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MEASURING MANUFACTURING SYSTEM DESIGN EFFECTIVENESS BASED ON THE MANUFACTURING SYSTEM DESIGN DECOMPOSITION

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ABSTRACT

Manufacturing systems are traditionally measured with performance metrics such as unit labor cost and machine utilization, as well as a myriad of other financial measures. These measures are supposed to be indicators of performance and cost. It is far more important to design a manufacturing system well and measure the effectiveness of the system design. The Manufacturing System Design (MSD) Evaluation Tool has been developed to assess the design of manufacturing systems, not their performance. The tool was developed based on the Manufacturing System Design (MSD) Decomposition. The MSD Evaluation Tool measures how well a system is designed based on the criteria outlined in the MSD Decomposition. Six levels of manufacturing system design achievement have been defined: Job Shop or Departmental Layout, Departments Arranged by Product Flow, Assembly Line or Transfer Line, Pseudo-Cell, Assembly or Machining Cells, and Linked-Cell Manufacturing System. The Linked-Cell Manufacturing System is considered the highest physical achievement of system design known today. However, there are always continuous improvements which can be made to any design. The MSD Evaluation Tool provides a method to evaluate qualitatively a manufacturing system design. By doing this, areas of the system design which need the most improvement can be identified easily. In addition, quantitative measures have been developed to aid in the assessment and improvement process. Finally, the MSD Evaluation Tool is aimed to be widely applicable to most repetitive, discrete-part manufacturing systems.

Keywords: Axiomatic Design, Manufacturing System Design (MSD) Decomposition, MSD Evaluation Tool, Levels of Achievement

1 INTRODUCTION

When a system is as complex as a manufacturing plant, it is often very difficult to assess its design and operational performance. Most companies measure performance with management cost accounting systems [Kaplan and Cooper, 1998]. This financial information has been said to give an outdated picture of operational health [Upton and Macadam, 1997]. More importantly, it does not lead to or point out system design weaknesses and opportunities for improvement. This paper presents the MSD Evaluation Tool, a method to measure how well a manufacturing system is designed and how well that design is implemented. Using this analysis tool, improvements may be directed in the most critical areas, and changes in design and capability can be documented. This analysis tool is based on the Axiomatic Design [Suh, 1990] methodology and builds upon the ‘lean’ Manufacturing System Design Decomposition (MSDD) [Suh, Cochran and Lima, 1998]. The MSDD decomposes a generalized manufacturing system which is designed with the philosophy of the Toyota Production System (TPS) in mind [Monden, 1998]. The use of the MSD Evaluation Tool will be to assess and aid in the design of current and future manufacturing systems.

2 MOTIVATION

2.1 DEFINING A “GOOD” DESIGN

An extremely important distinction that must be made is that this paper attempts to evaluate the design of a manufacturing system instead of measuring its performance. This can be a difficult distinction to make because often, systems are evaluated based on cost performance alone. In addition, traditional performance measures such as commercial value, cost, quality, innovation and customer satisfaction are also measures of success. In manufacturing, many factors may contribute to the success or failure of the venture including many issues outside the realm of manufacturing such as product design, marketing and distribution. Therefore, assessing a manufacturing system based on traditional performance measures does not necessarily indicate the level of successful design, the level of successful implementation, or the opportunities for improvement in the manufacturing system. In order to address these issues, the goal is to evaluate the design, not the performance, of a manufacturing system.

In Axiomatic Design, an optimal design is characterized by independently satisfying the functional requirements with design
parameters having the minimum information content [Suh, 1990].
In concept screening, the Pugh concept selection methodology is
used [Pugh, 1991, Ulrich, Eppinger, 1995]. First, a selection
matrix is formed with the potential concepts and weighted
selection criteria. Second, each concept receives a score for each
criterion multiplied by their weights, and the scores for all the
criteria are summed for each concept. The concepts are then
rank-ordered based on their scores. This method is used to aid in
the selection or screening of concepts.

In the two approaches mentioned above, the design
parameters or concepts are assessed by how each impacts the
many functional requirements or design selection criteria. This
type of approach will be followed in this paper, again in the
context of Axiomatic Design.

