**First International Conference on Axiomatic Design**
**Cambridge, MA – June 21-23, 2000**

# THE IMPACT OF PERFORMANCE MEASUREMENT ON MANUFACTURING SYSTEM DESIGN

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## ABSTRACT

A company's performance measurement system drives its behavior and thus, affects its ability to achieve its strategic objectives. Therefore, developing performance measures that are aligned with the enterprise objectives plays a crucial role in accomplishing a company's long-term goals. This paper explains the cause and effect relationships between performance measurement and manufacturing system design from a system design perspective. As an example, it is illustrated why current performance measurement methods cause plants to evolve into mass production systems. Based on this understanding, this paper discusses the usefulness of the axiomatic design approach to develop performance measures that are aligned to the objectives of a company. Furthermore, a new strategic performance measurement method is proposed by using the manufacturing system design decomposition, which is a generic design model for manufacturing system design based on the axiomatic design method.

**Keywords**: Performance Measurement, Axiomatic Design, and Manufacturing system design.

## 1 INTRODUCTION

The behaviors of systems as well as the ability to achieve strategic objectives are affected by the way systems are measured. It is often true that the strategic goals of an organization are not achieved due to the complex interactions within the organizational hierarchy. In the lower levels of the organization, the performance measures, not the strategic objectives drive the behavior of the employees since they seek to make their performance measures look good. For this reason, an improper set of measurements can lead to dysfunctional or unanticipated behavior, which does not contribute to the organization objectives [Fry (1995)].

According to Wisner and Fawcett [Wisner and Fawcett (1991)], the role of performance criteria is twofold. First, it provides a firm with a method to assess its current competitive position with respect to its competitors and the demands of the market, and to identify avenues for improvement. Second, it monitors the firm's progress in moving towards its strategic objectives. From this point of view, it is repeatedly argued that the greatest problem associated with traditional performance criteria is the failure to provide sufficient guidance in the formation of tactical decisions to achieve simultaneous objectives [Eccles (1991)], [Wheelwright (1978)]. An enterprise production system must be designed to achieve the goals of cost, quality, flexibility and delivery time simultaneously [Suh, Cochran, and Lima (1998)]. The simultaneous achievement of these goals at the lowest possible cost is the manufacturing system design problem.

The manufacturing system design decomposition has been developed to illustrate the simultaneous goal and solutions that must be considered when implementing a manufacturing system [Suh, Cochran, Lima (1998)]. Performance measures should be tied to the enterprise or production system design and thus help sub-systems to achieve the functional requirements of the organization, which will eventually contribute to the goals of a company. To achieve long-term goals of a company, it is very important to develop and maintain the right performance measures at each organizational level those are aligned with the enterprise objectives [Cochran (1994)].

In this paper, the cause and effect relationships between performance measurement and manufacturing system design are explained from a system design perspective. As an example, it is first illustrated why current performance measurement methods cause plants to evolve into mass systems. Figure 1 illustrates that the performance measures significantly affect the manufacturing system design. To achieve the system design objectives, it is proposed that the performance measures must be aligned with the Functional Requirements (FRs) of the Manufacturing System Design (MSD). The design of the manufacturing system must be based on the manufacturing strategy, which is affected by many elements (see Figure 1).

Given the preceding explanation, a strategic performance measurement methodology is proposed by using the Manufacturing System Design Decomposition (MSDD), which provides a communication and design tool to define the objectives, called Functional Requirements (FRs) and corresponding design solutions, called Design Parameters (DPs) for an organization based on the axiomatic design methodology [Carrus and Cochran (1998)]. Figure 1 illustrates that the Performance Measures (PMs) must be derived from the FRs of the MSDD. The usefulness of the axiomatic design approach to develop performance measures that are aligned to the objectives of a company is also discussed.

Figure 2 illustrates that today's PMs dictate the FRs of the MSD and are not connected with the enterprise goals and strategy.

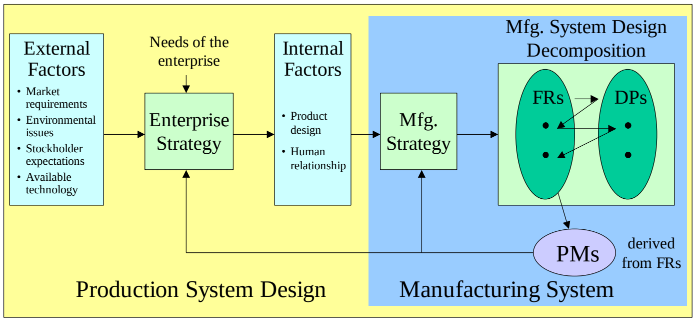


*Figure 1. Performance Measures to Achieve the Goals of the Manufacturing System Design and Production System Design*

