Rationalizing the Design of the Toyota Production System: A Comparison of Two Approaches

J. Won¹, D. Cochran¹, H. T. Johnson², S. Bouzekouk¹, B. Masha¹

¹Production System Design Laboratory, Department of Mechanical Engineering
Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
²School of Business Administration, Portland State University, Portland, Oregon, USA

Abstract
This paper examines two recent attempts to develop frameworks to explain the Toyota Production System (TPS). In Decoding the DNA of the Toyota Production System, Spear and Bowen assert that the design, operation and improvement of manufacturing systems can be captured in four basic rules. In A Decomposition Approach for Manufacturing System Design, Cochran et. al. show how a Manufacturing System Design Decomposition (MSDD) can express the relationships between the design requirements and corresponding solutions within a manufacturing system. This paper compares and contrasts how each of these approaches incorporates the requirements of successful manufacturing system design.

Keywords: Production System Design, Axiomatic Design, Methodology

1 INTRODUCTION
Various theories for the design and operation of manufacturing systems have been advanced to rationalize the system design process [1] [2] [3] [4] [5] [6]. The two approaches under consideration in this paper each provide a unique view of the Toyota Production System (TPS). An essential aspect of either approach is the de-emphasis on the tools and methods characteristically associated with TPS and 'lean' manufacturing.

In Decoding the DNA of the Toyota Production System, Spear and Bowen consider TPS as a model manufacturing system. The essence of TPS is described by four basic rules. These rules were developed based on extensive empirical research. In A Decomposition Approach for Manufacturing System Design, Cochran et. al. developed an axiomatic-based design decomposition approach to distinguish the objectives from the means (or steps) in system design. The approach identifies the way that a particular solution achieves and interacts with the system design requirements.

This paper examines how well these two distinctly different approaches meet the basic requirements of modern manufacturing system design.

2 MANUFACTURING SYSTEM DESIGN
2.1 Introduction
A system has definite inputs and outputs and acts on its inputs to produce a desired output [7]. Furthermore, a system is comprised of many deeply interrelated sub-systems [8]. The interactions among sub-systems affect the output of the system as a whole. The sub-systems must act as an integrated whole to produce the desired result.

A manufacturing system is a subset of the production or enterprise system [1] [9]. More specifically, a manufacturing system is the arrangement and operation of elements (machines, tools, material, people, and information) to produce a value-added physical, informational or service product whose success and cost is characterized by measurable parameters of the system design [9]. There are four types of operations in any manufacturing system: transport, storage, inspection and processing. To ‘optimize operations’ means to improve one element or operation of the system at a time. Improvement of operations in most cases does not lead to improvement of the system [8] [10] [11]. Improving system performance requires understanding and improving the interactions among the elements within a system.

A primary objective of any manufacturing system is to sustain its purpose. An aspect of a firm’s purpose may be to grow sales and increase profit margins. But neither goal can be achieved without realizing and constantly improving the entire enterprise and manufacturing system design.

A manufacturing system design may be thought of as an enabler to eliminate waste. To reduce true cost in a manufacturing enterprise requires the elimination of true waste. To eliminate waste, a system must be designed to expose waste. Many companies have attempted to target areas within their companies for waste reduction only to find waste re-emerging in another part of the business. (See the seven wastes defined by Ohno: overproduction, conveyance, inventory, waiting, processing, motion and correction [12]) Reducing waste outside of the context of a system design can be an arbitrary, wasteful activity.

According to Deming, management goals cannot be achieved by unstable systems [13]. Waste can only be reduced when a manufacturing system has been designed to be stable. The attributes of a stable manufacturing system are:

1. Producing the right mix
2. Producing the right quantity
3. Shipping perfect-quality products on-time to the customer

The manufacturing system design must enable people to achieve the above objectives:
4. In spite of variation (internal and external) to the system
5. While rapidly recognizing and correcting problem conditions in a standardized way
6. Within a safe, clean, bright, ergonomically sound working environment for workers who are doing standardized work

These attributes for a successful manufacturing system are discussed in a variety of writings [14] [15] [16] [17]. Cochran asserts that achieving these requirements defines a stable manufacturing system. Only when the manufacturing system is stable can waste be permanently reduced. When true waste is reduced, true cost is reduced [11] [18].