2.2 IMPACT OF EVALUATION METHODS ON SYSTEM
EVOLUTION

An important theme of the Production System Design
laboratory is that designing a manufacturing system to satisfy
operation-based performance metrics leads to poorly designed
systems. The classic example is the focus on machine utilization
and direct labor costs. In order to ensure that machines are fully
utilized, workers monitor them (one machine, one operator) to
keep the uptime maximized. In addition, in order to decrease
direct labor costs, the number of machines is reduced, resulting in
extremely fast, complex machines grouped in functional
departments. Throughput time, inventory, and quality traceability
are all sacrificed in this system. The Toyota Production System
addresses these problems by arranging machines in cells
according to product flow. The cells are designed so that an
operator can run several machines, as long as the manual cycle
time is less than or equal to the system takt time. In this system,
machine utilization may be lower, but the machine designs are
simplified to achieve a desired system takt time. Quality issues are
resolved quickly, inventory levels and throughput times are low;
workers are more efficient, the system has greater flexibility, and
continuous improvement is enabled.

The above description is a very abbreviated comparison
between departmental and cellular manufacturing [Cochran and
Dobbs, 1999]. It illustrates that management cost accounting
drives the manufacturing system design, and it should not
[Cochran, Kim, and Kim, 2000].

2.3 CURRENT ‘LEAN’ PRODUCTION ASSESSMENTS

As the implementation of ‘lean’ manufacturing becomes
more widespread, companies and consultants have developed
methods to evaluate how ‘lean’ their manufacturing systems are.
These evaluation tools observed at Toyota, Visteon, and Boeing,
just to name a few, are very similar in nature. These tools rate
systems based on certain criteria, which may include management
involvement, levels of inventory, scheduling methods,
implementation of cells, standardization, man-machine separation
and shop floor attitudes. In each of these categories, levels are
declared which qualitatively describe achievements from poorly
operated ‘mass’ production to the ultimate in ‘lean’ production as
depicted in Fig. 1.

These evaluation tools are designed to allow someone (‘lean’
guru) to visit a manufacturing plant and through physical
observation, to make an assessment on how ‘lean’ the system is
and where improvements should be made. This evaluation can be
done because many of the elements of TPS are visible, such as U-
shaped cells, standardization, low levels of inventory and
workplace.

Although these assessments indicate whether a manufacturer
looks like Toyota and may give some direction for improvements,
they do not reflect how the tools are being used to achieve the
objectives of the manufacturing system design. This paper
presents a structured method to analyze a manufacturing system
to identify whether the objectives of the system design adhere to
the objectives of “lean”. In addition, the impact of elements on
each other and on upper level requirements is shown. This
approach provides the user with a better understanding of the
system design and where to concentrate improvement efforts.

3 METHODOLOGY

To evaluate a design, there must be a structured method to
describe the design. In this paper, Axiomatic Design is used to
describe and compare designs and is only briefly introduced here.

3.1 INTRODUCTION TO AXIOMATIC DESIGN

Axiomatic Design (AD) is a design methodology which
attempts to provide a science base for design [Suh, 1990].
Traditionally, design has not been viewed as a scientific process;
design has been considered a skill that is innate to some, not a
skill that can be developed. AD provides a structured method to
relate requirements and solutions for a design problem.

Figure 2. Mapping FRs to DPs in Axiomatic Design

Axiomatic Design is structured such that the customer wants
lead to the definition of the functional requirements (FRs) which
then lead to the identification of the design parameters (DPs) for
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a design, as shown in Fig. 2. The FRs identify what needs to be achieved, and the DPs identify how each FR can be satisfied. Each DP is decomposed into lower level FRs, which state what needs to be done in order to accomplish the DP. This decomposition process continues until the DPs sufficiently explain the design, at which point the design is complete.

Two axioms govern the development of a good design in AD. The Independence Axiom asserts that good designs should maintain the independence of the FRs. The Information Axiom asserts that good designs should have minimum information content.

