

Manufacturing System Design of Automotive Bumper Manufacturing

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Abstract

This paper presents an evaluation of the manufacturing system design of two automotive manufacturing plants, located in North America. The manufacturing system designs are evaluated in terms of the achievement of design requirements stated by the Manufacturing System Design Decomposition (MSDD). The accomplishment of the design requirements is assessed through aggregated measurables, which are then related to the MSDD. The qualitative outcome of this study illustrates that the plant that more closely achieves the requirements stated by the MSDD, better satisfies the desired results of a manufacturing enterprise.

Keywords: *Axiomatic Design, Lean*

Manufacturing, Manufacturing System Design

Decomposition

1. Introduction

A system has definite inputs and outputs and acts on its inputs to produce a desired output^[1]. Furthermore, a system is comprised of many interrelated sub-systems^[2]. These interrelationships affect the output of a manufacturing system as a whole.

A manufacturing system is a subset of the production or enterprise system^{[3],[4]}. 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^{[5],[6],[7]}. 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^{[2],[8],[9]}. Improving system performance requires understanding and improving the interactions among the elements within a system.

A primary requirement of any manufacturing system is to sustain the desired results. Aspects of a firm’s desired results may be to provide jobs, increase market share, or increase return on investment. A system design defines these relationships, or the work that is necessary to achieve a system’s desired results. Results

are only achieved by improving the underlying interrelationships within the system that is responsible for the achievement of the desired results.

A manufacturing system design covers all aspects of the creation *and* operation of a manufacturing system to achieve the desired results. Creation includes the physical arrangement of equipment, equipment selection, work loop design (manual and automatic), standardized work procedures, etc. The result of the creation process is the factory as it looks during a shut down. Operation includes all aspects, which are necessary to run the created factory.

A manufacturing system design may also be thought of as an enabler to reduce cost. To reduce true cost in a manufacturing enterprise requires a system design that enables 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 reemerging in another part of the business. (See the seven wastes defined by Ohno: overproduction, conveyance, inventory, waiting, processing, motion and correction^[10]) Reducing waste outside of the context of a system design can be an arbitrary, wasteful activity.

This paper illustrates how to use the Manufacturing System Design Decomposition (MSDD) framework to evaluate manufacturing system designs^{[4],[11]}. In particular, the MSDD is used to evaluate the design of two automotive component-manufacturing plants located in North America. In addition, the paper demonstrates how the application of the MSDD has assisted system designers to improve the performance of one of the plants studied.

2. The Manufacturing System Design Decomposition Framework

2.1 Motivation

Various theories for the design and operation of manufacturing systems have been advanced to rationalize the system design process. Fundamentally, many provide a framework to relate tools for the design and operation of manufacturing systems^{[12],[13],[14],[15]}. An essential aspect of the MSDD is the de-emphasis on the tools and methods with a focus upon understanding the relationships between the requirements and the means (e.g. tools and methods). Tools and methods, in the absence of functional understanding, do not explicitly connect the means to the system's overall requirements. Within manufacturing systems, it is argued that effective management necessitates a

framework that systematically balances requirements with the means to achieve them^[14].

The primary objective of the MSDD is to provide a structured approach for the design of manufacturing systems through the definition of design requirements and the means of achievement. These requirements are decomposed from a broad or high level to a detailed level of operational activities. The MSDD attempts to satisfy the following requirements of a system's design:

1. To clearly separate requirements from the means of achievements.
2. To relate high-level goals and requirements to low-level activities and decisions, thus allowing designers to understand how the selection of manufacturing solutions impacts the achievement of the requirements of the manufacturing system.
3. To portray and limit the interactions among different elements of a system design.
4. To effectively communicate the decomposition of requirements and means for an organization, so that manufacturing system designers have a roadmap to achieve the "strategic" objectives of an organization^[16].

In order to satisfy the above requirements, the MSDD was developed using Axiomatic Design—a

methodology that has been developed by Suh to provide a structured approach for the generation and selection of good design solution^{[17],[18]}.

2.2 Axiomatic Design

Design may be described by the continuous interplay between *what* we want to achieve and *how* we want to achieve it. Design requirements are always stated in the *functional domain*, whereas the solutions are always defined in the *physical domain*. More formally, design may be defined as the creation of synthesized solutions that satisfy perceived needs through the *mapping* between the requirements in the functional domain and the solutions in the physical domain^[17].

The Axiomatic Design methodology focuses a designer on first determining the requirements of a design, which are stated in terms of the Functional Requirements (FRs) of a design. A designer then chooses the Design Parameters (DPs) to satisfy the stated FRs (requirements). By separating the functional space from the physical space, the design requirements are defined in a solution-neutral environment without any preconceived notion of a physical solution in mind. Axiomatic Design thus guides a designer to solve a particular Functional Requirement by the selection of a

specific means (DP), rather than focusing on just the means themselves. The design process is illustrated in Figure 1 where DPs in the physical domain are chosen to satisfy FRs in the functional domain.

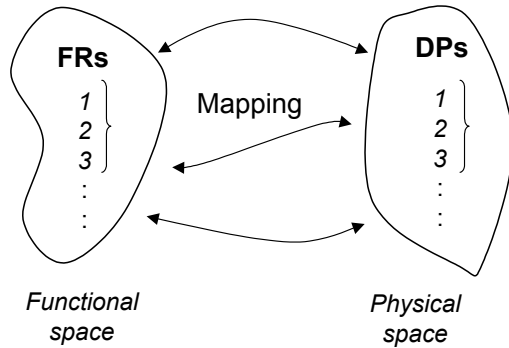


Figure 1
Representation of the design process

In part, Axiomatic Design is a process of determining the DPs to satisfy the FRs. 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: Maintain the independence of the FRs through the selection of DPs. In other words, the solution set of DPs is chosen to satisfy the FRs so that the FR implementation is independent (i.e. – one-to-one relationship, or uncoupled).
2. Information Axiom: Minimize the information content of the design. In other words, simpler designs are better than complex designs. Among alternatives, the design with the DPs

that have the highest probability to meet the FRs, within tolerances, is the best.

The process of decomposition establishes a design hierarchy based upon the selection of DPs to satisfy the FRs at increasingly refined levels of detail. To advance to the next level of detail in a decomposition requires the fulfillment of the Independence Axiom. Once a set of DPs has been determined at one level of decomposition, the next step is to decide if further decomposition to another level of FRs and DPs is necessary.

In Axiomatic Design, the relationships between the FRs and DPs are represented in either vector or graphical form. In graphical form, an off-axis arrow from an FR-DP pair to another FR represents the influence of that DP upon the other FR. The decomposition, or mapping process, is depicted in Figure 2 below.

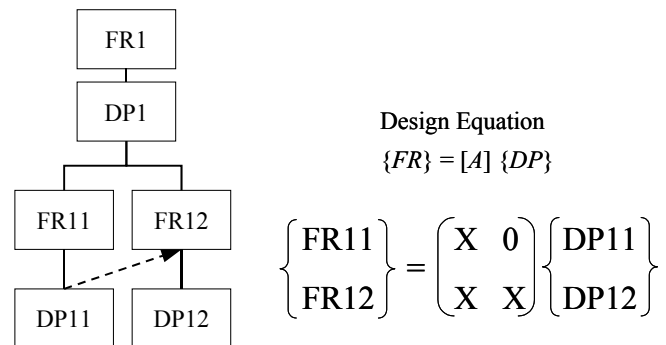


Figure 2
Mapping the FRs to the DPs

Both uncoupled and partially-coupled (decoupled) designs are said to satisfy the requirement of functional independence¹, as stated by the Independence Axiom. An uncoupled design, the best type of design, is defined as the case where one DP affects only one FR. A partially-coupled design also satisfies the Independence Axiom. In order to satisfy the Independence Axiom, the DPs must be implemented in a particular order. The order is based upon the level of the DP's influence on the FRs. In other words, the sequence is based on choosing the DP that affects the most FRs first, followed by the DP that affect the second-most FRs, and so on. The specific implementation sequence results in a physically implementable system design that does not require iteration to achieve the desired FRs. Within Axiomatic Design convention, the implementation sequence is graphically represented by a left-to-right ordering so that the DP that affects the most FRs is on the left (ref. Figure 2). The required steps for the Axiomatic Design process can therefore be summarized by Figure 3.