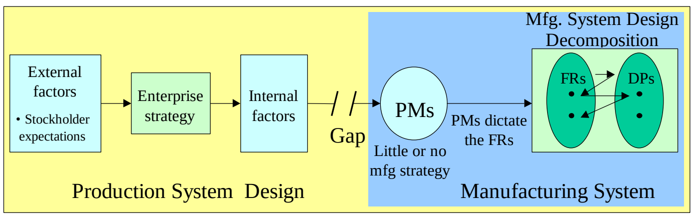


*Figure 2. Incomplete Performance Measures Driving Manufacturing System Design*

## 2 UNIT COST EQUATION AND MASS MANUFACTURING SYSTEM DESIGN

The traditional manufacturing cost accounting system, which is now widely used as the basis for manufacturing management decisions, was developed in the 1920s by du-Pont and General Motors [Johnson and Kaplan (1987)]. This management cost accounting approach is based on the realities of the 1920s, when direct labor was a single dominant factor of all manufacturing costs other than raw materials. Consequently, this cost accounting system typically equates "cost" with direct labor cost. All other costs are "miscellaneous," then lumped together as an overhead, which are then allocated based on direct labor time. In this management cost accounting system, the unit cost equation for estimating product cost is given by equation (1) [Horngren, et al. (1999)].

$$a = \frac{(C_{dl} + C_m + C_{oha})}{N_p}$$

$$C_{dl} = W_{dl} \times DL_p,\ C_{oha} = b \times C_{ohp},\quad b = DL_p / DL_{tot}$$

where $a$ = unit cost of product, $C_{dl}$ = direct labor cost,

$C_m$ = material cost, $C_{oha}$ = overhead allocation of product, (1)

$W_{dl}$ = wage of direct labor per hour

$b$ = burden rate, $C_{ohp}$ = total plant overhead cost,

$DL_p$ = direct labor hours comsumed by the product

$DL_{tot}$ = total direct labor hours of plant

$N_p$ = number of parts produced

This unit cost equation measures the performance of an outdated production environment in which direct labor is the dominant factor of production cost.

### 2.1 UNIT COST COUPLED WITH OPERATION-FOCUSED ENGINEERING

The traditional unit cost equation shown in equation (1) has long been the performance measure of manufacturing cost. If we combine the operation-focused engineering, which is a term that describes the design and optimization of single manufacturing process or machine in the isolation of the product flow [Shingo (1989)], and the unit cost equation method, the departmental mass environment is the typical result. Capacity for each operation is calculated by

$$m_i = \frac{Y_i}{X} = \frac{\sum_{j=1}^{N} M_{CT_{ij}}}{X} \qquad (2)$$

where,

$m_i$ = number of machines for operation $i$

$Y_i$ = total processing time required per day for operation $i$

$X$ = available operating time per day

$N$ = number of different products

$M_{CT_{ij}}$ = machining cycle time for operation $i$ and product $j$

A departmental plant layout is then the result of the machining capacity calculation given by equation (2). Each department in the plant corresponds to a processing operation. The type of automation that results from this type of "system design" has been referred to as "islands of automation" [Amber and Amber (1962)]. Furthermore, the people in this type of manufacturing system typically operate one or at most two machines. The departmental, mass manufacturing fabrication environment is illustrated by Figure 3. This figure illustrates a plant layout in which 78 billion part flow-pat combinations are possible [Duda, et al. (1999)]. Figure 4 illustrates the operation-based processing environment in which one-person, operates one machine. In this environment the unit labor cost is coupled with the production rate of the machine.

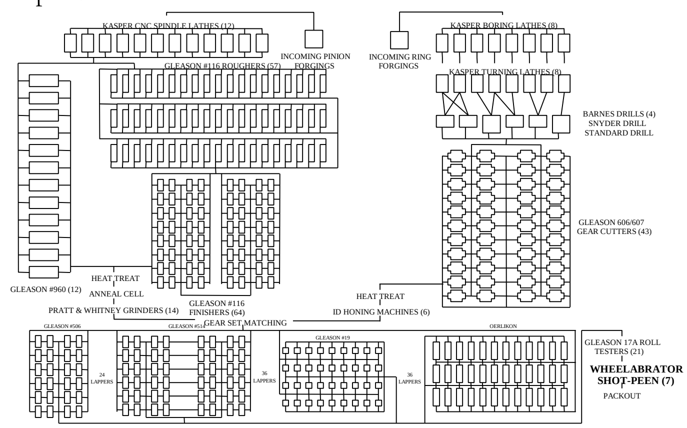


*Figure 3. Schematic View of Departmental Mass Production System Layout*

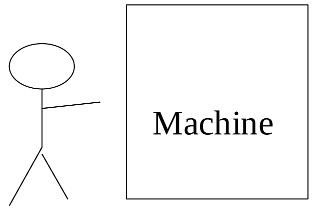


*Figure 4. Traditional One Machine per One Operator Situation*

Enterprises that utilize equation (1) as their cost accounting system attempt to reduce unit cost by determining at least three FRs which affect the mass manufacturing system design.