Excellent designs are uncoupled, path-independent, and simple, in which each DP affects only one FR; the Design Matrix is diagonal. Acceptable designs are decoupled and path-dependent, in which some DPs affect more than one FR; the Design Matrix is triangular. Poor designs are coupled and complicated, in which some DPs affect each others’ FRs; the Design Matrix is not triangular. These design differences are shown in Fig. 3.

Figure 3. Difference Among Design Using Axiomatic Design

3.2 AXIOMATIC DESIGN: WATER FAUCET EXAMPLE
In order to illustrate the two axioms, the classic water faucet example is presented in Fig. 4 [adapted from Swenson and Nordlund, 1996]. The functional requirements (FRs) of a water faucet are controlling the water temperature and flowrate. The first figure shows a water faucet with a hot water valve and a cold water valve, the two design parameters (DPs). The Design Matrix shows that this is a poor, coupled design since both DPs affect both FRs. The second figure shows a water faucet with a water temperature valve and a flowrate valve, two different DPs. The Design Matrix shows that this is a good, uncoupled design since each DP affects only one FR. Notice that physically integrated DPs can still satisfy each FR independently.

Figure 4. Water Faucet Example for Axiomatic Design

4 APPLICATION
4.1 DEVELOPMENT OF THE MSD DECOMPOSITION
The MSD Decomposition shown in Fig. 5 is a generalized model of a manufacturing system design, which has been developed using Axiomatic Design. The FRs may be assessed to determine how well the design adheres to this decomposition. It should be noted that the MSD Decomposition is a decoupled, path-dependent design.

Figure 5. Manufacturing System Design (MSD) Decomposition

The MSD Decomposition is broken down into five branches of functional requirements: Quality, Predictable Output, Delay Reduction, Operating Costs, and Investment.

The Quality (\(\sigma_Q\)) branch decomposes the FRs of achieving quality output from the processes of the system. The Predictable Output (\(\sigma_X\)) branch decomposes the FRs of reducing variation in the manufacturing throughput time. The Delay Reduction branch decomposes the FRs of reducing the mean manufacturing throughput time. The Operating Costs branch decomposes the FRs of minimizing the costs of direct and indirect labor. The Investment branch decomposes the FRs of minimizing the total investment for a system.

Fig. 6 illustrates the mean and variation of manufacturing throughput time in the linked-cell manufacturing system design (Predictable Output and Delay Reduction branches) [Black 1991].
The curved arrows pointing from left to right signify material flow, and the curved arrows pointing from right to left signify information flow. The straight arrows signify material flow within each cell.

![Diagram showing material and information flow in a manufacturing system](image)

**Figure 6. Linked-Cell Manufacturing System Design to Reduce Mean Throughput Time and Variation**

### 4.2 Determining Which Level of the Decomposition to Evaluate

The MSD Decomposition has been developed by determining the functional requirements (FRs) for a manufacturing system design and the corresponding design parameters (DPs). Each FR can be satisfied by many different DPs. From these possible choices, one DP, which matches the overall manufacturing system objectives, is chosen to satisfy each FR (Design Phase). This Design Phase is shown in the left side of Fig. 7.

Each FR can then be evaluated based on how effectively its chosen DP has been implemented after design (Implementation Phase). This Implementation Phase is shown in the right side of Fig. 7.

The MSD Evaluation Tool evaluates the effectiveness of a chosen DP satisfying its FR. A more detailed discussion of the differences between the Design Phase and Implementation Phase is provided later in the Discussion section of this paper.

