ICAD058

# THE ALIGNMENT OF PERFORMANCE MEASUREMENT WITH THE MANUFACTURING SYSTEM DESIGN

David S. Cochran

dcochran@mit.edu Assistant Professor Yong-Suk Kim

yskim@mit.edu Graduate Research Assistant Jongyoon Kim

kimjy@mit.edu Graduate Research Assistant

Massachusetts Institute of Technology 77 Massachusetts Avenue, Cambridge, MA 02139 U.S.A

### **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

**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.

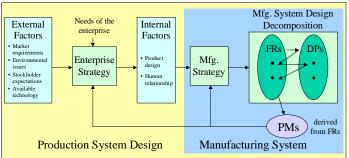


Figure 1. Performance Measures to Achieve the Goals of the Manufacturing System Design and Production System Design

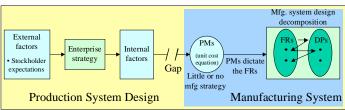


Figure 2. Incomplete Performance Measures Driving Manufacturing System Design

## 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)].

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

$$C_{dl} = W_{dl} \times DL_{p, C_{oha}} = \beta \times C_{ohp}, \quad \beta = \frac{DL_p}{DL_{tot}}$$
where  $\alpha$  = unit cost of product,  $C_{dl}$  = direct labor cost,
$$C_m = \text{material cost}, \quad C_{oha} = \text{overhead allocation of product}, \quad (1)$$

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

$$\beta = \text{burden rate}, \quad C_{ohp} = \text{total plant overhead cost},$$

$$DL_p = \text{direct labor hours comsumed by the product}$$

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

$$N_p = \text{number of parts produced}$$

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

$$\mu_{i} = \frac{Y_{i}}{X} = \frac{\sum_{j=1}^{N} M_{CT_{ij}}}{X} \tag{2}$$

where,

 $\mu_i$  = 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

 $M_{CT_{ii}}$  = 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.

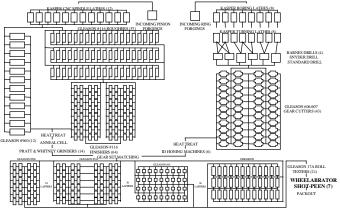


Figure 3. Schematic View of Departmental Mass Production System Layout

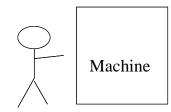


Figure 4. Traditional One Machine per One Operator Situation

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:  $DL_p \rightarrow 0$ 

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

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

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).

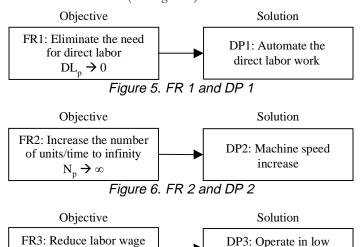


Figure 7. FR 3 and DP 3

wage country

## 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.

Business Objectives / FR Physical Implementation / DP DP1 FR1 Maximize Provide Return on Products at investment Min. Cost FR11 FR12 FR13 DP11 DP12 DP13 Production Minimize Production Machine sales Production Production to Maximize to Minimize Utilization revenue Investment Output Unit Cost Maximized

Figure 8. The Decomposition of the Mass Manufacturing System Design

$$ROI = \frac{Sales - Cost}{Investment} \tag{3}$$

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.

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

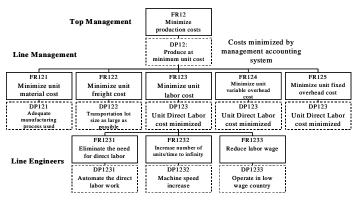


Figure 9. Further Decomposition of Mass Production System – Line Management Level

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.

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

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.

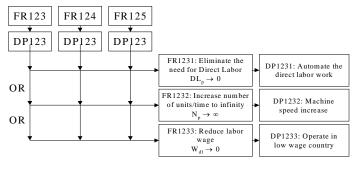


Figure 10.Further Decomposition of Mass Production System – Minimization of Direct Labor Cost

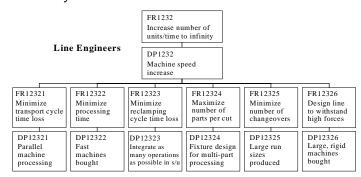


Figure 11. Design Decomposition of Unit Labor Cost Minimization – Line Engineers Level

Further decomposition of the unit direct labor cost reveals design parameters that characterize current mass production plant design and operation. In Figure 11, one of the sub-FRs to minimize the unit direct labor cost (FR1232) is further decomposed using the zig-zagging process.

# 2.4 SYSTEM DYNAMICS EXPRESSION OF ADVERSE EFFECTS OF UNIT COST EQUATION IN MASS MANUFACTURING

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. The dotted lines in the Figure 12 illustrate 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 may not achieve the ultimate goal, which is the long-term profitability of the enterprise.

