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.
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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

$$
\mu_j = \frac{Y_j}{X} = \frac{\sum_{i=1}^{M} C_{r_{ij}}}{X}
$$

where,
- $\mu_j$ = number of machines for operation $i$
- $Y_j$ = total processing time required per day for operation $i$
- $X$ = available operating time per day
- $N$ = number of different products
- $M_{CT_j}$ = 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.

$$
\alpha = \frac{(C_{d} + C_{r} + C_{oh})}{N_p}
$$

where $\alpha$ = unit cost of product, $C_d$ = direct labor cost, $C_r$ = material cost, $C_{oh}$ = overhead allocation of product, $W_d$ = wage of direct labor per hour, $\beta$ = burden rate, $C_{oh}$ = total plant overhead cost, $DL_p$ = direct labor hours consumed by the product, $DL_{tot}$ = total direct labor hours of plant, $N_p$ = number of parts produced.
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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)].

 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.

\[ \text{FR 1: Eliminate the need for direct labor: } DL_p \rightarrow 0 \]
\[ \text{FR 2: Increase the number of units / time to infinity: } N_p \rightarrow \infty \]
\[ \text{FR 3: Reduce labor wage: } w_{dl} \rightarrow 0 \]

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).

\[ \text{ROI} = \frac{\text{Sales} - \text{Cost}}{\text{Investment}} \]

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.

\[ \begin{bmatrix} \text{FR11} \\ \text{FR12} \\ \text{FR13} \end{bmatrix} = \begin{bmatrix} X & O & O \\ X & X & O \\ X & X & X \end{bmatrix} \begin{bmatrix} \text{DP11} \\ \text{DP12} \\ \text{DP13} \end{bmatrix} \]
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Figure 10. Further Decomposition of Mass Production System – Minimization of Direct Labor Cost

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 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 optimizing the manufacturing system design. Figure 12 illustrates the negative side effects of the unit cost equation. The irony is that the negative side effects are not validated by 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.
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 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)].

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)].

![Diagram](image-url)
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Table 1. FRs and DPs Affecting Equipment Design

<table>
<thead>
<tr>
<th>FR</th>
<th>DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR-Q11 Eliminate machine</td>
<td>DP-Q11 Selection / maintenance</td>
</tr>
</tbody>
</table>

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.

\[
\alpha = \frac{C_Q + C_{ML} + C_f(\bar{X}) + C_f(\bar{X}) + C_{DL} + C_{INV} + C_M + C_{INV}}{N_p}
\]

where \( \alpha \) = unit cost
\( C_Q \) = quality cost
\( C_{ML} \) = cost due to not improving
\( C_f(\bar{X}) \) = cost due to mean throughput time
\( C_f(\bar{X}) \) = cost due to variation of throughput time
\( C_{DL} \) = direct labor cost
\( C_{INV} \) = indirect labor cost
\( C_M \) = material cost
\( C_{INV} \) = investment cost
\( N_p \) = 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.

5. REFERENCES

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

**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>
<thead>
<tr>
<th>FR</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR-Q1 Stabilize process</td>
<td>Process capability, First time through production %</td>
</tr>
<tr>
<td>FR-Q3 Improve capability of process</td>
<td>Process capability improvement over time</td>
</tr>
<tr>
<td>FR-R1 Respond rapidly to production disruptions</td>
<td>Mean time to repair, line downtime to fix problems</td>
</tr>
<tr>
<td>FR-P1 Minimize production disruptions</td>
<td>Mean time to failure, unplanned line downtime</td>
</tr>
<tr>
<td>FR-T1 Reduce run size delay</td>
<td>Run size</td>
</tr>
<tr>
<td>FR-T2 Reduce process delay</td>
<td>% of subsystems operating at customer takt time</td>
</tr>
<tr>
<td>FR-T3 Reduce lot delay</td>
<td>Transportation lot size</td>
</tr>
<tr>
<td>FR-T4 Reduce transportation delay</td>
<td>Total transportation distance</td>
</tr>
<tr>
<td>FR-T5 Reduce systematic operational delays</td>
<td>Amount of production shortfall due to interference</td>
</tr>
<tr>
<td>FR-R11 Eliminate machine assignable causes</td>
<td>Number of defects caused by machine errors</td>
</tr>
<tr>
<td>FR-Q121 Operator has knowledge of required tasks</td>
<td>Operator training</td>
</tr>
<tr>
<td>FR-Q122 Operator consistently performs tasks correctly</td>
<td>The ability of operators to follow standard work methods.</td>
</tr>
<tr>
<td>FR-Q123 Ensure operator human errors do not translate to defects</td>
<td>Number of defects caused by human error</td>
</tr>
<tr>
<td>FR-Q13 Eliminate method assignable causes</td>
<td>Process capability of the method used</td>
</tr>
<tr>
<td>FR-Q14 Eliminate material assignable causes</td>
<td>Number of defective parts received</td>
</tr>
<tr>
<td>FR-Q3 Improve capability of process</td>
<td>Process capability improvement over time for each machine</td>
</tr>
<tr>
<td>FR-R11 Rapidly recognize production disruptions</td>
<td>Mean time to recognize disruptions (where, when, what)</td>
</tr>
<tr>
<td>FR-R12 Communicate problems to the right people</td>
<td>Mean number of people contacted to solve disruptions</td>
</tr>
<tr>
<td>FR-R13 Solve problems immediately</td>
<td>Average time to solve problems</td>
</tr>
</tbody>
</table>

**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.

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