**Figure 7. Design Phase: Choosing a DP to Satisfy an FR**

**Implementation Phase**

<table>
<thead>
<tr>
<th>Functional Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR is not satisfied</td>
</tr>
<tr>
<td>FR is slightly satisfied</td>
</tr>
<tr>
<td>FR is somewhat satisfied</td>
</tr>
<tr>
<td>FR is partially satisfied</td>
</tr>
<tr>
<td>FR is mostly satisfied</td>
</tr>
<tr>
<td>FR is fully satisfied</td>
</tr>
</tbody>
</table>

**Choice among many possible DPs to satisfy a single FR**

<table>
<thead>
<tr>
<th>Functional Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choose DP 1 to satisfy FR</td>
</tr>
<tr>
<td>Choose DP 2 to satisfy FR</td>
</tr>
<tr>
<td>Choose DP 3 to satisfy FR</td>
</tr>
<tr>
<td>Choose DP 4 to satisfy FR</td>
</tr>
<tr>
<td>Choose DP 5 to satisfy FR</td>
</tr>
<tr>
<td>Choose DP 6 to satisfy FR</td>
</tr>
</tbody>
</table>

**Figure 8. Derivation of the MSD Evaluation Tool from the MSD Decomposition**

**Figure 9. MSD Evaluation Tool**

### 4.3 Development of the MSD Evaluation Tool Based on the MSD Decomposition

The MSD Evaluation Tool is directly linked to the MSD Decomposition. In general, the Level 4 FRs of the MSD Decomposition are used as evaluation criteria in the MSD Evaluation Tool. Fig. 8 shows exactly which FRs of the MSD Decomposition are used as evaluation criteria for the MSD Evaluation Tool. The singular importance of the MSD Evaluation Tool over traditional assessment methods is the fact that it evaluates the system design, not the system performance.

**Figure 8. Derivation of the MSD Evaluation Tool from the MSD Decomposition**

Using higher level FRs of the MSD Decomposition for the MSD Evaluation Tool may create a tool that is too general to provide an effective assessment whereas using lower level FRs may result in a tool that is too specific to offer a useful assessment tool across a wide range of manufacturing environments. The complete MSD Evaluation Tool is shown in Fig. 9.

**Figure 9. MSD Evaluation Tool**

### 4.4 Definition of Levels of Achievement

The evaluation criteria of the MSD Evaluation Tool have been selected from the FRs of the MSD Decomposition as shown in Fig. 8; now the evaluation approach is developed. For each evaluation FR, there are six levels of DP achievement:

- **Level 1: Job Shop or Departmental Layout**
Level 2: Departments Arranged by Product Flow
Level 3: Assembly Line or Transfer Line
Level 4: Pseudo-Cell
Level 5: Assembly or Machining Cells Only
Level 6: Linked-Cell Manufacturing System

Level 1 is the most basic, traditional manufacturing system, which is not designed from a system perspective at all. Level 6 is the ultimate achievement of a manufacturing system design based on the MSD Decomposition.

4.5 EXAMPLE: FR 111 ‘DELIVER NO DEFECTS’

One of the main ways in which a manufacturing system increases customer satisfaction is delivering perfect quality. A survey of automobile manufacturers [Womack, Jones, Roos, 1991] showed that some non-Japanese manufacturers were able to achieve quality comparable to Japanese manufacturers based on the number of defects per 100 cars. However, the non-Japanese manufacturers achieved this quality with end-of-line rework areas using highly skilled technicians while the Japanese manufacturers achieved this quality without expensive, time-consuming rework.

The basis for integrated quality is dependent upon each process supplying only good parts to subsequent processes [Monden, 1998]. The key point here is that in order to deliver no defects, defects must not be produced (waste of producing defects). Integrating quality control [Black, 1991] also eliminates wastes of repairing, reworking, or replacing bad parts. Achieving this degree of quality also reduces variation in production, which allows less inventory between processes and enables consistent, on-time delivery.

In order to assess the manufacturing system design in terms of quality, the following levels of achievement have been defined for FR 111 ‘Deliver no defects.’

Level 1
Defects are delivered to the customer. FR 111 is not fulfilled.

Level 2
End-of-line inspection is used to ensure no defects are delivered. FR 111 is beginning to be fulfilled by the use of rework areas, but there are high levels of scrap, as well as wasted manufacturing efforts.

Level 3
In-line, dedicated inspection stations used to catch defects earlier, as well as end-of-line inspection. FR 111 is somewhat fulfilled although scrap levels and wasted manufacturing efforts are reduced.