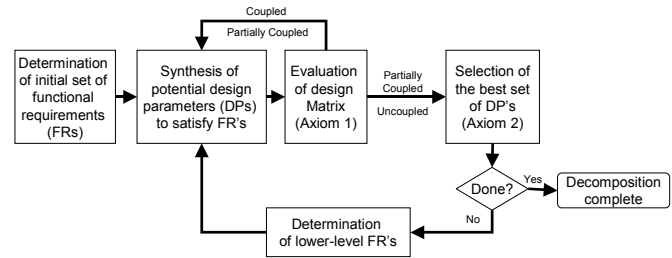


Figure 3

Simplified Axiomatic Design decomposition Process

The determination of design solutions is a creative process that requires content knowledge of the subject. Axiomatic Design provides a methodology to structure one's thinking during the design process, and provides a logical approach to defining the functional requirements (FRs) and the means of achievement (DPs).

2.3 The Manufacturing System Design Decomposition

Based on the Axiomatic Design methodology, the MSDD currently defines the foremost requirement for any manufacturing system as 'maximization of long-term return on investment.' The DP for this requirement was determined to be the design of the manufacturing system. This requirement is then decomposed into three sub-requirements: maximize sales revenues, minimize production cost, and minimize investment over the manufacturing system's lifecycle. Accordingly, DPs are selected to satisfy the given Functional Requirements and the Independence Axiom.

¹ Functional independence should not be confused with *physical* integration, which is often desirable as a consequence of Axiom 2. Physical integration without functional coupling is advantageous, since the complexity of the product is reduced.

Figure 4 illustrates the first two levels of decomposition.

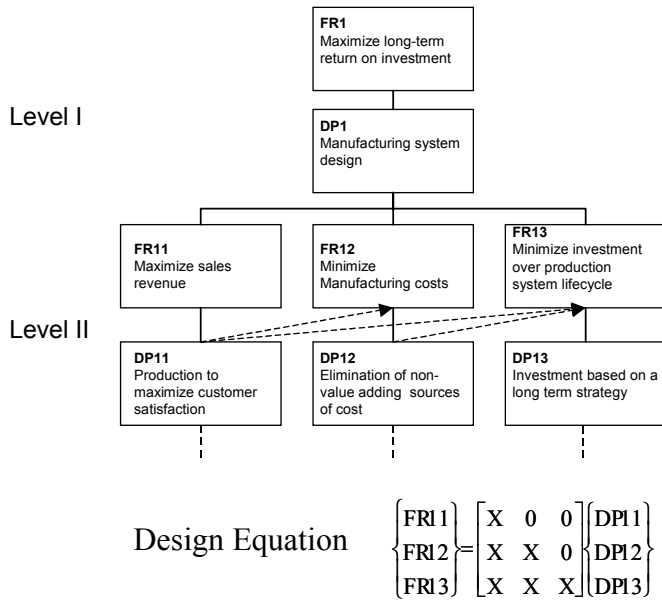


Figure 4

The first 2 of 6 levels of the MSDD's decomposition

Each of these three DPs is then decomposed into FRs and DPs at the next lower level. At this next level, the FRs are organized into six different branches (1: Quality, 2: Identifying and Resolving Problems, 3: Predictable Output, 4: Delay Reduction, 5: Operational Costs and 6: Investment). The decomposition process continues through succeeding levels until activities and decisions reach an operational level of detail. The basic structure of the MSDD is presented in Figure 5. The entire Manufacturing System Design Decomposition is included in Appendix A.

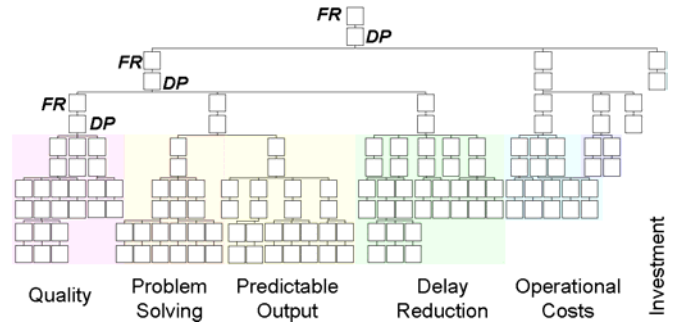


Figure 5

The MSDD and its different branches

Underlying the MSDD is the philosophy that a system cannot be improved if it is not stable^[2]. A ‘stable’ manufacturing system design is defined as producing every shift:

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

In addition, the manufacturing system must enable people to achieve the above requirements:

4. In spite of variation or disturbances that act on the system
5. While rapidly recognizing, reacting to, and correcting problem conditions in a standardized way
6. Within a safe, ergonomically sound working environment

Once the system has been designed to be stable, cost reductions can be achieved by eliminating waste within

the context of the stable system design. In short, the objective of the MSDD is to provide a design framework that enumerates the requirements and means necessary to achieve a stable and improvable manufacturing system design that is based on a logical, science-based foundation.

As a partially-coupled design, the MSDD states that *stable* manufacturing system design is dependent upon the correct implementation sequence, as reflected by the left-to-right ordering of the MSDD's branches. The significance of the implementation sequence, for example, describes why reducing cost (i.e. Operational Cost branch) without consideration of Quality, Problem Identification & Resolution, Predictable Output, and Delay Reduction will not have sustainable long-term cost reduction impact. Inherent in the creation of the MSDD is the concept that all sources of variation can be reduced through system design. These sources of variation not only pertain to disturbances in equipment processes, but to variations such as in methods (e.g.-problem solving), materials (e.g.-purchased parts), and planning (e.g.-part flow logistics).

As a consequence of giving equal importance to the requirements, the means, and the logical dependencies between them, the MSDD creates a holistic, systems-view for understanding the design relationships

necessary for any manufacturing system. The MSDD helps structure and communicate manufacturing problems in a way that gives clear reasons (requirements) for the solutions being implemented^[19]. Through the Axiomatic Design decomposition approach, the MSDD focuses on selecting the appropriate means to support the functional requirements, rather than aimlessly implementing best practices or using rules that are thought to be universally applicable^[20]. Furthermore, the MSDD incorporates sources from industry and literature such as Shewart and Deming's quality framework^[21], Shewart's idea of assignable and common cause^[22], and Gilbreth's ideas on wasted human motion^[23]. The MSDD attempts to encompass and codify all these ideas into one coherent framework.

3. Description of two Automotive Supplier Plants

The plants studied for this manufacturing system design evaluation contrasts two different automotive supplier plants, which produce plastic fascias for automobile bumpers. Data from each plant were gathered through a series of site visits by the authors. In general, the production of the bumper fascias requires 3 basic operations: injection molding, painting and assembly. These processes are the same for both of the

plants studied here. The following sections present an overview of each plant's general operating environment.

3.1 Description of Plant A

Plant A produces an average daily volume of approximately 7500 bumper fascias. The machines are grouped into departments based upon the manufacturing process being performed. Seventeen injection molding machines feed one high-speed paint line, which supplies the painted fascias to 10 assembly stations (Figure 6). Between departments, parts are stored in an automated storage and retrieval system (AS/RS). These racks are transported throughout the plant by automated guided vehicles (AGV's) or via an overhead conveyor system.

Of particular note is the average first-time-through yield, in paint, of 82% with variation between 25% and 95%.

Plant A receives several types of electronic production information from its customers: daily requirements, a ten-day forecast and a five-day schedule. Scheduling information is translated into production schedules for every department through cross-checking with the amount of unpainted and reworked parts available in the AS/RS. Due to high variability in paint and shipping delays, the schedules are changed frequently during a shift.

The primary focus of manufacturing performance is on the reduction of direct labor as a means to reduce manufacturing cost. Labor efficiency is measured by a performance ratio calculated from the ratio of CWS time (Current Work Standard) divided by the actual time worked.