*FR 1*: Eliminate the need for direct labor: $DL_p \to 0$

*FR 2*: Increase the number of units / time to infinity: $N_p \to \infty$

*FR 3*: Reduce labor wage: $W_{dl} \to 0$

It is assumed that $C_m$ cannot be decreased in the preceding analysis.

To eliminate the need for direct labor, automated machines are implemented as the design parameter (DP) to minimize the direct labor time (see Figure 5). The second FR to achieve unit cost reduction is to maximize the number of units produced during a certain time interval. Increasing the processing speed of the machine becomes the DP to achieve this FR (see Figure 6). The third FR to minimize the unit cost is to directly reduce the labor wage. Moving plants to low-wage countries is now a popular DP to achieve this FR (see Figure 7).

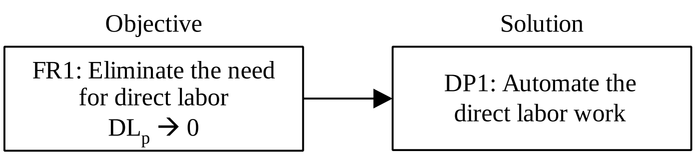


*Figure 5. FR 1 and DP 1*

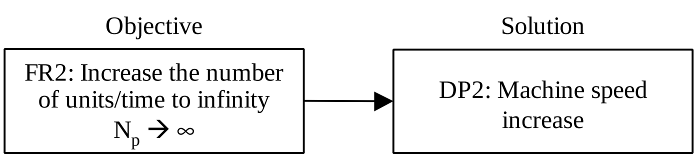


*Figure 6. FR 2 and DP 2*

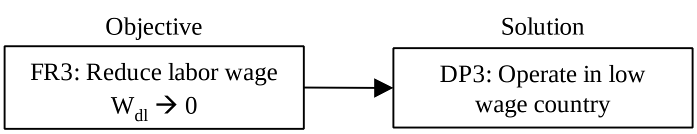


*Figure 7. FR 3 and DP 3*

## 2.2 MASS MANUFACTURING SYSTEM DESIGN AS A RESULT OF THE UNIT COST EQUATION

The effect of the unit cost equation is profound with respect to manufacturing system design. It has led management to envision the concept of the "lights out factory" [Hampton (1988)].

## 2.3 THE DECOMPOSITION OF THE MASS MANUFACTURING SYSTEM DESIGN

As shown in Figure 8, one of the primary goals of a company may be to maximize the long-term return on investment (ROI). The return on investment is calculated by Equation (3). To maximize the return on investment, the FRs become: increase sales revenue, minimize production costs, and minimize production investment. However, the way to achieve these FRs can be different depending on the market environment. For example, in the 1910s, when the Ford model T was introduced, the pre-sale rate was over 98% [Arnold and Faurote (1915)]. Ford could sell whatever quantity was produced. Therefore, the DP for the first FR (increase sales revenue) was to maximize production output. Similarly, the DP for the second FR, (minimize production costs) was to produce at minimum unit cost. In addition, to maximize machine utilization became a DP for the third FR (minimize production investment). These FRs and DPs are summarized in Figure 8.

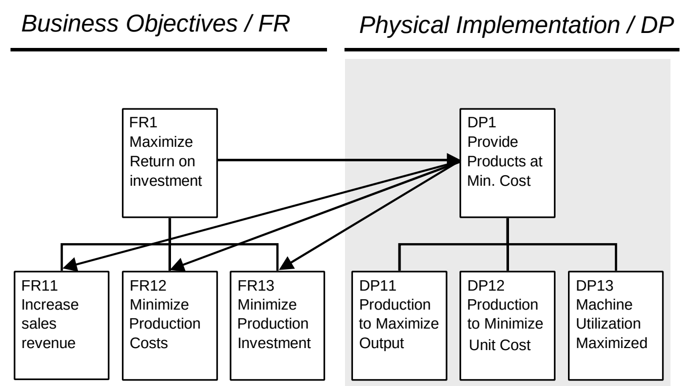


*Figure 8. The Decomposition of the Mass Manufacturing System Design*

$$ROI = \frac{Sales - Cost}{Investment} \qquad (3)$$

The design decomposition shown in Figure 8 is a rational design solution to achieve the FRs considering the market conditions of Henry Ford's era. The design equation in this case is shown in Equation (4) [Suh, Cochran, and Lima (1998)]. The design matrix shows that this is a decoupled design.

