as to whether rewards drive temporary or permanent compliance. Kohn [17] views rewards as buying temporary compliance. Once the rewards disappear, people return to their old behavior. Rewards do not create enduring commitment to any value or action. The intrinsic motivator is the self-directed (not reward driven) interest in work.

Suzawa [27] describes the Japanese philosophy on rewards. Suzawa notes that all activities are encouraged to be team activities and thus those efforts are rewarded as teams. Raises and bonuses are awarded to individuals but teamwork is used to assess an individual’s performance. Team performance is measured in two dimensions:

- Hard Dimension: Dollars saved; Value added,
- Soft Dimension: Level of accepted challenge, Quality of Teamwork

If the group achieves more than the individual, then the team contributors (the group) must be rewarded. This strengthens camaraderie and permits the teams to accept new challenges.

From the internship experience at Boeing, the author recommends that the IRC consider devising a small group incentive plan for the work cells. This is sensible because the work cells are clearly an identifiable group of interdependent workers. This plan would provide rewards for sharing know-how in lean manufacturing principles and for working together to fix the problems in work flow through the system. The incentive can be directly tied to delivery, quality, inventory, and productivity performance - not just total output. This type of plan may also be applicable to the management group as well where cooperation and cohesiveness is beneficial. The system must be designed to encourage knowledge sharing, not competitiveness.

The drawbacks include:

- Groups may act in their own best interest, not the system as a “whole”.
- Individual high performers may feel unrewarded.
In reviewing Suzawa’s arguments above, these drawbacks may be “managed” if the system is designed to encourage “sharing of knowledge” among the entire production community and to encourage quality teamwork within the work cell. Even if the incentive plan generates temporary compliance, this may be the needed to “kick” for the desired behaviors consistent with lean manufacturing principles.

6.1.5 Correlation of Performance Measures with IRC Lean Vision and Boeing Executive Lean Metrics

One undefined issue throughout this project that of the IRC’s manufacturing strategy. The performance measures should be aligned with an organization’s manufacturing strategy. Unfortunately, the only strategy identified was that of “Going Lean”. This is too ambiguous for a manufacturing strategy. It wasn’t until November 1997 that the IRC Lean Vision was identified and used to provide focus for the IRC. Table #6-1 compares the new performance measures with those derived from the 1998 IRC Lean Vision and those designated by the Boeing Executive Team.

<table>
<thead>
<tr>
<th>Category</th>
<th>New Performance Measures</th>
<th>IRC Lean Vision</th>
<th>Boeing Executive Lean Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Time</td>
<td>Throughput Times</td>
<td>70-90% Lead-time reductions</td>
<td>Average Flow Time/Unit of Output</td>
</tr>
<tr>
<td>Inventory</td>
<td>Inventory Levels &amp; Turns</td>
<td>6X increase in inventory turns</td>
<td>Inventory $/Seat</td>
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<tr>
<td>Delivery</td>
<td>On-Time Delivery % &amp; Adherence to Takt</td>
<td>100% on-time deliveries</td>
<td></td>
</tr>
<tr>
<td>Quality</td>
<td>First Time Through Perfect</td>
<td>10X reduction in defects (internal &amp; escapes)</td>
<td></td>
</tr>
<tr>
<td>Productivity</td>
<td>Labor Productivity</td>
<td>30-50% unit cost reductions</td>
<td>Total $/Seat &amp; Employees/Seat</td>
</tr>
<tr>
<td>Space</td>
<td></td>
<td></td>
<td>Square Feet/Seat</td>
</tr>
<tr>
<td>Safety</td>
<td></td>
<td></td>
<td>10X reduction in injuries</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Changeover Time</td>
<td></td>
<td>Computing Workstations/Employee</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table #6-1 - Performance Measure Comparison
From Table #6-1 it appears that the new performance measures are reasonably aligned with the IRC Lean Vision measures. In comparison to the executive lean measures, however, there are discrepancies. *Quality, delivery, and flexibility have no corresponding measure in the executive level measures.*
7.0 Assessment & Conclusions

7.1 Thesis Assessment

In terms of satisfying goals and objectives, this thesis accomplished developing a sound set of performance measures for lean manufacturing system control. The majority of work focused at the work cell level whereas the area management and factory management measures are “roll ups” of the work cell measures. Performance measure design was relatively straightforward once the models were developed and applied. This project, however, fell short in complete implementation throughout the IRC. Only the pilot work cells (plus 2-3 other work cells) began implementing the new work cell performance measurement boards. A good 2-3 months of the project were spent “selling” the new measures and convincing work cell members/management of the benefits of the new measures. This was especially difficult when the work cells were still being measured by management against the old performance measures. The author was also unsure of the IRC’s intent to truly embrace a lean manufacturing system -- Would management commit to “stop the line” and fix quality problems? Would management empower the work cell members to take action and affect the system “real-time? Would the IRC stop using the old measures? The IRC should be aware that long-term improvement will come from capable and stable processes with a sustained and ingrained continuous improvement culture, not just “tampering” with the system in the short-term with the new fad in manufacturing. The goal of Manufacturing System Design is to incorporate a system that can be improved.