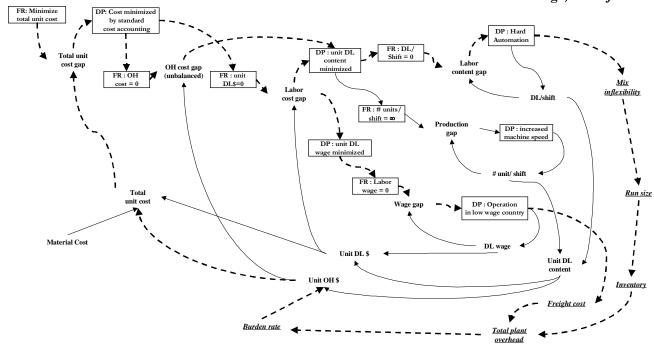


Figure 12. System Dynamics Expression of Adverse Effects of Unit Cost Equation in Mass Manufacturing System

## 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, many 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)].

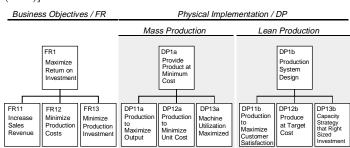


Figure 13. Comparison between Mass Production and Lean Manufacturing system design

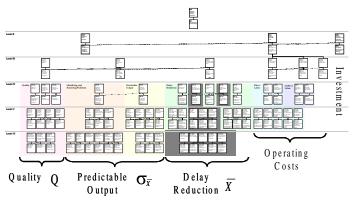


Figure 14. Manufacturing System Design Decomposition Reflecting Today's "Lean" Manufacturing Objectives

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 15, 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 16). The machine in Figure 15, 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.

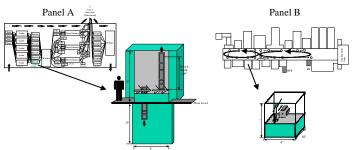


Figure 15. Comparison of Mass and Lean Broach Machine Design [Cochran and Dobbs, 1999]

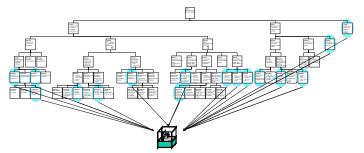


Figure 16. FR-DP Pairs Affecting Machine Design

Table 1. FRs and DPs Affecting Equipment Design

Table III No and Dr o / moothing Equipment Doorgin	
FR	DP
FR-Q11 Eliminate machine	DP-Q11 Selection / maintenance
assignable causes.	of equipment

Car	mbridge, MA – June 21-23, 2000
FR-Q13 Eliminate method	DP-Q13 Process plan design
assignable causes.	
FR-Q123 Ensure operator	DP-Q123 Mistake proof
human errors do not translate to	operations (Poka-yoke)
defects.	
FR-R113 Identify nature of	DP-R113 Context sensitive
disruption.	feedback
FR-P12 Ensure predictable	DP-P12 Maintenance of
equipment output.	equipment reliability
FR-T12 Ability to produce in	DP-T12 Design quick
sufficiently small run sizes	changeover for material handling
Sufficiently Silian Full Sizes	and equipment
FR-T221 Automatic cycle time	DP-T221 Design of appropriate
<= minimum takt time	automatic work content at each
- imminum takt time	station
FR-T51 Ensure that support	DP-T51 Subsystems and
resources don't interfere with	equipment configured to separate
production resources.	support and production access
r	requirements
FR-T52 Ensure that production	DP-T52 Ensure coordination and
resources (people/automation)	separation of production work
don't interfere with one another.	patterns
FR-T53 Ensure that support	DP-T53 Ensure coordination and
resources (people/automation)	separation of support work
don't interfere with one another.	patterns
FR-D11 Reduce tasks that tie	DP-D11 Machines & stations
the operator to the	designed to run autonomously
machine/station	
FR-D21 Minimize wasted	DP-D21 Configure
motion of operators between	machines/stations to reduce
stations.	walking distance
FR-D23 Minimize wasted	DP-D23 Ergonomic interface
motion in operators' work	between the worker, machine and
preparation	fixture
FR123 Minimize facilities cost	DP123 Reduction of consumed
	floor space
FR13 Minimize investment over	DP13 Investment based on a
production system life cycle.	long term system strategy

(note: FR-Qs: FRs in quality branch, FRRs: FRs in identifying and resolving problemsbrance, FR-Ps: FRs in predictable output branch, FR-Ts: FRs in delay reduction branch, FR-Ds: FRs in direct labor branch, FR-Is: FRs in indirect labor branch)

### 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 ubservient 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.

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

where  $\alpha = \text{unit cost}$ 

 $C_0$  = quality loss

 $C_{NI}$  = opportunit y cost due to not improvable system

 $C_T(\overline{X})$  = opportinit y cost due to mean throu ghput time

(6)

 $C_T(\sigma_X)$  = opportunit y cost due to on - time delivery

 $C_{DL}$  = direct labor cost

 $C_{IDL}$  = indirect labor cost

 $C_M$  = material cost

 $C_{INV}$  = investment

 $N_p$  = number of parts produced

### 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	Throughput time / minimal
lead time	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

	nanagonione
FR	PM
FR-Q1 Stabilize process	Process capability, First time
	through production %
FR-Q3 Improve capability of	Process capability improvement
process	over time
FR-R1 Respond rapidly to	Mean time to repair, line
production disruptions	downtime to fix problems
FR-P1 Minimize production	Mean time to failure, unplanned
disruptions	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	Total transportation distance
delay	Total transportation distance
FR-T5 Reduce systematic	Amount of production shortfall
operational delays	due to interference
FR121 Reduce waste in direct	% of value-adding work time of
labor	direct labor
FR122 Reduce waste in	% of support time of indirect
indirect labor	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 diverse nature of line engineers' work content.

Table 4. Examples of Performance Measures for Line Engineers

Engineers		
PM		
Number of defects caused by		
machine errors		
Number of defects caused by		
operator's lack of knowledge		
Number of defects severed by non		
Number of defects caused by non-		
standard work methods.		
N		
Number of defects caused by human error		
numan error		
Process capability of the method		
used		
Number of defective parts		
received		
Process capability improvement		
over time for each machine		
Mean time to recognize		
disruptions (where, when, what)		
Mean number of people contacted		
to solve disruptions		
Average time to solve problems		