$$\begin{bmatrix} FR11 \\ FR12 \\ FR13 \end{bmatrix} = \begin{bmatrix} X & O & O \\ X & X & O \\ X & X & X \end{bmatrix} \begin{bmatrix} DP11 \\ DP12 \\ DP13 \end{bmatrix} \qquad (4)$$

To illustrate the impact of the unit cost equation on the manufacturing system design, further decomposition of the mass system design is shown in Figure 9. In this decomposition, DP12 - Produce at Minimum Unit Cost is decomposed. As shown in Figure 9, five FRs result from the decomposition of DP12.

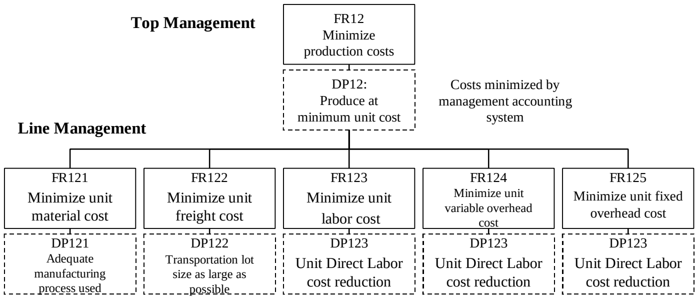


*Figure 9. Further Decomposition of Mass Production System – Line Management Level*

This design is an incomplete design from the axiomatic design point of view since one DP (DP123) is used to achieve three FRs (FR123, FR124, and FR125) [Suh (1990)]. Equation (5) indicates that the unit cost equation reinforces the use of DP123 to reduce the perceived unit cost.

The design equation clearly shows the emphasis on decreasing of unit direct labor cost. As previously discussed, there are three approaches for reducing the unit cost by reducing unit direct labor cost. These approaches provide the next level of the mass manufacturing system design decomposition. It is essential to notice that automation, manufacturing in low wage countries and the design and operation of high-speed machine are options for unit cost reduction. The next layer of the mass production decomposition is best illustrated by Figure 10.

$$\begin{bmatrix} FR121 \\ FR122 \\ FR123 \\ FR124 \\ FR125 \end{bmatrix} = \begin{bmatrix} X & O & O \\ O & X & O \\ O & O & X \\ O & O & X \\ O & O & X \end{bmatrix} \begin{bmatrix} DP121 \\ DP122 \\ DP123 \end{bmatrix} \quad (5)$$

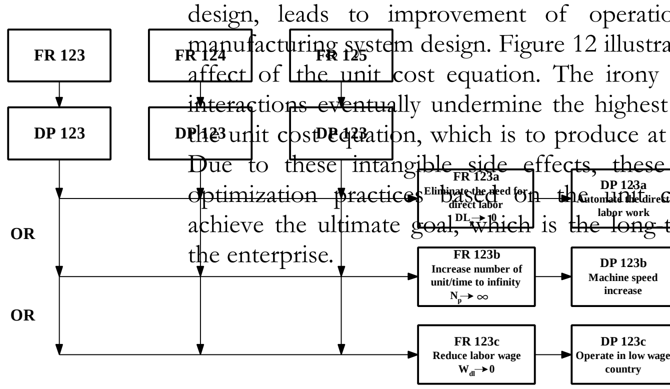


*Figure 10.Further Decomposition of Mass Production System – Minimization of Direct Labor Cost*

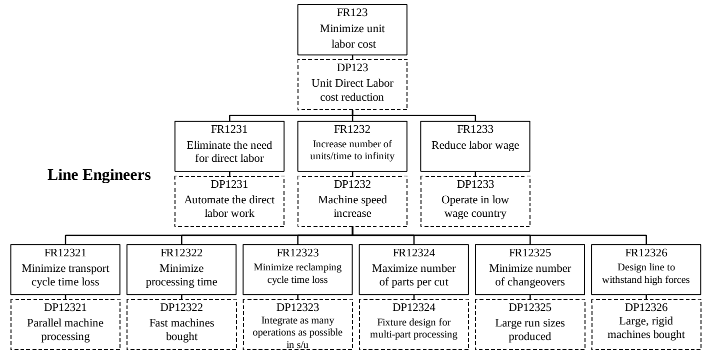


*Figure 11. Design Decomposition of Unit Labor Cost Minimization – Line Engineers Level*

Further decomposition of the unit direct labor cost reveals design parameters that characterize current mass production plant design and operation. In Figure 11, the efforts to minimize the unit direct labor cost are further analyzed by decomposition using the zig-zagging process.