2.2 Relationship to TPS

The Toyota Production System was developed by Toyota Motor Corporation as the physical embodiment, or means, to achieve these six requirements with the ultimate goal of cost reduction [15]. Once a stable manufacturing system design was in place, cost reduction could then be realized through the elimination of waste. These central features are reflected in the two pillars of JIT and Jidoka and in the foundation of standardized work and kaizen (Figure 1). JIT (Just-in-Time) means to make only what is needed, when it is needed and in the quantity needed. Jidoka is the practice of designing machines and processes to deliver perfect quality through rapid recognition and solution of problems. Implicit in every part of TPS, especially in standardized work and kaizen, is a deep concern for safe and ergonomic working conditions at all times.

TPS

Cost control through the elimination of waste

J

Right Qty

JIT

Right Mix

Right Time

Jidoka

Perfect Quality

Figure 1: Toyota Production System framework [19].

3 DECODING THE DNA OF TPS

3.1 The Four Rules

Spear and Bowen (referred to hereafter as Spear) have developed an understanding of the Toyota Production System (TPS) that traces its success to a ‘seemingly paradoxical’ situation—namely, that Toyota’s rigidly specified and scripted factory operation is inherently flexible and adaptable. From a field study of various facilities, the research concluded that the paradox is unraveled by realizing that rigid specification actually stimulates flexibility and creativity at Toyota. Key to this understanding is that TPS creates a ‘community of scientists’ who rigorously implement the scientific method. According to Spear, TPS is described as being built upon the foundations of the scientific method—observation, hypothesis, formulation, prediction of results, and performance of experimental tests—as a means to provide a reliable, consistent and non-arbitrary methodology to design and improve upon manufacturing processes.

So why do so many companies find it so difficult to develop Toyota-like production systems? According to Spear, the difficulty in replicating Toyota’s successes lies in articulating a system that grew naturally and largely unwritten over the course of five decades. Spear believes that the workings of TPS can be captured by the Four Rules:

Rule 1: All work shall be highly specified as to content, sequence, timing, and outcome.

Rule 2: Every customer-supplier connection must be direct, and there must be an unambiguous yes-or-no way to send requests and receive responses.

Rule 3: The pathway for every product and service must be simple and direct.

Rule 4: Any improvement must be made in accordance with the scientific method, under the guidance of a teacher, at the lowest possible level in the organization.

Each of the Four Rules requires that problems be identified automatically by built-in feedback signals for each and every activity, connection, and flow path. Spear submits that continually responding to problems with rigorous application of a scientific method of inquiry makes a flexible and adaptable system from one that is seemingly rigid. The Four Rules are also believed to create a nested, modular organizational structure—a structure that allows Toyota to introduce changes and improvements to its operations while remaining stable at the same time.

Beyond instilling conviction in the scientific method at all levels of the organization, Spear found that the people involved share a common goal or vision of what an ideal production system would be, much like that of Figure 1. This vision is believed to inspire and drive further improvements to existing production systems, from the highest to lowest levels of the organization. According to Spear, the Four Rules, aligned with a common vision of the ideal and not any specific practices and tools, form the ‘essence of Toyota’s system [20].’

3.2 Discussion

Spear believes the Four Rules are the means by which TPS generates value [17]. In other words, the Rules express the physical implementation and process by which to achieve the desired goals of the system. Although these ‘Rules’ indicate how work will be done, they do not explicitly connect work to the system’s objectives. Shigeo Shingo, a key engineer who taught and developed the Toyota Production System, emphasized the need to know why, not just how the system works [10]. Hopp and Spearman argued that effective management of manufacturing systems necessitates a framework that systematically balances objectives with the means to achieve them [21]. The Rules are not explicit about the system’s objectives and how the rules affect each other. Thus, it is not clear how to systematically apply the Rules. Nor is it obvious how the Rules affect each other.

