Evaluating Manufacturing System Design and Performance with the Manufacturing System Design Decomposition Approach

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Abstract

This paper contrasts the design of the manufacturing systems at two North American automotive component manufacturing plants with the Manufacturing System Design Decomposition (MSDD)[1]. Manufacturing system designs should not be characterized based on name alone. Instead of characterizing a manufacturing system as "mass" or "lean," it should be described in terms of the achievement of the manufacturing system requirements. The following analysis quantifies the performance of a so-called "lean" plant relative to a so-called "mass" plant based on the achievement of the system design requirements decomposed by the MSDD.

Keywords: *Axiomatic Design, Lean Manufacturing, Manufacturing System Design*

1. Introduction

This first objective of the paper is to introduce the Manufacturing System Design Decomposition (MSDD). The MSDD is the result of a design decomposition process to identify clearly the requirements of a manufacturing system and the means of achieving those requirements. The ability of a system design to achieve its requirements can be evaluated with measurable parameters or measures[2,3].

A "mass" production system is the result of attempting to optimize the piece-parts or individual operations within a system. A mass system optimizes specific parts of a system, instead of the whole. Lean production is a name given to an *enterprise* system design to achieve the requirements of the enterprise as a whole[4,5].

The understanding of what the term "lean" means can be interpreted in many different ways and has often led to misinterpretation and misunderstanding. The purpose of the Manufacturing System Design Decomposition (MSDD) is to eliminate this ambiguity by providing a foundation that states clearly the requirements and means that exist within a system design. The MSDD applies specifically to the design of discrete-part, repetitive manufacturing systems. The requirements are called Functional Requirements (FRs) and the means are called Design Parameters (DPs) according to the design methodology used to develop the Manufacturing System Design Decomposition.

By stating the FRs and DPs of a manufacturing system design rigorously, the MSDD[6,7] provides a logical foundation to determine whether a manufacturing system achieves the stated FRs. This foundation enables the evaluation of existing manufacturing systems and guides the development of new manufacturing systems. The MSDD is the result of applying the Axiomatic Design methodology to develop a design decomposition to reflect modern manufacturing requirements.

Definitions proposed in this paper for the terms "manufacturing system" and "manufacturing system design" are as follows:

Manufacturing system: The arrangement and operation of 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.

Manufacturing system design: Manufacturing system design covers all aspects of the creation and operation of a manufacturing system. Creating the system includes equipment selection, physical arrangement of equipment, work design (manual and automatic), and standardization. The result of the creating process is the factory as it looks during a shutdown. Operation includes all aspects, which are necessary to run the created factory (ie., problem identification and resolution process).

One motivation for developing the MSDD is to eliminate the ambiguity of defining a system design with one-word explanations or as a set of physical tools that are implemented. We assert that it is impossible to become "lean" simply by implementing "lean tools."[8,9,2] The tools of lean are indicative of a physical means to achieve certain requirements. These tools encapsulate the achievement of multiple functional requirements. In Axiomatic Design, this encapsulation is known as physical integration.

The decomposition approach first concentrates on stating the requirement (FR) and then the corresponding means (DP). Many levels of decomposition are required before any specific physical system design becomes apparent. Furthermore, it must be re-iterated that a lean tool may achieve multiple FRs simultaneously. This fact is common to Axiomatic Design which distinguishes *physical integration* and *functional independence*[10]. A physical entity can achieve multiple FR and DP pairs and yet be one physical unit. A problem occurs when a physical tool is used when the corresponding FR(s) that drove the original development for that tool no longer exist or are not understood. The requirements and means must first be understood before the correct solution can be designed. The MSDD approach first defines the manufacturing system requirements (FRs). How the FRs are accomplished by the means (DPs) is defined next.

This paper uses a set of performance measures and the MSDD to evaluate two automotive component-manufacturing plants located in North America. The designs of the two plants are evaluated based on the achievement of the FRs stated by the MSDD and the performance measures.

One hypothesis or mental model of this research is that a manufacturing system design that achieves the requirements (FRs) stated by the MSDD will perform more cost effectively than a manufacturing system design that does not effectively achieve the FRs of the MSDD. This assertion is based on the fact that the MSDD states an apropos set of FRs relative to modern manufacturing needs. A key idea is that the concept of system design as proposed herein requires the achievement of multiple requirements simultaneously. The manufacturing "strategy" is, therefore, to achieve all requirements well and simultaneously.