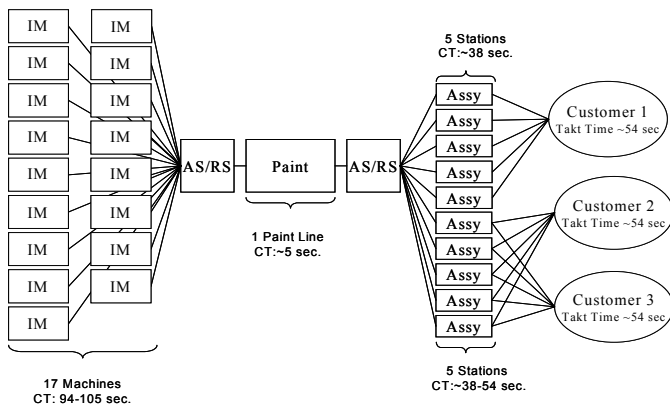


Figure 6
Material flow in plant A

Plant A operates 5 days a week in three, eight-hour shifts to supply fascias to three external customers, which operate five days a week with two, nine-hour

$$Performance\ ratio = \frac{CWS\ time}{Actual\ time\ worked}$$

$$CWS\ time = parts\ produced * CWS$$

The CWS time is calculated by multiplying the number of parts produced during a shift at an operation by the current work standard (CWS), which defines the standard processing time based upon industrial engineering time standards. The area manager's and the

plant manager’s performance is gauged on this labor (or production efficiency) measure. This measure does not reward the management of the plant to produce the right quantity and right mix of parts based on customer consumption.

3.2 Description of Plant B

On a daily basis, plant B produces six different fascias and supplies about 4200 parts to final automobile assembly. As shown in Figure 7, the plant consists of two main areas: the injection molding area and the paint area. Five injection molding machines feed the standard work in process (SWIP) area in injection molding. The SWIP area supplies parts to both paint-assembly systems. Each paint line operates at a cycle time of 23 seconds, which equals 46 seconds for each painted pair of bumpers. The parts are assembled at the end of each paint line.

Plant B operates 5 days a week in two, nine-hour shifts to deliver bumper fascias to one of the two final automobile assembly lines, which also run two, nine-hour shifts daily. Of particular note is the average first-time through yield, in paint, of 95%.

Assembly Line Control (ALC) issues daily build schedules based on the true demand requirements in final auto assembly. When orders are processed in auto body painting the part types and colors are communicated to both the paint systems and delivery shipping via “one-time-use-kanban”. The paint lines receive this information in order to determine part colors. The shipping area obtains the same kanban for in-sequence delivery to final assembly. Injection molding is scheduled by kanban as well.

Plant B focuses on operating and improving a system design that simultaneously achieves the requirements of quality, responsiveness, delivery and cost as defined by the MSDD. Personnel in plant B collect various measures including percent delivery to takt time², overtime, repaired parts, plant and non-plant

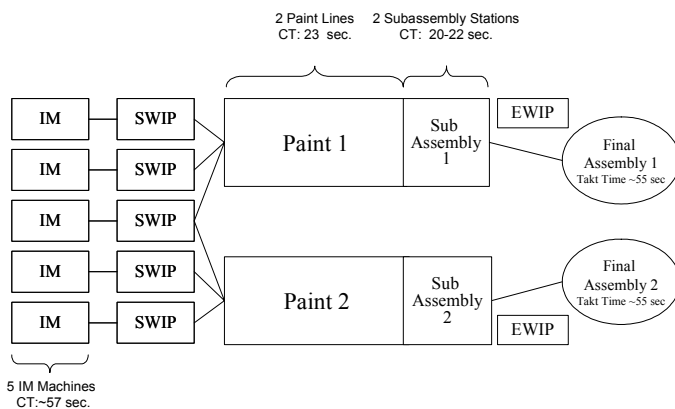


Figure 7
Material flow in plant B

² Takt time is defined as the time necessary to produce one piece of product. This time is equivalent to the total available working time divided by the required production quantity. Note that takt time is not the same as cycle time.

fault scrap, standard work in process levels, and results of improvement activities.

The evaluation of these metrics is used to identify the reason for non-satisfactory performance of the plant and to calculate the operation cost. Solutions for the identified problems are then determined. The measures reward management *and* production workers to produce the right quantity and right mix of parts based on customer consumption.

4. Evaluation of Plants

4.1 Motivation

Traditionally, performance measures have been used to evaluate the overall performance of manufacturing systems. Typically, these measurables evaluate aspects such as floor area, inventory, capital investment, and direct labor. In any industry, performance of the manufacturing system is closely linked to the long-term sustainability of the enterprise. In this respect, the MSDD has taken a systemic perspective into manufacturing system design and evaluation. Within the framework of the MSDD, a well-designed manufacturing system should achieve high performance in *both* quantifiable and non-quantifiable measures, and not just 'optimally' along financial measures. For this reason, this case study seeks to determine whether there

is a relationship between superior achievement of the FRs and superior performance of the plant as observed by a set of traditional performance measures.

4.2 Evaluation of Manufacturing System Design using the MSDD

In the following sections the general performance of each plant's manufacturing system will be assessed along with a set of measurables. Appendix B explains the method to normalize these measures. In short, the evaluation of the manufacturing systems is based only on the leaf FRs, i.e. the FRs that are not decomposed any further. The 42 leaf FR-DP pairs used in the evaluation are shaded in gray in Figure 8.

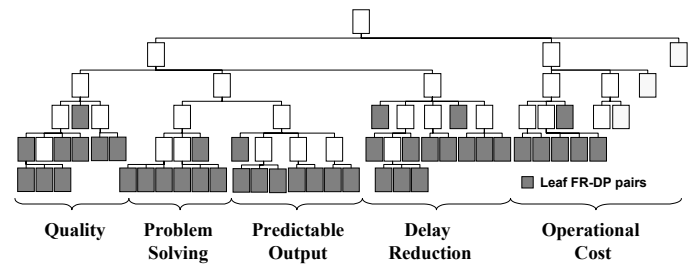


Figure 8

Leaf FR-DP pairs of the MSDD

The evaluation approach adheres to the principles of Axiomatic Design, where the higher-level FRs are only satisfied if the lower level FRs have been achieved. The evaluation results will be explained through the discussion of the key FRs that have not been fulfilled. The complete evaluation of the FRs is shown in Appendix C.

4.3 Overall MSDD Evaluations

4.3.1 Plant A MSDD Evaluation

A summarized overview of the FRs achieved in plant A is shown in Figure 9. Among the 42 leaf-level FR-DP pairs, there are 6 very poor, 16 poor, 13 moderate, and 7 good scores. Within each branch, the breakdown of scores indicates performance of the manufacturing system in the poor-to-moderate region.

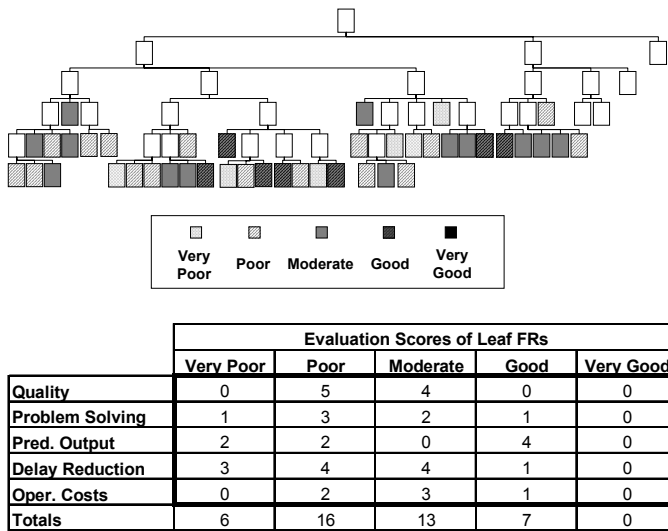


Figure 9

Overall evaluation of plant A

Overall the performance of plant A is poor-to-moderate. The evaluation also highlights the observation that within many branches of the MSDD, the performance of the plant varies widely.

4.3.2 Plant B MSDD Evaluation

A summarized overview of the FRs achieved in plant B is provided in Figure 10. Among the 42 leaf-

level FR-DP pairs, there are 1 moderate, 16 good, and 25 very good scores. Within each branch, the breakdown of scores indicates performance of the manufacturing system is firmly in the good-to-very good region.