Through inductive analysis of field data, Spear asserts that the Four Rules are key to the creation of a nested, modular organization. Nested, modular describes a form of social/technical organization in which a series of modules (such as a linked-cell manufacturing system, as described by Black [1]) is grouped into a larger module but without direct connection to the central core. According to Spear, the nested, modular organization not only facilitates local
and system change, but also promotes frequent and finely-grained diagnostics of activities, activity-connections, and flowpaths, thereby reinforcing process improvement and learning [17]. Although Spear acknowledges the benefits of a nested, modular organization, the Rules do not necessarily and observably demonstrate a structured methodology to achieve this organization. Instead, Spear asserts the necessity of having people (sensei) who are knowledgeable in the Rules, and of having mechanisms for teaching the Rules through frequent, structured, and directed problem solving [17].

A benefit of this rule-based approach is that the Rules can handle a variety of problems by focusing on general directions rather than detail. However, the choice of the term ‘rule’ is unfortunate as the term can lead to misinterpretation. An example of this point is Boothroyd & Dewhurst’s rule-based Design For Manufacturing (DFM) methods. These DFM methods, to make a product easier to manufacture, may indeed minimize the number of parts to make the product during the design phase of the development process. However, DFM methods alone do not fully capture the potentially negative relationships to product development time, nor do they adequately reflect the economic implications of detailed design decisions [22]. While rules may indeed be valid, the danger may be in their simplicity. Simple statements to describe complex systems, such as rules, may invite casual readers to confuse the simplicity of ideals with simplicity of implementation [21]. In addition, the Rules do not address some essential issues in manufacturing system design, as stated by Monden and Shingo, such as defining and designing systems to customer takt time, smoothed production to help adapt to demand changes and reduce inventory, process layout for shortened lead times, machine layout to help realize flexible workshops, and balanced operations to attain production with minimum labor [10] [15].

The Rules certainly provide upper and middle management important insight into the fundamentals that drive and enable the Toyota Production System [17]. Moreover, it may provide guidance to strategic decision making. However, the Rules do not provide a process as to how to physically implement and achieve the goals of a manufacturing system design.

4 A DECOMPOSITION APPROACH TO MANUFACTURING SYSTEM DESIGN

4.1 The Manufacturing System Design Decomposition (MSDD)

Motivation

The Manufacturing System Design Decomposition (MSDD), developed by Cochran and his Production System Design Laboratory at MIT, provides further definition of TPS and other principles significant to manufacturing system design [14]. The MSDD attempts to satisfy the following requirements:

1. To clearly separate objectives from the means designed to achieve them.
2. To relate low-level activities and decisions to high-level goals and requirements, thus allowing designers to understand how the selection of manufacturing solutions impacts the achievement of the objectives of the manufacturing system.
3. To portray the interrelationships among different elements of a system design.
4. To effectively communicate the logical decomposition of the objectives and means across an entire organization, thus providing manufacturing system designers with a roadmap to understand, communicate and achieve the strategic objectives of an organization.

In order to satisfy the above requirements, the MSDD uses axiomatic design—a methodology that has been developed by Suh to provide a structured approach for the generation and selection of good design solutions [23].

Axiomatic Design

The axiomatic design methodology focuses a designer on first determining objectives of a design, which are stated in terms of Functional Requirements (FR’s) of a design. The unique aspects of the approach are Design Parameters (DP’s), the design matrix, and decomposition. A designer chooses the DP’s (solutions) to satisfy the FR’s (objectives). The key is that the axiomatic design process guides how the DP’s are chosen to satisfy the FR’s. An uncoupled design, the best type of design, is defined as the case where one DP affects only one FR. Thus, the axiomatic design process controls how the DP (the solution) interacts with and achieves the FR (the objective).