## 2.4 System Dynamics Expression of Adverse Effects of Unit Cost Equation in Mass Manufacturingn

Figure 12 shows how manufacturing processes in the traditional mass manufacturing system have evolved toward meeting the performance measures of the unit cost equation. The current unit cost equation, as a sole dominant factor among the performance measures of production system and equipment design, leads to improvement of operation, instead of the manufacturing system design. Figure 12 illustrates the negative side affect of the unit cost equation. The irony is that the negative interactions eventually undermine the highest and original FR of the unit cost equation, which is to produce at minimum unit cost. Due to these intangible side effects, these production system optimization practices based on the unit cost equation never achieve the ultimate goal, which is the long-term profitability of the enterprise.

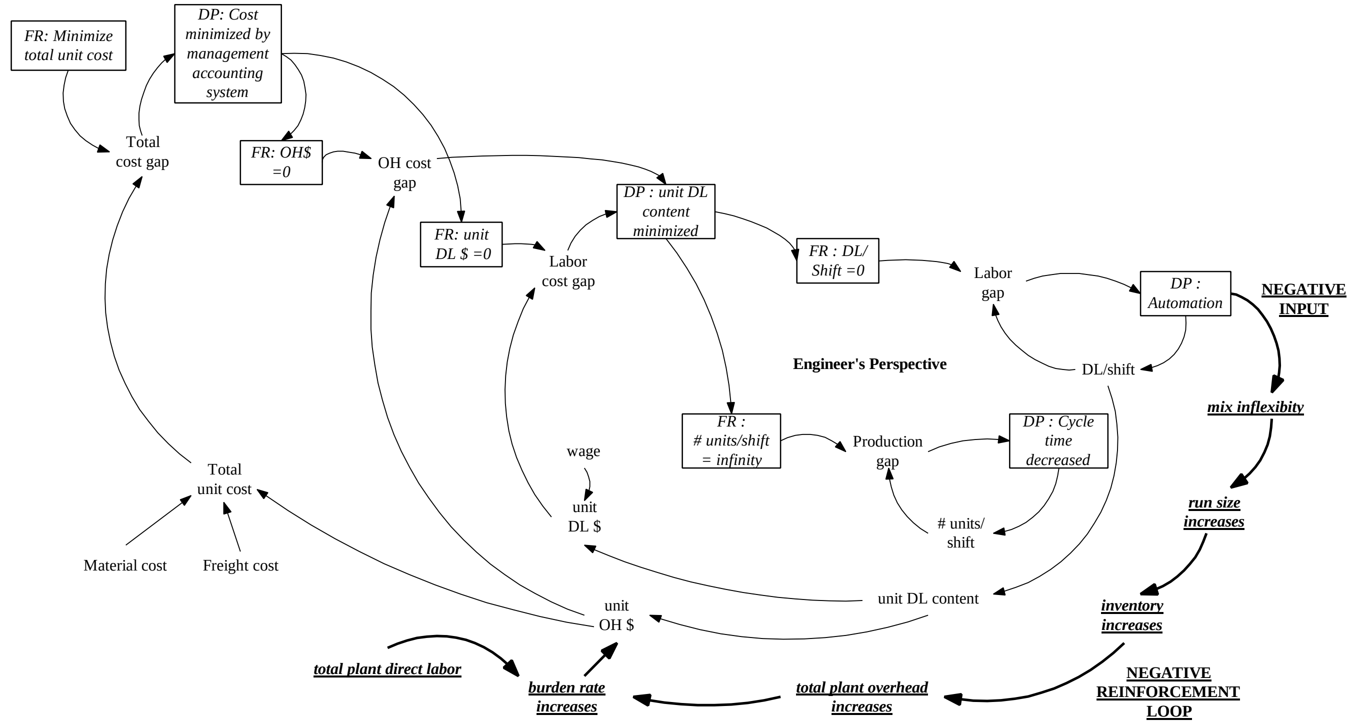


*Figure 12. System Dynamics Expression of Adverse Effects of Unit Cost Equation in Mass Manufacturing System*

## 3. THE MANUFACTURING SYSTEM DESIGN (MSD) AND NEW PERFORMANCE MEASURES

### 3.1 THE MSDD REFLECTS THE SYSTEM DESIGN FRS AND DPS THAT ARE NECESSARY TO SOLVE TODAY'S COMPETITIVENESS PROBLEM.

Due to the high competition and volatile customer requirements today, companies cannot sell as many products as they produce. In addition low price does not guarantee sales any more. Therefore, other competitive aspects such as responsiveness, on-time delivery, quality, and product variety are very important. For this reason, a different set of objectives (FRs) and solutions (DPs) is required to achieve the goals of a company. "Lean" manufacturing is the name that has been given to the manufacturing system design that has successfully achieved these objectives in today's environment. In today's manufacturing systems, sales revenue is increased by maximizing customer satisfaction rather than simply producing more. In addition, since charging more than market price is almost impossible in today's highly competitive market, the production costs are reduced to the target cost, which is determined by market price and expected profit. To reduce the production cost down to the target cost, all types of non-value adding sources of cost are eliminated. Finally, to minimize production investment, an investment based on a long-term system strategy is sought so that right-sized, general-purpose machines are used instead of highly-automated, high-speed machines. The differences in terms of design parameters between mass manufacturing systems and today's "lean" manufacturing systems are summarized in Figure 13.