A second assertion is that to achieve multiple FRs simultaneously requires a manufacturing system to be *designed.* The decomposition process represents the thinking and the specification of the corresponding solutions to achieve multiple FRs, simultaneously.

2. The MSDD

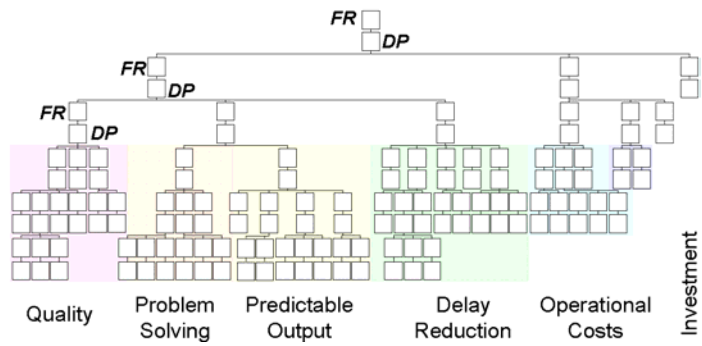


Figure 1
The Manufacturing System Design Decomposition (MSDD)

The Manufacturing System Design Decomposition (MSDD), shown in Figure 1, has been developed according to the Axiomatic Design methodology.[10,11] Axiomatic Design defines design as the "creation of synthesized solutions in the form of products, processes, or systems that satisfy the perceived customer needs through *mapping* between Functional Requirements (FRs) and Design Parameters (DPs)." Two design axioms are specified: the Independence Axiom and the Information Axiom. The Independence Axiom (Axiom 1) states that a good design must, "*maintain the independence of the functional requirements*." The Information Axiom requires *minimizing the information content of the design.*

To accomplish independence of the Functional Requirements requires defining a means, a Design Parameter (DP), to affect only one Functional Requirement (FR). Independence also means that the selection of the DPs ensures that the FRs are independently satisfied.

2.1 The Design Process

Step 1 in the design process is to define the top-level FRs for the manufacturing system being designed. A type of *Zig-Zagging* process is a term that characterizes decomposition. Figure 2 illustrates.

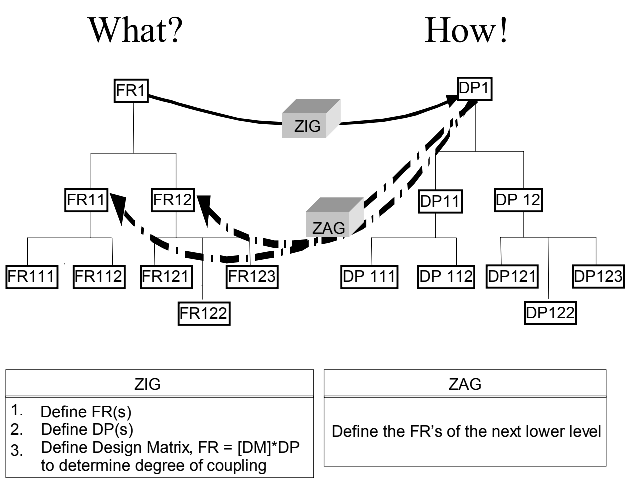


Figure 2
The Decomposition Process

Step 2 in the design process is determining the DPs that correspond to the FRs. This step is sometimes called *zigging.* Step 3 requires the Independence Axiom, Axiom 1, to be satisfied at the current level before decomposition can proceed to the next level. Axiom 1 is satisfied when a design is uncoupled or partially coupled. Coupled designs do not satisfy Axiom 1.

Step 4, which defines the next level of FRs in the decomposition, may occur once the independence axiom is satisfied. The FRs at the next level of decomposition provide a statement of the requirements necessary to further define and elaborate on the parent FR-DP pair. This step is sometimes called *zagging*.

For example, if FR1 states, "Go from MIT to the Airport." The corresponding DP1 might be, "Mass Avenue Cab use." The selection of DP1 limits the choice of possible solutions for the next level of FRs: namely FR11, FR12… FR1n.