Since different physical designs can achieve the same customer needs, axiomatic design uses the following two axioms to select the best set of possible design parameters:

1. Independence axiom: When multiple FR’s exist, a solution that satisfies each FR without affecting the other FR’s is superior. Such a design is said to be uncoupled and is better than a coupled design.
2. Information axiom: Simpler designs are better than complex designs. Complexity increases with the amount of information required to achieve the objectives of the design. Among alternative designs, the one with highest probability to meet the FRs, within tolerances, is the best.

The process of decomposition establishes a design hierarchy based upon the selection of DP’s to satisfy the FR’s at increasingly refined levels of detail. To advance to the next level of detail in a decomposition requires an uncoupled or partially coupled design. In axiomatic design, the relationships between the FR’s and DP’s are represented by design matrices. The design matrix information can be represented in either vector or graphical

Figure 2: Example of how FR's are decomposed.
form. In graphical form, an off-axis arrow from a DP to an FR represents a partially-coupled relationship. Once a set of DP's has been determined at one level of decomposition, the next step is to decide if further decomposition to another level of FR's and DP's is necessary. Figure 2 shows an example of a two-level, partially coupled decomposition.

The conception of design solutions is an inherently creative process. Axiomatic design simply provides a framework to structure thinking during the design process, and provides a logical approach to defining the objectives and their means of achievement.

**The MSDD**

Based on the axiomatic design methodology, the MSDD currently defines the goal for any manufacturing system as ‘maximization of long-term return on investment.’ This objective is then decomposed into three sub-objectives: maximize sales revenues, minimize production cost, and minimize investment over the manufacturing system’s lifecycle. Each of these three FR’s is then decomposed into FR’s and DP’s at the next lower level. At this next level, the FR’s are organized in different branches (Quality, Identifying and Resolving Problems, Predictable Output, Delay Reduction, Operational Costs and finally Investment). The decomposition process continues through succeeding levels until activities and decisions reach an operational level of detail.

Underlying the MSDD is the philosophy that a system cannot be improved if it is not stable [8]. ‘Stability’ means the system can produce repeatedly the required quality, mix, quantity, delivery time, and cost in spite of variation (reduction of deviation around the mean). Once the system has been stabilized, improvements can be made to increase quality, reduce delivery time, and reduce cost (reduction of the mean). In short, the objective of the MSDD is to achieve a stable and improvable system that ultimately produces at the right pace, the right mix of products as demanded by the customer, with perfect quality and minimum total cost. Inherent in the creation of the MSDD is the conception that sources of variation can be reduced through system design.

**4.2 Discussion**

**How the MSDD relates to TPS**

As a consequence of giving equal importance to the objectives, the means, and the logical dependencies between them, the MSDD creates an holistic, systems-view of understanding and designing any manufacturing system, not just one that resembles TPS. The scientific and systemic axiomatic approach to manufacturing system design marks a departure from the conventional design process, which has been dominated by non-systemic empiricism, and trial and error. Suh submits that without scientific principles, the design field will never be systematized, and thus will remain a subject difficult to comprehend, codify, teach and practice [23].

The MSDD’s focus on FR’s sheds light on why most manufacturing firms fail at implementing TPS. In many cases, companies fail to implement TPS because they do not understand or articulate the FR’s that TPS is meant to solve. In other words, companies see TPS as a collection of tools to solve local optimization problems defined by conventional finance-driven management concerns, and not the systemic optimization envisioned by the original architects of TPS. Indeed, conventional management practices focus too often on quantitative targets as the goal, instead of on the FR’s. By considering financial targets as the goals of the manufacturing system, the connection between the means and the objectives is greatly diminished, if not destroyed, by this limited way of thinking [11]. It is not enough for a business enterprise to state to its management to ‘reach the target’ without stating the means to achieve the objective. The MSDD helps structure and communicate manufacturing problems in a way that gives clear reasons (objectives) for the solutions being implemented [18].