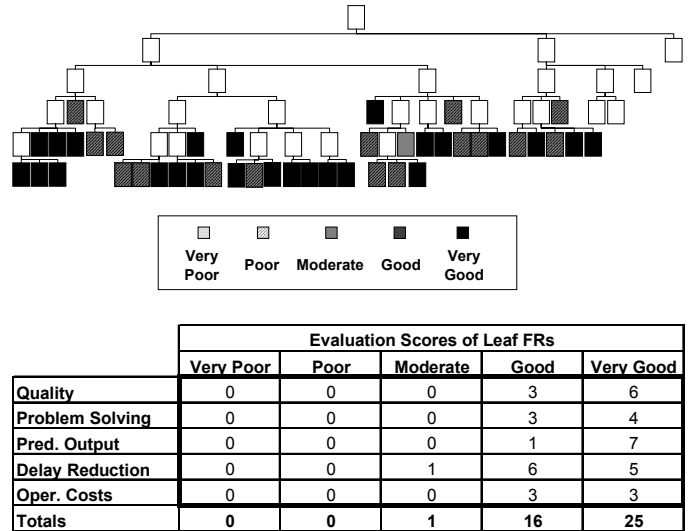


Figure 10

Overall evaluation of plant B

Of the 42 FR-DP pairs evaluated, forty-one showed good-to-very good performance. The evaluation illustrates plant B's superior fulfillment of the FRs relative to Plant A.

4.4 Design and Measurement Relationship

The data in Table 1 compares the overall operations for injection molding, paint and assembly of both plants. A breakdown of the normalized measures for each of the individual areas is provided in Appendix D.

*Table 1***Operational Measure – Performance and FR Relationship**

Clearly the performance of plant B is superior in both measurable performance and achievement of the FRs. Plant B needs significantly less WIP, and uses direct and indirect labor more effectively to produce more products with a much lower throughput time. Plant B achieves these superior results with nearly 33% less capital investment.

The one advantage that Plant A shows is in floor area. The high-rise style AS/RS helps plant A to greatly reduce consumed floor space. Also, all paint systems have essentially the same processes requiring the same floor space for each process. In this case, plant B has two complete paint systems—each system dedicated and balanced to one vehicle assembly line (ref. Figure 7). In contrast, plant A used one high-speed paint line for nearly twice the production volume of bumpers.

*Table 2***Overall achievement of MSDD leaf FRs.**

The superior measurable performance of plant B can be attributed to the better design and operation of the manufacturing system as a whole, as indicated by achieving the FRs of the MSDD. The evaluation results, summarized in Table 2, clearly show that advantage. Plant B demonstrates higher overall achievement of the FRs, on average with less variation.

5. System Design Comparison

Sections 4.3 and 4.4 presented an introduction into the application of the MSDD through summarized qualitative evaluations (i.e – MSDD) and quantitative results (i.e. – performance measurables). The following sections intend to describe the MSDD analyses of both plants in greater detail. General observations are followed by a discussion of each decomposition branch of the MSDD in each section. A detailed evaluation of the FR-DP pairs is given in Appendix C.

5.1 General Observations

At a high level, the MSDD evaluation tied with the measurables shows clearly that plant B achieves more of the leaf FRs than plant A (ref. Table 1). A key reason is that plant B ensures the production of right quantity and right mix of parts through their system design. This is achieved through simple material flow, and an information flow which is highly visible and conveys the actual demand of the customer. In addition, the standardization of work, the standardization of inventory, and problem solving methods are a major asset for plant B.

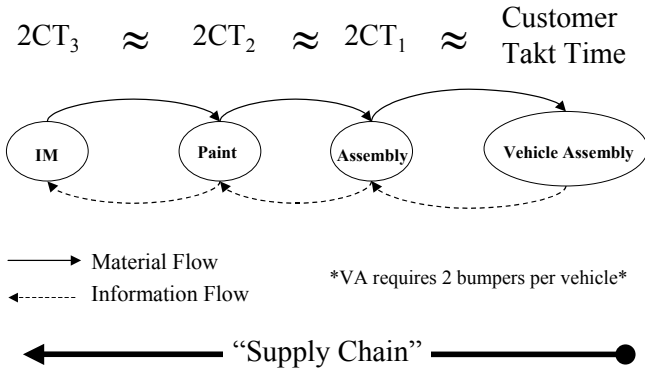


Figure 11

Ideal balanced design with linked cells³

A major reason for the superior performance of plant B is that the system was designed to be balanced to customer takt time. Figure 11 represents an ideal bumper production system design that is balanced to the vehicle assembly customer takt time.

In plant B, bumper production is closely modeled after the ideal balanced system of the Figure 11. Plant B integrated assembly work with paint unload work to achieve balance to takt time. More specifically, some assembly tasks were shifted from bumper assembly to final vehicle assembly to ensure a balance between production cycle time and customer takt time. In addition, the integration of paint with assembly enabled plant B to supply bumpers directly to final assembly

without storage. In contrast, the focus at Plant A is on the operation. Plant A separated all processes into separate departments. As a result, there are high system imbalances, high product path complexity, and large amounts of inventories between departments.

As mentioned in Sections 0 and 0, the performance measurement criteria used by both plants is different. In plant A, performance measurement is focused directly upon direct labor performance and machine utilization, regardless of customer demand. The Current Work Standard-based performance ratio is used for purposes of pure labor cost reduction through focusing upon labor efficiency even though labor cost is mainly a fixed cost due to the labor contract. The MSDD's five branches highlights that labor efficiency comes after meeting quality, identifying and resolving problems, and throughput time reduction in terms of the design path dependency stated by the MSDD.

Within plant B, the focus is upon making improvements to the work that benefits the entire system rather than achieving labor and equipment cost targets that are operation specific. Their focus is on improving the work within the system design framework that is represented by the MSDD.

³ A balanced system requires all processes to be designed and operate at takt time. In practice, the immediate upstream production cell's cycle time is slightly greater than the downstream process. For example, $CT_{i+1} = CT_i (1 + \text{Safety Coefficient}) \geq CT_i$. The magnitude of the safety factor will increase as the production cell's (i.e. cell $i+1$) process variation increases.

5.2 Quality

The Quality branch of the MSDD focuses on the ability of individual processes to manufacture products according to product specifications.

	Quality				
	Very Poor	Poor	Moderate	Good	Very Good
Plant A	0	5	4	0	0
Plant B	0	0	0	3	6

Table 3

Quality branch comparison

Overall, plant A is quite deficient in the Quality branch. Of the worst FRs performers, the deficiencies in plant A pertain to the existence of assignable causes and process variation. For example, most causes of defective parts that can be assigned to the injection molding machines have been identified but have not been removed (FR-Q11: Eliminate machine assignable causes). Operator assignable causes of quality problems are apparent in the non-standard work methods of the operators (FR-Q122: Ensure that operator consistently performs tasks correctly). In paint, operators can misload the bumpers onto the racks and cause scratches and nicks. Process noise, such as dirt, can cause many bumpers to be out of specification (FR Q31 - Reduce noise in process inputs). Higher defect rates in plant A can be explained through the lack of addressing the root cause for defects and the non-standardized work.

In contrast, plant B continuously works on improving the method and machine quality. For example, problems commonly found in plant A’s paint system have been more vigorously counteracted. For example, method assignable causes are prevented by the use of mistake-proofing devices (FR-Q123: Ensure that operator human errors do not translate to defect). Improvements in work methods are captured and shared across shifts through the rigorous assurance of standardized work methods (FR-Q122: Ensure that operator consistently performs tasks correctly).

5.3 Identifying & Resolving Problems

The scope of the Identifying & Resolving Problems branch relates how production disruptions are recognized, communicated, and resolved.

	Identifying & Resolving Problems				
	Very Poor	Poor	Moderate	Good	Very Good
Plant A	1	3	2	1	0
Plant B	0	0	0	3	4

Table 4

Identifying & Resolving Problems branch comparison

Plant A’s performance varies from ‘good’ to ‘very poor’ in the Identifying & Resolving Problems branch. Plant A does a moderate job of communicating production issues to the proper personnel. However, the initial identification and, more importantly, the resolution of the issues are quite poor. For example, the flow of bumpers through the AS/RS prevents visibility of inventory on the shop floor. In addition, electronic

inventory counts of bumpers within the AS/RS are recorded, however the reliability of that information is problematic and inaccurate. Two method assignable causes are the improper loading (e.g – not completely filling the rack) and mis-identification of bumpers (e.g. – entering the wrong color code in the AS/RS controller) sent to the AS/RS from the paint area. Not achieving the FRs of the Quality branch has resulted in a very complex and time-consuming problem identification process. Time pressures and process instabilities lead to ‘fire fighting’ rather than the elimination of root cause. The approach in plant A does not achieve FR-11 (Rapidly recognize production disruptions) well.