Level 4
Inspection is integrated into the line, but the root causes of defects are not identified or eliminated. Therefore, the same defects occur repeatedly. FR 111 is partially fulfilled.

Level 5
The transition to defect-free production has been made. Root cause analysis has been implemented, eliminating assignable sources of quality problems so that production is now predictable. Inspection is integrated into operator work patterns.

The response time to eliminate problems has been greatly reduced. FR 111 is mostly fulfilled.

Level 6
Defects cannot be made because all processes are capable, reliable, and predictable. Root causes of defects resulting from equipment, operators, methods, and materials are identified and eliminated. All operations are standardized and mistake proofed (e.g. poka-yoke devices [Shingo, 1989]). FR 111 is completely fulfilled.

4.6 QUALITATIVE EVALUATION

After the six levels of achievement have been defined for each FR evaluated by the MSD Evaluation Tool, there must be some method of scoring a manufacturing system design. Therefore, a qualitative scoring method has been developed, shown in Fig. 10.

In order to evaluate a system design, the actual characteristics of the plant are matched to the closest description among the six levels of achievement. Because it is unlikely that an entire plant has uniform characteristics, it may be necessary to score part of a plant at Level 3 and score another part of the plant at Level 5, for example.

As a result, the pie-chart scoring method was developed. The pies at each level of achievement represent the percentage of the plant that has achieved the indicated level. For each FR, or column, the total pie-chart score should add up to 100%. By using this scoring method, it becomes visually apparent which areas of the manufacturing system design need the most concentrated improvement efforts.

4.7 QUANTITATIVE EVALUATION

Along with the qualitative evaluation just described, the FRs of the MSD Evaluation Tool may also be quantitatively evaluated. To this end, performance metrics have been aligned with each FR of the MSD Evaluation Tool. Each of the performance metrics is stated below its corresponding column in the MSD Evaluation Tool.
4.8 Applicability to Manufacturing Systems Across Different Industries

The MSD Decomposition assumes that manufacturing system designs are independent of both volume and product type. This means that the design of manufacturing systems is not influenced by the volume of production, nor is it influenced by the type of product to be produced by the system [Cochran, 1999]. With this idea in mind, it is believed that the MSD Decomposition applies to most repetitive, discrete-part manufacturing systems.

Although this method assesses a manufacturing system based specifically on the MSD Decomposition and does not specifically account for designs which do not adhere to the Decomposition or which select different DPs, it is still widely applicable to most manufacturing system designs. Therefore, the MSD Evaluation Tool is intended to be applicable to most repetitive, discrete-part manufacturing systems.

Moreover, although this methodology has been applied to the design of manufacturing systems, it may also be applicable to the design of other types of systems using Axiomatic Design.

5 Discussion

5.1 Design Phase and Implementation Phase of the MSD Decomposition

Two different phases of the MSD Decomposition have been described in this paper: Design Phase and Implementation Phase. The Design Phase means choosing the most appropriate DP for an FR as shown by the left side of Fig. 7. The Implementation Phase means assessing the implementation effectiveness of a DP as shown by the right side of Fig. 7.

At the Design Phase, several possible DPs may actually satisfy a given FR, but some may cause coupling or impact other FRs negatively. The DP which best matches the manufacturing system objectives is chosen for each FR.

5.2 Design Phase: Choosing Among Different DPs for Each FR

In the Design Phase, the different possible DPs for a single FR must be identified and compared. This comparison can be done by following the two design axioms of Axiomatic Design. DPs which maintain the independence of the FRs and which contain the minimum information are most desirable. In addition, the chosen DP should be aligned with the overall manufacturing system objectives.

An example from the MSD Decomposition related to quality in a manufacturing system is shown in Fig. 11. A DP must be chosen to satisfy FR 111 ‘Deliver no defects.’ There are several possible DPs which can ensure that defects are not delivered. One possible DP is to scrap an entire lot of parts if a defect is found in that lot. A second possible DP is to use 100% inspection and rework to fix defects. A third possible DP is to improve the processes enough such that only human errors can lead to defects. A fourth possible DP is to design the system with integrated quality such that defects cannot be made at all.