The author also submits that the work cell measurement board may have extended Boeing’s “conservative” culture too far. The author was driving Total Employee Involvement in data recording and system control. It was unclear whether this “process” of collecting and recording information would continue. It appeared that most of the work regarding performance measures, daily operational issues, and continuous improvement activity was directed at the work cell engineer. This person could easily become overburdened with all the tasks assigned to him. This person is also not a direct “controller” of the system, but rather an “influencer”.

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In general, the benefits of the recommended performance measures for lean manufacturing system control included:

- A system designed for "closed loop" manufacturing system control and improvement.
- Measures that influenced behavior consistent with the lean principles of Takt-Flow -Pull.
- Measures aligned with manufacturing system design & control.
- Simple, timely and easy to use measures.
- A system that incorporated variation measurement and SPC as a management system.
- A balanced approach to capture missing information on inventory, throughput times, product flexibility, process quality and labor productivity.

From a work cell specific view point, the following representative results were achieved:

- 50% WIP reduction.
- 15% First Time Through Perfect (FTTP) increase.
- Changed focus to On Time Delivery of “Customer Demanded Quantity”, not just total output.
- Validated that Changeover Times at Press Area were unreliable at 10 minutes – An effective sequence of parts through the work cell could not be achieved without an inventory “buffer”.

7.2 Managerial Challenges

Transferring philosophy is much harder than transferring technology (Donald F. Ephlin, Retired Vice President, United Auto Workers)

The constraint in the system in the IRC is not physical – it is educational. Key personnel lack the knowledge of how to operate the highly disciplined TPS system. The operators and managers must abide by the "rules of the game" if they want to succeed and achieve superior performance improvements. This means the operators and managers must be educated, trained, and have practice in lean manufacturing principles. Extending the "airplane cockpit" analogy described previously, the operators and managers are like airplane pilots -- well trained and educated individuals with an accumulated history of practice flight hours. Kaplan [12] asserts that managers must learn to actively intervene in
the production process to improve quality, reduce set-up times, increase manufacturing flexibility, overcome restrictive workforce rules, and reduce randomness caused by variations in supply, poor quality, and erratic machine performance.

Senge's [24] "Limits To Growth" system archetype applies to the educational challenge within the IRC and is depicted in Figure #7-1. The model illustrates growth by a reinforcing process and a slowing action by a balancing process as a "limit" is approached. Continued efforts initially lead to improved performance, but over time, the system encounters a limit which causes performance to slow down or decline even as efforts continue to rise. The management principle in this model is to not push on the reinforcing process, but remove (or weaken) the source of limitation to foster growth. An analogy would be that of a person taking up tennis. Initially, as a person practices the game, he would "grow" up to his natural ability. Even if he continues to practice he may not see the any performance improvements. His limit is that of his natural ability. To increase performance, the person would seek professional lessons to learn new techniques to overcome his natural ability. With the IRC, continued efforts to implement lean manufacturing may not be providing the benefits expected because of the educational constraint. The IRC obtained great performance benefits with the formation of work cells, but now must seek continued performance increases. This is accomplished by removing limits, not just pushing more lean principles into the system that are not understood.

Figure #7-1 - Senge's "Limits To Growth" System Archetype
7.3 Conclusion & Key Learnings

In summary, the author would like to share some general conclusions identified during the internship project at the Boeing IRC. First, the question - “What is the right performance measure to use?” is a question that has no single right answer. The author believes that the “right measure” is dependent on what needs to happen during a given time period. Thus, there isn’t a single answer, but various answers depending on the organization’s goals. One of the most difficult things to overcome in this project was learning to ignore “interesting” data and focusing on the vital few measures. The author also believes that the measures may change as an organization “matures” in the lean manufacturing principles. The major setback in this project was in the implementation of the new performance measures. The design of the measures was easy. Finally, performance measures themselves do not fix the system, they highlight where to focus resources to take action. People in the system affect performance. Performance measures are a necessary but not sufficient condition for lean manufacturing.

Organizations wanting to improve system performance must design the system to function as a “closed loop” control system. “Open loop” control does not provide an ample sampling of measures to determine “errors” and to make adjustments in an attempt to achieve the desired result. In the manufacturing system, the people closest to the “controlled processes” (i.e. the work cell personnel) must act as the “controllers”. They must want to be recipients of the performance information and must be given the authority to make decisions/actions to improve performance. This may require a change in the company’s culture, which is a difficult and time-consuming process which must be vehemently led by senior management.
References