In contrast, plant B performs well in the area of problem solving. The problems encountered in plant B’s injection molding department are recorded and solutions are worked on immediately (FR-R13: Solve problems immediately). Plant B’s low complexity of the paint lines enables problems to be detected and understood quickly (FR-R123: Minimize time for support resource to understand disruption). Also, the SWIP area enables an increased visual sampling of inventory. Whenever material is picked up from injection molding and delivered to paint, the material handling operator can see potential material shortages

and relays the information to the proper individual (FR-R11: Rapidly recognize production disruptions).

5.4 Predictable Output

The Predictable Output branch distinguishes the resource’s information, equipment, people and material in order to state the requirements of the manufacturing system to minimize production disruptions through predictability from the production resources.

		Predictable Output				
		Very Poor	Poor	Moderate	Good	Very Good
Plant A		2	2	0	4	0
Plant B		0	0	0	1	7

Table 5

Predictable Output branch comparison

In plant A, predictability of output is a major problem. Scheduling information is disseminated to every area in plant A from a central scheduling office. The schedule is not based on the downstream customers demand, but rather on the difference between AS/RS levels and forecast demand (FR-P11: Ensure availability of relevant production information). Since the demand is not based on actual consumption from the downstream process, FR-P11 is not met. High process variability, particularly in paint, necessitates the frequent readjustment of the daily schedules. The output of the operators in plant A’s assembly has great cycle time variability within a given product, which can be as high as 30%. Stable output of the operator is not achieved well by plant A’s manufacturing system,

which is to reduce the variability of task completion time.

In addition, problems with absenteeism can severely affect the plant’s ability to produce as machines are not being consistently operated in plant A (FR-P122: Ensure availability of workers). Plant A’s paint system has high frequency of downtime due, in part, to its design complexity which is linked to its high processing speed. The plant schedules very little preventive maintenance—rationalized to avoid reducing the paint line’s capacity even further. Because plant A mostly addresses problems with short-term solutions in order to minimize downtimes, most problems re-occur (FR-P132: Service equipment regularly).

In contrast, predictability in production is a system design requirement in plant B. The demand in plant B is based solely on the actual consumption from downstream operations (FR-P11: Ensure availability of relevant production information). In order to ensure predictable output of the machines, plant B has invested a great amount of labor for maintenance of the equipment and a regularly scheduled maintenance program (FR-P132: Service equipment regularly). The availability of material is ensured through the defined

standard work in progress at plant B (FR-P141: Ensure that parts are available to the material handlers).

5.5 Delay Reduction

The Delay Reduction branch describes the system design aspects necessary to meet customer expected lead time. Five delays are defined: lot size delay, process delay, run size delay, transportation delay, and systematic operational delays. The goal is to meet expected customer lead time by reducing each of these delays as much as possible by implementing the corresponding DPs.

		Delay Reduction				
		Very Poor	Poor	Moderate	Good	Very Good
Plant A		3	4	4	1	0
Plant B		0	0	1	6	5

Table 6

Delay Reduction branch comparison

At plant A, performance in the Delay branch is the poorest of all 5 branches. For example, takt time has not been defined in plant A (FR-T21: Define takt time). At plant A, policies exist to run a machine as long a possible with the same part type in order to minimize the number of changeovers. Therefore as many parts as possible are produced once a machine has started up (FR-T3: Reduce run size delay). The large run size creates run size delay due to the fact that parts are not produced in the desired mix and quantity during each demand interval. In addition to the transportation delay

required at plant A because of storage in the AS/RS, delay occurs because parts are stored before being sent to the rework area (FR-T23: Ensure part arrival rate is equal to service rate). Plant A needs approximately 40 minutes to transport parts between the AS/RS and subsequent processes (FR-T4: Reduce transportation delay).

In plant B the paint systems are designed to run at takt time (FR-T21: Define takt time). As reflected by paint/assembly's 46-second cycle time and vehicle assembly's 55-second cycle time, there is good balance between the two areas (ref. Figure 7). However, due to the time required to injection-mold and cool a bumper, injection-molding machines do not achieve the defined takt times in either plants. As reflected in the low injection molding cycle time of 57 seconds, plant B constantly works on satisfying this requirement (FR-T221: Ensure that automatic cycle time <= minimum takt time). At plant B, transportation delay is shortened through storing the parts on the shop floor and the short distance between injection molding and paint (FR-T4: Reduce transportation delay). The single piece flow at plant B prevents run size delay (FR-T23: Ensure that part arrival rate is equal to service rate). At plant B defective parts are either sent directly back into the

paint system or reworked immediately (FR-T4: Reduce transportation delay).

5.6 Operational Costs

The focus of the Operational branch is the effective utilization of direct labor by eliminating non-value sources of costs.

	Operational				
	Very Poor	Poor	Moderate	Good	Very Good
Plant A	0	2	3	1	0
Plant B	0	0	0	3	3

Table 7

Operational Costs branch comparison

For plant A, the performance in the Operational Cost (or Labor) branch is 'poor-to-moderate.' Figure 12 shows the physical layout of plant A's bumper assembly. For this assembly workstation vehicle assembly requires the bumpers in a specific color sequence called the In-Line Vehicle Sequence (ILVS). First, Operator 1 unloads bumpers from the incoming AS/RS racks, and loads the bumper into the appropriate color lane. In similar fashion, the Operator 2 selects the proper color from the color lane, and places the bumper on a short conveyor. The operators at position 3 then pick up the bumpers, attach the purchased parts, and then load them into the ILVS racks.

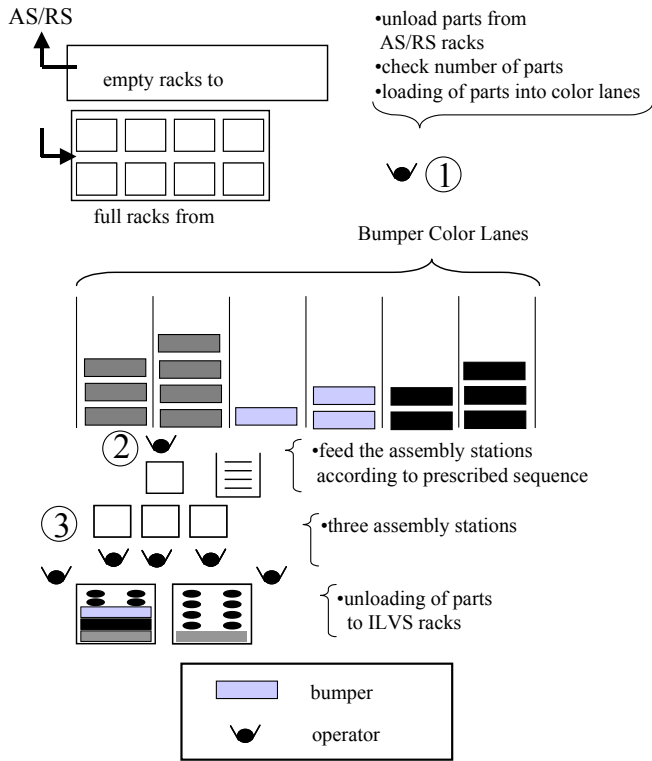


Figure 12

Plant A - Physical layout of bumper assembly

For both operators 1 and 2, their dedicated tasks require less time than bumper assembly requires. As a result, both operators 1 and 2 have significant idle times (FR-D3: Eliminate operators' waiting on other operators). Also, the operators' tasks in bumper assembly require a lot of motion. For example, in assembly the loading and unloading operations require a lot of walking between the racks and the conveyor. In fact, for each 8 incoming racks, Operator 1 repeats the sorting process ninety-six times, and covers over a half-mile in the process (FR-D21: Minimize wasted motion of operators between stations). After the bumpers are assembled at area 3, the operators cover the bumpers

with a protective film in order to minimize damage during shipment to the final assembly plant (FR-D11: Reduce time operators spend on non-value added tasks at each station).