Although all four possible DPs can satisfy FR 111 ‘Deliver no defects,’ they must be analyzed with respect to their impact on other FRs. In the MSD Decomposition, the production of defects immediately impacts delivering products on time and meeting customer expected lead time, shown by the Design Matrix in Fig. 12. Because it is very important to avoid producing defects rather than detecting and reworking the parts, the fourth possible DP is chosen for FR 111. This DP, which states to design the system with integrated quality such that defects cannot be produced, is labeled DP 111 ‘Defect-free production processes’ in Fig. 12.

5.3 Implementation Phase: Evaluating the Effectiveness of a DP Satisfying Each FR

In the Implementation Phase, the satisfaction of each FR is evaluated based on how well the chosen DP is implemented in the system. For each FR, a DP has been chosen which coincides with the overall manufacturing system objectives. However, the chosen DP can be implemented with varying levels of success, and it is important to understand how successfully it has been implemented. An example from the MSD Decomposition of FR-D1 ‘Eliminate operators’ waiting on machines’ is presented in Fig. 13.
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Figure 13. Implementation Phase Example: Evaluating the DP Implementation Effectiveness of FR-D1

In this example, FR-D1 ‘Eliminate operators’ waiting on machines’ is being evaluated based on how well DP-D1 ‘Human-Machine Separation’ has been implemented. Six levels of achievement have been defined for this FR-DP pair. Level 1 is the worst, in which an operator watches the machine run; this obviously does not satisfy the FR. Level 6 is the best achievement, in which operators have defined work routines and machines run autonomously upon operator instruction; this achieves the FR unquestionably. Using this approach, it is possible to describe the implementation of a new or existing manufacturing system design with respect to achievement of the FRs of the system design.

5.4 INTERACTION OF REQUIREMENTS

In an attempt to perform a design evaluation, one additional issue which must be addressed is how assessments of one FR impact parent or sibling FRs.

Each FR can be given a score, labeled \( y_i \), which is an evaluation of how well an FR is satisfied by the system design. This score may affect parent FRs or sibling FRs. Fig. 14 depicts the relation between the achievement of FRs to a parent FR. FR 1 is satisfied by DP 1 and is further decomposed into the FRs 11, 12 and 13. It can then be said that FR 1 is fully satisfied when the decomposed FRs are satisfied, and its score is a function of the decomposed FRs’ scores as shown by the equations in Fig. 14. Depending on their relative importance, each lower level FR will have a different weighting factor associated with it, as in the concept selection algorithm. The fact that upper level scores are dependent upon lower level scores suggests that the evaluation will be carried out in a bottom-up approach.

Figure 14. Relationship of Scores Across Levels of Decomposition

The satisfaction, or score, of an FR is also dependent upon how well sibling FRs are satisfied, if sibling DPs impact the FR being evaluated. This condition is depicted in Fig. 15 along with the equations. If DPs 11 and 12 have an impact on FR 13, then FR 13’s score will be a function of the scores of FRs 11 and 12. Again, the weightings (which may be negative if the DPs impact the FR negatively) are determined based on their relative importance and impact on each FR. In addition to the fact that the evaluation proceeds bottom-up, it is also path-dependent within a single level according to the Design Matrix. However, this fact is true for only decoupled designs; uncoupled designs are path-independent, and coupled designs provide no clear path for evaluation.

Figure 15. Relationship of Scores Among Sibling FRs

Given the structure of Axiomatic Design, the relationships established in the MSD Decomposition and Design Matrices provide a simple mechanism for determining the impact of FR scores upon each other in a bottom-up and path-dependent approach.

6 CONCLUSIONS AND RECOMMENDATIONS

From experiences with using this tool at various companies, it was found that although the general concepts are widely applicable, it may be helpful to alter the descriptions and metrics to suit the specific industry under evaluation. A version of this model has already been implemented into the manufacturing system evaluation procedure of one company, which uses it to assess new programs.

7 ACKNOWLEDGEMENTS

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8 REFERENCES


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