Today's manufacturing system design can also be decomposed. The approach is to increase revenue by satisfying customer while decreasing cost and minimizing investment. To increase customer satisfaction, competitiveness in three areas is emphasized: quality, on-time delivery, and shortened delivery time. To minimize production costs, lean manufacturing systems are designed to be able to eliminate all types of non-value adding waste coming from direct and indirect labors and equipment. To minimize investment, a long-term capacity strategy is considered, so that right-sized, general-purpose machines are usually acquired. Figure 14 presents the manufacturing system design decomposition that reflect the necessary FRs and DPs in today "lean" manufacturing environment [Cochran and PSD lab (2000)].

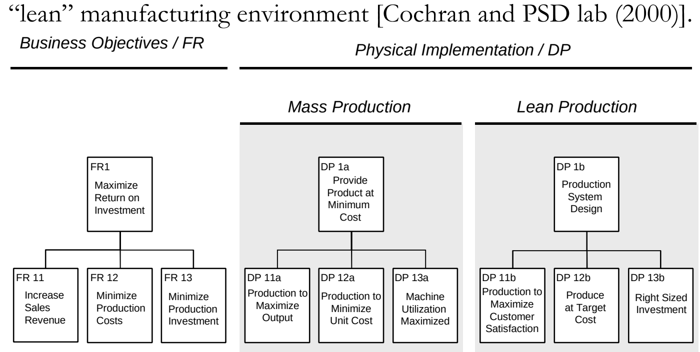


*Figure 13. Comparison between Mass Production and Lean Manufacturing system design*

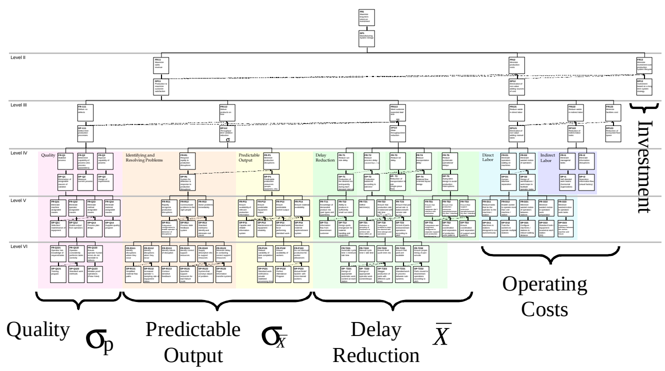


*Figure 14. Manufacturing System Design Decomposition Reflecting Today's " Lean" Manufacturing Objectives*

With this design decomposition, the differences between equipment design in "lean" and "mass" plants can be explained. By looking at some characteristic FR-DP pairs in this chart, it is recognized that the equipment in mass manufacturing systems is the result of operation-focused thinking while the equipment in lean production systems is the result of a new system design thinking, which uncouples labor cost from the speed of the machine. To reduce labor cost, operator's work content is matched to the customer demand cycle time. To reduce cost, the motions of the operator are decreased (see Figure 16, panel B). A machine represents the physical integration, which is necessary to satisfy multiple FR-DP pairs that are functionally independent by definition from the decomposition (Figure 17). The machine in Figure 16, panel B, achieves multiple FR-DP pairs as defined by the manufacturing system design decomposition. The FRs and DPs, which a machine must meet in this new manufacturing system design, are listed in Table 1.

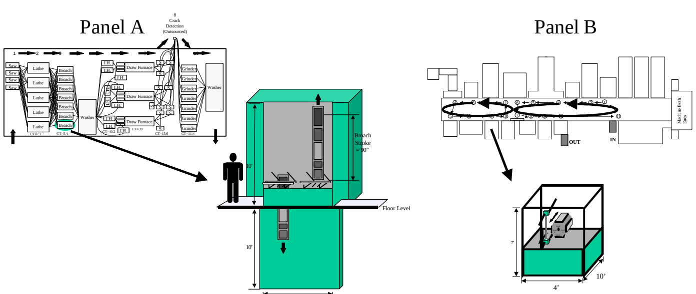


*Figure 16. Comparison of Mass and Lean Broach Machine Design [Cochran and Dobbs, 1999]*