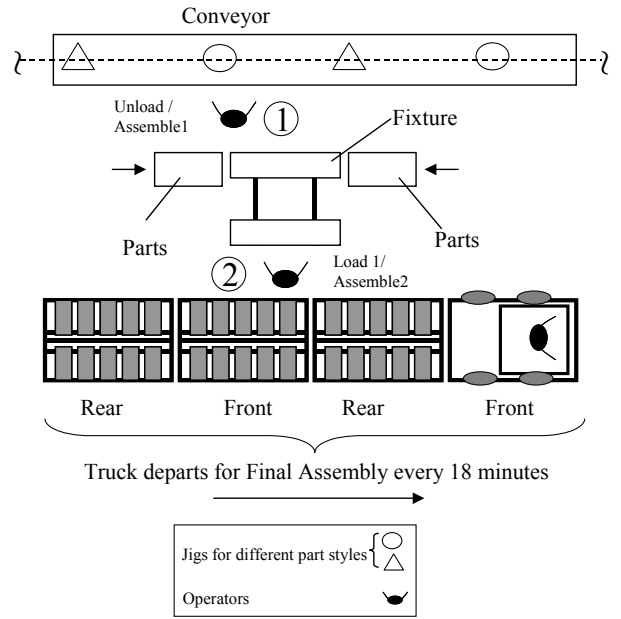


Figure 13

Plant B – Physical layout of paint unload and assembly

Figure 13 shows the equivalent layout of Plant B's paint unload and bumper assembly area. For paint unload, Operator 1 moves the bumpers directly from the paint system's conveyor to the assembly workstation, assembles some purchased parts, and slides the bumper down to operator 2. Operator 2 completes the assembly process, and loads the completed bumper into the racks beside the operator (FR-D23: Minimize wasted motion in operators' work tasks). Since these bumpers are delivered a short distance between bumper assembly and final auto

assembly, the bumper wrapping processed used in plant A is avoided at plant B (FR-D11: Reduce time operators spend on non-value added tasks at each station). Some waste in direct labor is observed in both plants, however plant B does a good job satisfying all of the FRs.

6. Equipment Design Comparison

Sections 4. and 5. provided the foundational analysis of the two manufacturing system designs under consideration. The analysis was presented from two perspectives: 1) the aggregated performance measures, and 2) the achievement of the FRs (ref. Table 1).

6.1 Paint System Design Comparison

As stated in Section 1. , a manufacturing system design covers all aspects of the creation and operation of a manufacturing system. As such, the performance of the system is contingent upon the performance of two attributes: the physical system design (e.g. – equipment, information, layout, work methods) and the system management aspects (e.g. – cost management, problem identification & resolution, improvement processes). Within the framework of the MSDD, these two attributes of system design are both necessary to achieve any manufacturing system design. These relationships are emphasized by focusing upon the

performance of the paint systems in both plants. In particular, the differences in changeovers will be discussed.

6.2 Physical system aspects

At each stage of the painting process in plant A, adhesion promoter, paint, and clear coat is applied by four robots. To enable the 5-second cycle time, each robot sprays only cover a 25% portion of the bumper with paint. There are two types of changeover: style changeovers require a program adjustment and are done instantaneously. This change affects equipment configuration only. However, the second type, color changeover exhibits four major problems. First, the color change requires 30 seconds resulting in losses to production (FR-T2: Reduce process delay). In addition, for every color change the paint guns and color hoses of the robots have to be flushed and cleaned (FR-T3: Reduce run size delay). The resulting costs are strongly attributable to the high degree of paint loss necessary to evacuate the long paint lines. As shown in Figure 14, the paint lines are so long because the centralized control box that switches over paint colors is over 50 feet away. In addition, the first parts of a new color batch are often of unacceptable quality, since paint particles remain in the paint booth for some time (FR-

Q31: Reduce noise in process inputs). Bumpers can be painted in batch sizes of 12 to 200 parts, but the paint changeover issues are a major reason for the attempt to maximize the color run size.

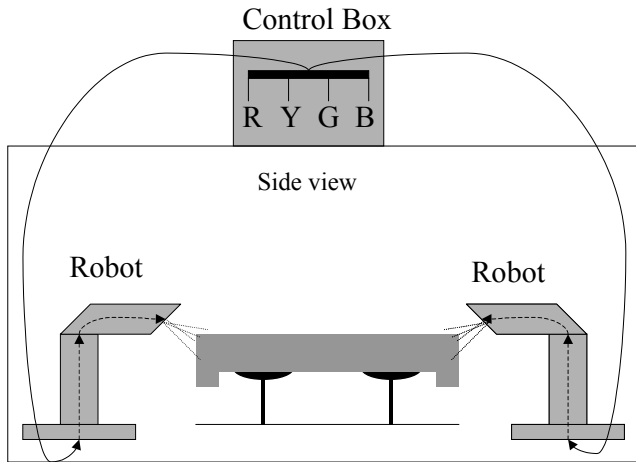


Figure 14

Schematic of plant A's bumper paint changeover system – side view

In plant B, the paint system consists of the same basic operations as plant A but the machine design is completely different. In plant B, paint changeovers do not lead to any quality loss or considerable costs in the paint booth. The topcoat and the paint are applied to the fascias either by robots or manual spray guns. For the manual painting represented in Figure 15, some colors have dedicated spray guns, but others are changed over by simply detach and engaging the spray nozzle from one color hose to another. In the manual paint booth, the operator removes the spray nozzle from paint color line 1 to paint color line 2, and sprays some paint to the floor to ensure that no paint of the previous color is left

in the gun (FR-Q122: Ensure that operator consistently performs tasks correctly). The six-second changeover does not lead to any loss of production time as the regular work loop leaves enough time to accommodate the changeover (FR-T222: Ensure that manual cycle time \leq takt time).

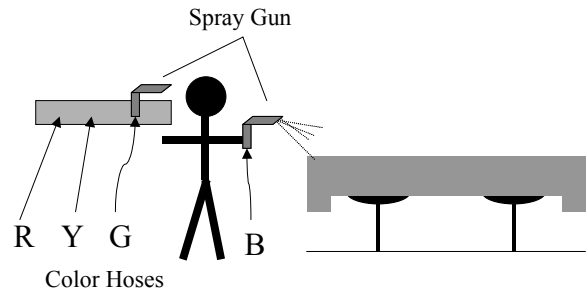


Figure 15

Schematic of plant B's manual paint changeover system

For the robots, the color changeover occurs at the spray nozzle. Each robot has separate color lines that are separated by an indexing device. The changeover simply requires an indexing of the spray nozzle to the proper paint line. The very strong top-to-bottom air flow inside the booth is so clean that operators do not have to wear masks (FR-Q31: Reduce noise in process input). Fascias can be painted in batches of 1, but are grouped when possible in order to minimize paint consumption (FR-T3: Reduce run size delay). The goal of paint is to provide assembly with the exact product mix and quantity 2.5 hours later

6.3 System Management Aspects

An understanding of the importance of management's role in manufacturing system design can be obtained from some historical motivation. For plant A, the original drivers for the selection of the original paint system were high-volume capacity, low direct labor and operation unit cost requirements. As such, the 5-second cycle time of the paint line was achieved through a single, highly automated equipment design. Additional future demand would be handled by the 'excess' volume capacity built into the original paint system. Quite simply, the paint process was not designed to meet the system FR of takt time (FR-T21: Define takt time). Instead, operational cost optimization guided management and engineering to develop a high-speed machine that does not account for the hidden costs in manufacturing (e.g. – repair, maintenance) that is eliminated by achieving the FRs of the MSDD.

In establishing the production takt time, management has control over setting the system design's available production time. At plant A, the management strategy is to schedule operations to run 24-hours a day with policies to run equipment as long as possible. These policies were established in order to minimize problematic changeovers and maximize potential output. However, the continuous production

policy left no provision for regular preventive maintenance (FR-P132: Service equipment regularly). Rather than focusing on the root cause of equipment reliability (FR-P13: Ensure predictable equipment output), management policy focused upon working around this problem.

In contrast, plant B's paint system was designed with strategic and system design intent. Currently, paint has two paint lines, each dedicated to one final vehicle line. Originally, plant B had only one paint line, with a cycle time of 23-seconds (per bumper) aligned to the pace of the 55-second final vehicle assembly line customer (FR-T22: Ensure that production cycle time equals takt time). When a second vehicle assembly line was added, a second identical paint 'module' was implemented as a modular chunk of capacity. The implementation of capacity in modular chunks has the advantage of predictable future costs and predictable system performance. This approach eases the financial, physical, and management support to add additional capacity.