A framework relating the elements of TPS to the higher-level objectives has been developed by Masafumi Suzuki of TRW Automotive in Japan. The framework presented in Figure 4 infers that a system design was put into place by Toyota to achieve the basic requirements of JIT and Jidoka, and that the ensuing implementation of the physical methods enables the elimination of waste. According to this framework, elimination of waste is important in terms of achieving the two high-level goals of cost reduction and improvement of productivity. This framework links the ideas and methods that Ohno and others at Toyota implicitly developed relative to the stated needs of JIT and Jidoka. Suzuki’s framework evidences Toyota’s early logical process of system design by linking the objectives to the physical methods used to achieve these objectives. Furthermore, his framework identifies the seven wastes that are eliminated as a result of the physical method developed.

![Figure 4: ‘Lean’ Manufacturing System Framework [24].](image)

Similarly, the MSDD relates the system’s objectives with the means of implementation. However, the MSDD goes beyond Suzuki’s framework by decomposing, mapping, interrelating, and clearly communicating the highest-level objectives (FR’s) to the lowest-level means (DP’s) of any manufacturing system design, not just that of Toyota. Also,
through the axiomatic design decomposition approach, the MSDD focuses on selecting the appropriate means to support the required objectives, thus de-emphasizing the tools and methods associated with TPS and ‘lean’ manufacturing.

The MSDD has analyzed tools associated with TPS, and has stated the objectives which those tools attempt to achieve. Furthermore, the MSDD not only relates to TPS, but also incorporates other sources from industry and literature such as Deming’s quality framework, Shewart’s idea of assignable and common cause, and Gilbreth’s ideas on wasted human motion. Toyota wasn’t the first to discover any of these ideas; however, they were the first to put most of them to use in a systemic way. The MSDD attempts to encompass and codify all these ideas into one coherent framework.

**How the MSDD relates to the Rules**

Figure 5 illustrates several instances where the means stated in the Four Rules are described by the DP’s (means) within the MSDD. The mapping uses the MSDD to show how the means stated in the Rules relate to the MSDD. Table 1 lists the Rules and the corresponding example FR-DP pairs as defined by the MSDD and Figure 5.

![Figure 5: Illustrative mapping of the Rules in the MSDD](image)

By using axiomatic design, the MSDD emphasizes the linkages and interrelationship between objectives and means. For example, the lower-level DP’s relating to Rule 3 (simplified and direct material flows) can be traced upward to the highest-level system objective (to maximize long-term ROI) through both the Problem Solving and Delay Reduction Branch. The decomposition approach to system design clearly and immediately identifies the relationships between the how’s and why’s emphasized by Shingo [10].

Through an understanding of the linkages between the FR’s and DP’s, the tools and methods associated with TPS and ‘lean’ manufacturing can be intentionally and sensibly applied to solve the appropriate objectives and adapted to unique situations. The Rules, by focusing only on the means, fail to make this connection.

The MSDD covers a broad range of issues considered in manufacturing systems and attempts to link these to the six attributes of successful and stable manufacturing systems. Elements of JIT (producing right quantity and mix) and Jidoka (perfect quality) can be found in the Delay Reduction and Quality Branch of the MSDD, respectively. For example, FR-T3 (reduce run size delay) relates to DP-T3 (production of the desired mix and quantity during each demand interval). Also, FR-Q123 (ensure operator errors do not translate into defects) relates to DP-Q123 (mistake proof, or poka-yoke, operations). Elements of the second three attributes of successful manufacturing systems can be found in the Predictable Output, Identifying and Resolving, and Operational (Labor) branches, respectively.

In contrast, the Rules take a different approach to linking the lower-level means to the higher-level system objectives by relying upon knowledgeable individuals (sensei) and the common vision of the ideal production system to drive and inspire further improvements. This method has proven quite successful for Toyota in practical operation. Nevertheless, some of the ‘essence of Toyota’s system’ Spear attempted to uncover still remains implicit.

A strength of the bottom-up approach utilized by Spear is the emphasis the Rules place on the relationships between people and the enterprise community. The Rules describe how people work as individuals in a collective, how people connect with each other, how the production line is designed in relation to people, and how to improve the system. The Rules make positive contributions through the focus on the humanistic viewpoint of the people-system relationships in a manufacturing system—an area which has not yet been fully and satisfactorily developed in the MSDD.