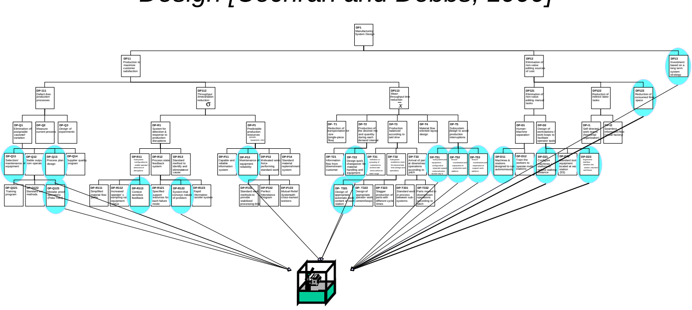

*Figure 17. FR-DP Pairs Affecting Machine Design*

**Table 1. FRs and DPs Affecting Equipment Design**

| FR | DP |
|---|---|
| FR-Q11 Eliminate machine assignable causes. | DP-Q11 Selection / maintenance of equipment |
| FR-Q13 Eliminate method assignable causes. | DP-Q13 Process plan design |
| FR-Q123 Ensure operator human errors do not translate to defects. | DP-Q123 Mistake proof operations (Poka-yoke) |
| FR-R113 Identify nature of disruption. | DP-R113 Context sensitive feedback |
| FR-P12 Ensure predictable equipment output. | DP-P12 Maintenance of equipment reliability |
| FR-T12 Ability to produce in sufficiently small run sizes | DP-T12 Design quick changeover for material handling and equipment |
| FR-T221 Automatic cycle time <= minimum takt time | DP-T221 Design of appropriate automatic work content at each station |
| FR-T51 Ensure that support resources don't interfere with production resources. | DP-T51 Subsystems and equipment configured to separate support and production access requirements |
| FR-T52 Ensure that production resources (people/automation) don't interfere with one another. | DP-T52 Ensure coordination and separation of production work patterns |
| FR-T53 Ensure that support resources (people/automation) don't interfere with one another. | DP-T53 Ensure coordination and separation of support work patterns |
| FR-D11 Reduce tasks that tie the operator to the machine/station | DP-D11 Machines & stations designed to run autonomously |
| FR-D21 Minimize wasted motion of operators between stations. | DP-D21 Configure machines/stations to reduce walking distance |
| FR-D23 Minimize wasted motion in operators' work preparation | DP-D23 Ergonomic interface between the worker, machine and fixture |
| FR123 Minimize facilities cost | DP123 Reduction of consumed floor space |
| FR13 Minimize investment over production system life cycle. | DP13 Investment based on a long term system strategy |

## 3.2 Aligning the Performance Measures (PMs) with the Manufacturing System Design

Since the manufacturing system design decomposition reflects general FRs of manufacturing system, the performance measures derived from it are also generally applicable to many types of manufacturing environment. Figure 1 illustrates when performance measures are clearly aligned with the FRs of the manufacturing system design. The performance measures are aligned to the FRs of the decomposition according to three levels of management. Details of the performance measures according to the levels of management are presented in the Appendix.

## 3.3 Characteristics of Cost Accounting System as a Performance Measure

According to Hiromoto [Hiromoto (1988)], it is noteworthy that in order to make accounting policies subservient to corporate strategy, Japanese manufacturing strategy places high premiums on quality and timely delivery in addition to low-cost production. Thus "lean" companies make extensive use of non-financial measures to evaluate factory performance.

Unlike accounting systems that support the preparation of periodic financial reports, cost accounting systems are not subjective to rules or standards such as generally accepted accounting principles. Therefore, there is no reason to think that there is a unique right cost accounting system. Enterprise can develop its own cost accounting system based on the market environment and long-term strategy. What is important is that a cost accounting system should have the characteristics previously presented to be aligned with the enterprise objectives.

Equation (6) is a proposed template of the new unit cost equation from the manufacturing system design decomposition.