Vehicle assembly, bumper assembly, paint and injection molding all operate the same 2-shift, 9-hour (total time of 8 work hours, 30 minute lunch, 2 15-minute breaks) operating pattern. The 3-hour time gap between shifts allows for preventive maintenance (FR-

P131: Ensure that equipment is easily serviceable), off-line shop floor training (FR-Q121: Ensure that operator has knowledge of required tasks), work method improvements (FR-Q13: Eliminate method assignable causes), workstation improvements (FR-D21: Minimize wasted motion of operators between stations), and provides the ability to ensure that the right quantity (FR-T21: Define takt time) and right mix (FR-T31: Provide knowledge of demanded part types and quantities) of parts are made even when overtime is required. The 2-shift, 9-hour structure improves the productivity of the workers and, most significantly, provides a system design that ensures consistent and predictable output.

6.4 Summary

Within the framework of the MSDD, the physical system design and system management are integral facets of a manufacturing system design. The notion of a system design necessitates that all DPs be implemented to satisfy all the FRs. If all DPs are not implemented, then the design is incomplete. By analogy, the paint system is the physical representation of the DPs intended to satisfy all the strategic FRs⁴.

Plant A took an operation-focused approach to manufacturing system design. In contrast, plant B approached the manufacturing system design from a systems perspective and aligned the means to their high-level objectives.

7. Improving Performance with the MSDD

Using the MSDD, a pilot program was designed to redesign and improve plant A's system design performance. The requirement of the redesign project was to ensure the production of right quantity and right mix, despite the high variability of the plant's paint system with a visual information flow. This objective was to be achieved by scheduling only assembly, linking assembly and paint with a kanban system, and establishing standard work in process between injection molding and paint, and between paint and bumper assembly. The MSDD was applied to this project in a five-step process, which is illustrated in Figure 16.

⁴ A single piece of equipment can, and generally will be affected by several FRs of the MSDD. Physical attributes (as DPs) may be combined to achieve multiple FRs (physical

integration). Design independence can still exist even though physical integration exists, through uncoupled or partially coupled designs.

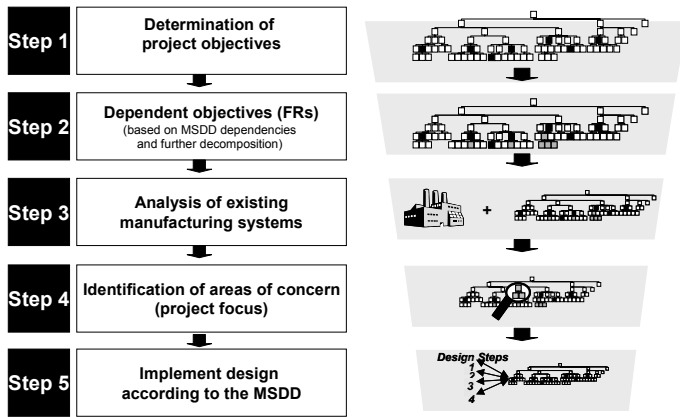


Figure 16
Application of the MSDD for Redesign

In the first step, the FRs directly pertaining to the goals of the program were identified as: 1) FR-I2: Eliminate information disruptions, 2) FR-T3: Reduce run size delay, 3) FR-P14: Ensure material availability even though fallout exists, and 4) FR-R111: Identify disruptions when they occur. The second step includes

focused on due to their importance to the program's success. As a third step, the plant was evaluated with respect to the FR's determined in steps 1 and 2. As a fourth step, areas of concern were identified as rapidly recognizing when problem conditions occur (FR-R111: Identify disruptions when they occur), establishing standardization of work (FR-P12: Ensure predictable worker output), establishing standard work-in-process (FR-P141: Ensure that parts are available to material handlers), production more balanced to takt time (FR-T2: Reduce process delay), and reduction of run sizes (FR-T3: Reduce run size delay). These areas of concern were thus set the project focus. The first four steps are reflected in Figure 17.

The fifth step is to implement the design according

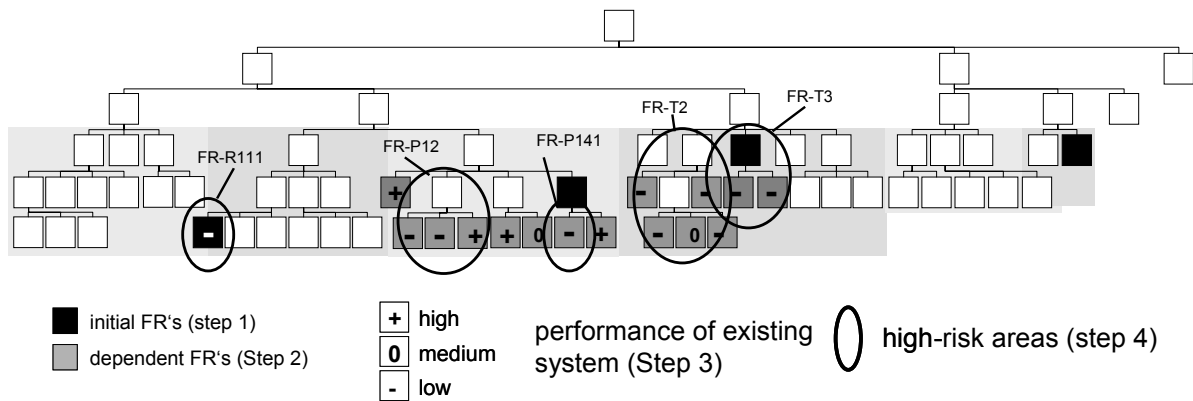


Figure 17
First four steps of the 5-step process

the identification of indirect requirements of the program. These FRs were derived either from the dependencies described by the design matrices or were

to the MSDD. The information disruptions were to be

eliminated by providing final assembly with a heijunka⁵ that reflects the true daily demand. Paint was to be scheduled on the basis of parts consumed in assembly. The run size delay was to be reduced by enforcing a smaller and standardized batch size in paint. A supplier-kanban system was implemented to ensure consumption-based delivery of purchased parts. By instituting production-kanban, to achieve the FRs of the MSDD, the information signaling that a defect occurred is translated back to the paint system immediately.

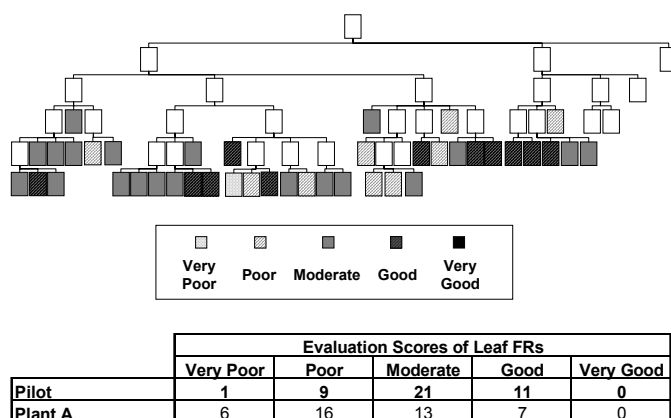


Figure 18

Performance of Pilot project

The project was implemented during the Autumn of 2000. The new system was evaluated approximately eight weeks after the initial learning and implementation phase. Figure 18 summarizes the results of the redesign project, and shows the enhanced

performance of the pilot project over Plant A's overall performance

Of the twelve FRs originally targeted in the pilot project redesign (ref. Figure 17), four FRs dramatically improved from 'poor' to 'moderate' or 'good' levels. However, the remaining eight targeted FRs did not change to achieve the desired results. With the MSDD evaluation of the pilot, key future improvement actions can be identified and appropriately implemented.

The preceding section illustrated an actual case of how the MSDD has successfully been used to determine the requirements and the prerequisites of actions taken in order to improve the design of the manufacturing system.

8. Summary and Outlook

This paper has presented a methodology for evaluating the manufacturing system design of two automotive supplier plants located in North America. The evaluation was based on a set of performance measures that were then related to the Manufacturing System Design Decomposition. The paper used the MSDD to explain the differences of the system design in plant A and B. Plant B achieves more of the MSDD's requirements than plant A and thus has the

⁵ A heijunka is a level scheduling tool that uses kanban cards. The heijunka controls the pace of demand placed on the production system^[24].

better manufacturing system design according to the MSDD.