<table>
<thead>
<tr>
<th>Rule</th>
<th>FR</th>
<th>MSDD</th>
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<tbody>
<tr>
<td>1</td>
<td>FR-Q122: Ensure operator</td>
<td>DP-Q122: Standard work methods</td>
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<tr>
<td></td>
<td>consistently performs task correctly</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>FR-P131: Reduce variability of task completion time</td>
<td>DP-P131: Standard work methods to provide repeatable processing time</td>
</tr>
<tr>
<td>2</td>
<td>FR-R121: Identify correct support resources</td>
<td>DP-R121: Specified support resources for each failure mode</td>
</tr>
<tr>
<td>2</td>
<td>FR-I2: Eliminate information disruptions</td>
<td>DP-I2: Seamless information flow (visual factory)</td>
</tr>
<tr>
<td>3</td>
<td>FR-R112: Identify disruptions where they occur</td>
<td>DP-R112: Simplified material flow paths</td>
</tr>
<tr>
<td>3</td>
<td>FR-T4: Reduce transportation delay</td>
<td>DP-T4: Material flow oriented layout design</td>
</tr>
<tr>
<td>4</td>
<td>FR-R13: Solve problems immediately</td>
<td>DP-R13: Standard method to identify and eliminate root cause</td>
</tr>
<tr>
<td>4</td>
<td>FR-I1: Improve effectiveness of production managers</td>
<td>DP-I1: Self-directed work teams (horizontal organization)</td>
</tr>
</tbody>
</table>

**Tools to Extend the Use of the MSDD**

The originality of the MSDD is its wide application to a variety of repetitive, discrete-part manufacturing systems and its ability to satisfy the requirements aforementioned. However, the MSDD is still a general framework. It doesn’t guide a designer to the complete specification of the physical manufacturing entity. The MSDD helps a designer understand the critical relationships and interactions between objectives (FR’s) and means (DP’s). Thus, the MSDD is a design decision support tool, which may be used with other physical design methods. With these basic attributes of the MSDD in mind, unique tools to provide a larger framework for system design are under development.
Known as the Production System Design and Deployment (PSDD) Framework [18], a few of these tools include:

1. Manufacturing System Evaluation Tool: Using the MSDD, this tool evaluates how well a design can achieve the overall objectives set for a system. Moreover, it identifies, in a given system, where problems are and how to resolve them. It allows measuring the quality of a given design by identifying areas where objectives are (or can not be) met.

2. Equipment Evaluation Tool: Using the MSDD, this evaluation tool evaluates if existing material/capital equipment allows the system to achieve its requirements and provides useful guidelines when considering the acquisition of new equipment.

3. Deployment Steps for Implementation: Using the MSDD as a step in the design of the new system, this tool provides users the steps to follow in a manufacturing system design process.

4. Manufacturing System Design Flowchart: Shows the precedence of design parameters (DP's) in implementing a system design.

Research is currently underway in several manufacturing sites around the world to validate the MSDD and its integration with the procedural system design process of the PSD framework [25].

5 CONCLUSION

Both the Four Rules and the MSDD attempt to provide a framework to communicate and satisfy the attributes of successful manufacturing systems. Based upon induction and observation, the Rules approach TPS from the bottom up. Though useful as a general set of guidelines, this bottom-up approach does not link lower-level activities to high-level strategic goals of the company. In contrast, the MSDD shows clearly how objectives (FR's) and means (DP's) connect to the primary goals of a manufacturing enterprise.

The MSDD takes an holistic, decomposition approach to explain how to understand, replicate and deploy Toyota-like manufacturing systems. However, the MSDD goes one step further. It develops a general framework of requirements for successful manufacturing system design, not just particular requirements for Toyota’s system design. Hence, the MSDD may someday point the way to the design and development of innovative and effective manufacturing systems that transcend current benchmark companies such as Toyota.

6 REFERENCES

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