Quality cost includes the influence of all quality problems of a product. That is, it should include not only the cost due to scrap and rework which take place within the factory, but also all the losses which are generated after products are shipped to the customers. Throughput time cost terms represents all the losses that take place when a manufacturing system fails to deliver products on time and meet customer expected lead-time. Overhead allocation should be determined in a manner that guarantees that there is no product cost distortion. It is clear that there is no unique correct way to estimate all the cost terms in equation (6). Finding a reasonable way to estimate these terms is a rigorous research topic. For this reason, we have proposed the approach given by Figure 1 to align performance measures to the manufacturing system design.

$$a = \frac{C_Q + C_{NI} + C_T(\overline{X}) + C_T(\overline{V}_X) + C_{DL} + C_{IDL} + C_M + C_{INV}}{N_p}$$

$$\begin{aligned}
\text{where}\quad a &= \text{unit cost} \\
C_Q &= \text{quality cost} \\
C_{NI} &= \text{cost due to not improving} \\
C_T(\overline{X}) &= \text{cost due to mean throughput time} \\
C_T(\overline{V}_X) &= \text{cost due to variation of throughput time} \\
C_{DL} &= \text{direct labor cost} \\
C_{IDL} &= \text{indirect labor cost} \\
C_M &= \text{material cost} \\
C_{INV} &= \text{investment cost} \\
N_p &= \text{number of parts produced}
\end{aligned} \qquad (6)$$

## 4. CONCLUSION

The true objective of the performance measurement system is to help management keep its enterprise competitive by adding value to the products and enhancing customer satisfaction. Again, in today's market, the factors that make products competitive include not only cost but also non-financial factors such as quality and delivery time. Therefore, performance measures should reflect these non-financial aspects so as to guide the system design to be more competitive. For this reason, axiomatic design is very useful to develop the right performance measurement system that will serve the real objectives of a firm. Axiomatic design reveals the cause-effect relationships of the functional requirements of a system and the corresponding design parameters and clearly presents them by the design decomposition procedure. Therefore, the development of a useful performance measurement system that reflects the goals of the system design is greatly facilitated.

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## 6. APPENDIX

***Top management level – high level FRs***

The performance measures of top management are derived from the high level FRs of the manufacturing system design decomposition. Financial performance measures that include revenue, cost, and investment are derived from the highest level of FRs while one lower level of FRs should be also considered to ensure these measures are valid for a long term. They are listed in Table 2.

**Table 2. New Performance Measures for Top Management**

| FR | PM |
|---|---|
| FR11 Maximize sales revenue | Sales revenue |
| FR12 Minimize production cost | Production cost, Cost reduction |
| FR13 Minimize investment | Investment as % of sales |
| FR111 Deliver no defects | Quality (number of defects) |
| FR112 Deliver products on time | On-time delivery % |
| FR113 Meet customer expected lead time | Throughput time / minimal throughput time |

***Middle management level – middle level FRs***

At the middle management level or product line management level, the performance measures may vary with the responsibilities of individuals. However, some common performance measures are also needed since middle management is responsible for some portion of the organization. In general more specific performance measures appear since more specific FRs are developed to support higher level FRs. Some of the performance measures are listed in Table 3.

**Table 3. Examples of Performance Measures for Middle Management**

| FR | PM |
|---|---|
| FR-Q1 Stabilize process | Process capability, First time through production % |
| FR-Q3 Improve capability of process | Process capability improvement over time |
| FR-R1 Respond rapidly to production disruptions | Mean time to repair, line downtime to fix problems |
| FR-P1 Minimize production disruptions | Mean time to failure, unplanned line downtime |
| FR-T1 Reduce run size delay | Run size |
| FR-T2 Reduce process delay | % of subsystems operating at customer takt time |
| FR-T3 Reduce lot delay | Transportation lot size |
| FR-T4 Reduce transportation delay | Total transportation distance |
| FR-T5 Reduce systematic operational delays | Amount of production shortfall due to interference |
| FR121 Reduce waste in direct labor | % of value-adding work time of direct labor |
| FR122 Reduce waste in indirect labor | % of support time of indirect labor |
| FR123 Minimize facilities cost | Floor space consumed |

***Line engineers level – lower level FRs***

At this level, more non-financial specific performance measures are derived. However, following the hierarchical structure of the design decomposition, the relationship with high-level performance can be easily identified. As with the performance measures for middle management, only some examples are presented in Table 4 due to the divergent nature of line engineers' work content.

**Table 4. Examples of Performance Measures for Line Engineers**

| FR | PM |
|---|---|
| FR-Q11 Eliminate machine assignable causes | Number of defects caused by machine errors |
| FR-Q121 Operator has knowledge of required tasks | Operator training |
| FR-Q122 Operator consistently performs tasks correctly | The ability of operators to follow standard work methods. |
| FR-Q123 Ensure operator human errors do not translate to defects | Number of defects caused by human error |
| FR-Q13 Eliminate method assignable causes | Process capability of the method used |
| FR-Q14 Eliminate material assignable causes | Number of defective parts received |
| FR-Q3 Improve capability of process | Process capability improvement over time for each machine |
| FR-R11 Rapidly recognize production disruptions | Mean time to recognize disruptions (where, when, what) |
| FR-R12 Communicate problems to the right people | Mean number of people contacted to solve disruptions |
| FR-R13 Solve problems immediately | Average time to solve problems |

 