The superior performance of plant B is a reflection of the superior achievement of the FRs. The system design approach guides the necessary investment to achieve the FRs of a system design. Plant B consistently seeks to achieve its FRs. In contrast, plant A is the result of investment cost-minimization driving the plant design. According to the MSDD, superior performance is the result of achieving the FRs of system design.

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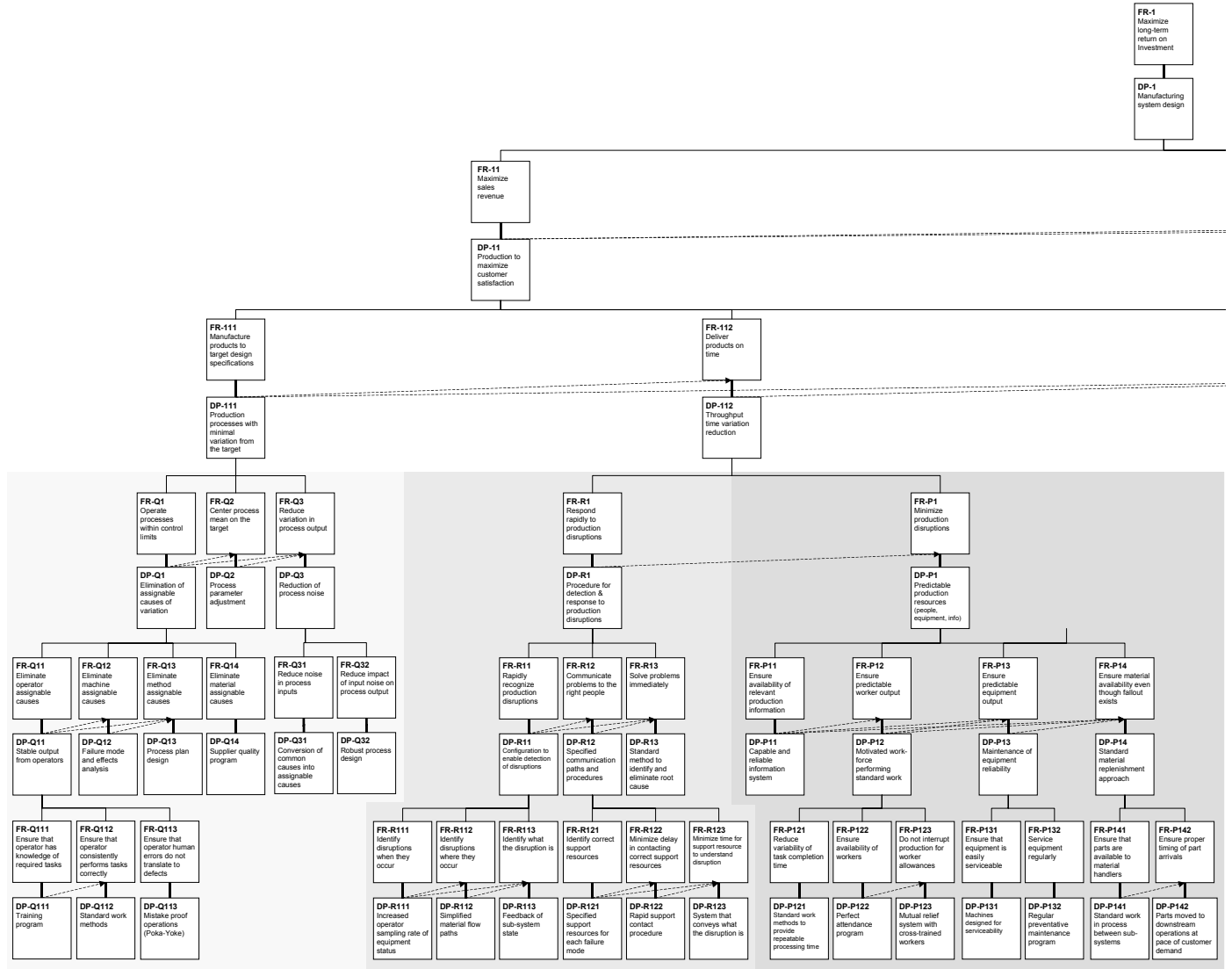
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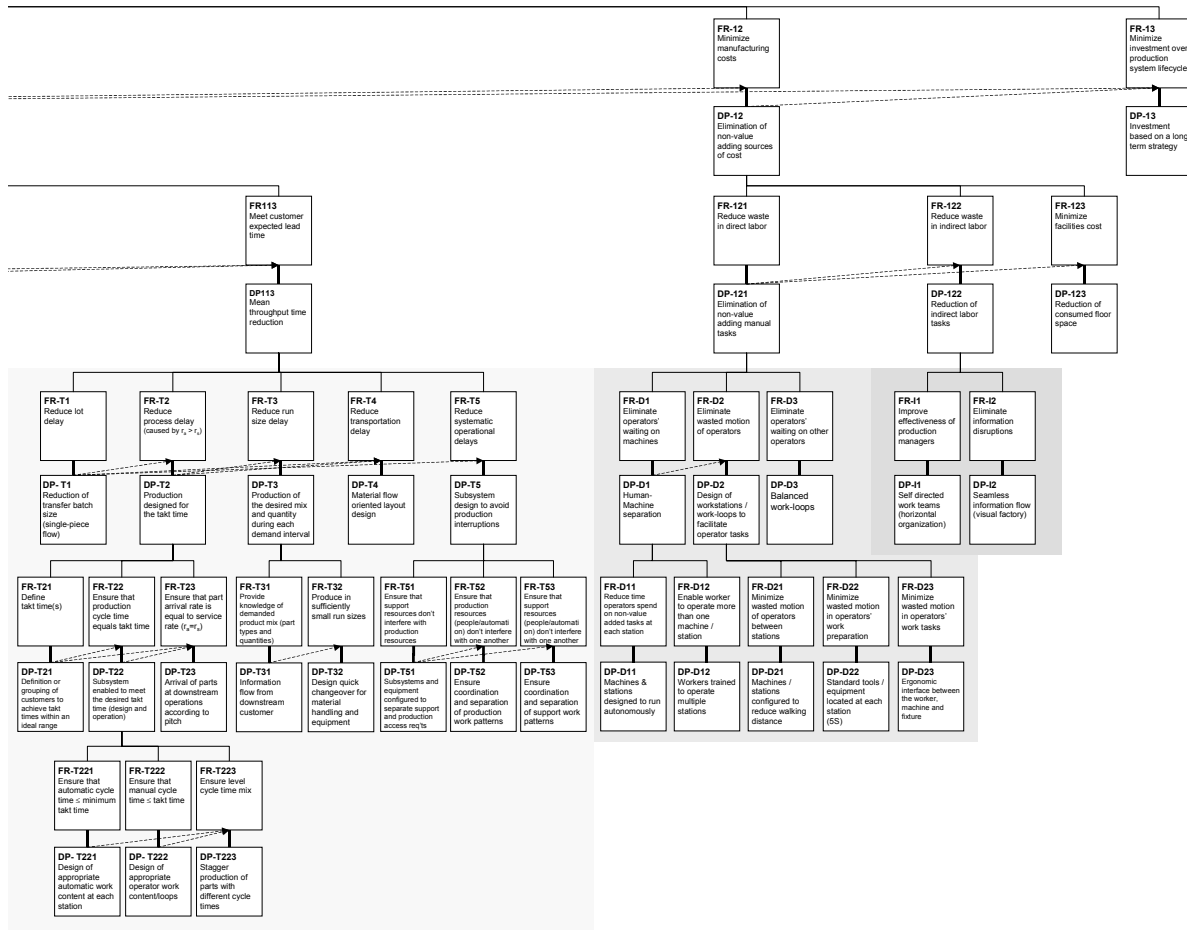
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Appendix A: The Manufacturing System Design Decomposition (Page 1 of 2)



Appendix A: The Manufacturing System Design Decomposition (Page 2 of 2)



Appendix B: Method of Data Calculation

Calculation for traditional measures

Calculation of Leaf FRs Satisfied by each Plant

Note: Indirect workers include supervisors, relief workers, repair workers, maintenance, scheduling, material handlers, and housekeeping.

For the purposed of Table 1, an FR was considered satisfied if the FR achievement scored at least a 4 of 5 total points.

Appendix C: MSDD Leaf FR's Satisfied by Plant A and Plant B

Appendix D: Breakdown of Measurable Data

Injection Molding

Paint

Assembly