The design process continues by determining the DPs to satisfy this next lower-level of FRs. Independence must be satisfied next. The decision to decompose a design further is based on the system designer's judgment in communicating the necessary level of detail.

Selection of DPs and FRs is an iterative process, even though it was described here linearly.

2.2 Communication and Research with MSDD

The use of the design process to develop the MSDD provides the ability to communicate one's thinking rigorously. If an alternative DP1 were chosen, the next level of design decomposition could be completely different. For this reason, this system design approach fills the huge void that exists today in modern corporations and institutions: *the thinking or thought process present in many corporations'* designs. The approach forces one to define one's thinking. The result of the decomposition process provides a structured and adaptable communication tool.

In prior research, Cochran has shown that axiomatic design may be used to describe the *thinking* that is present in mass manufacturing systems[5]. The authors define mass production as an incomplete design (fewer DPs than FRs… which violates axiom 1) and demonstrate that the unit cost equation used today by many companies' drives the physical manufacturing system design and the behavior within companies.

Many authors have written about the thinking that creates systems[12,13,14]. Yet, the problem has been the inability to effectively communicate one's thought process. The system design process with axiomatic design provides a tool to effectively communicate one's thought process. It also forces rigor in ones' thinking through the satisfaction of the axioms. Most importantly, from a research point of view, the MSDD provides a framework as a type of testable hypothesis, to prove or to disprove the effectiveness of a system design.

This study illustrates whether a plant with the so-called mass plant design performs better than a so-called lean plant in terms of achieving the FRs of the MSDD. The FRs define what the system design must be able to accomplish. Financial measures and unit cost equations, when used to drive a manufacturing system design, are too limited in defining what a system must do.

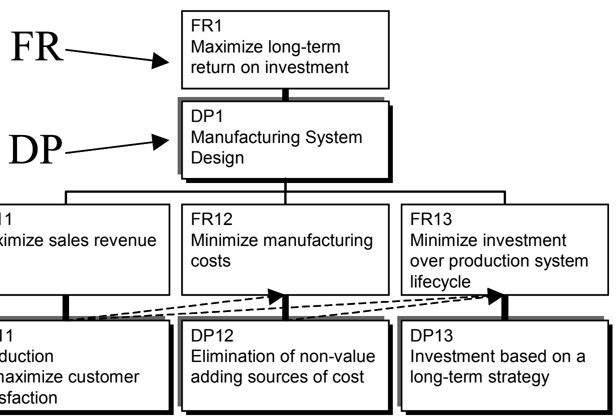
Optimization of financial measures does not always result in superior system performance[15]. For this reason, this case study seeks to determine whether there is a relationship between superior achievement of the FRs and superior performance of the plant as observed by a set of traditional performance measures.

2.3 Upper Levels of the MSDD

This section describes the thought process in developing the top two levels of the MSDD. It also illustrates how to determine if independence has been satisfied by a design. The design matrix for the second level of the MSDD is shown in Figure 3.[11]

The top level FR states that a top-level goal of a manufacturing system is to increase a company's long-term return on investment (ROI). The corresponding

DP to satisfy the FR is *manufacturing system design*. In contrast to attempting to implement a set of "lean" tools[16], system designers and system users must have a common understanding and mental model of how a system design works. The MSDD is purposed to provide the means to communicate the mental model.



$$\begin{Bmatrix} FR11 \\ FR12 \\ FR13 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP11 \\ DP12 \\ DP13 \end{Bmatrix}$$

Figure 3
Level 1 and 2 FRs and DPs and Design Matrix

The second level FRs, FR11, FR12 and FR13 are derived from the Return on Investment (ROI) ratio.

$$\text{ROI} = \frac{\text{Sales - Cost}}{\text{Investment}} \qquad (4)$$

FR11 calls for **maximizing sales revenue**. FR12 specifies **minimizing manufacturing costs**. FR13 requires **minimizing investment over the production system lifecycle**. The design matrix for the second level of the MSDD is partially coupled, as illustrated by the lower triangular matrix in Figure 3. Partially coupled designs are acceptable, but are path dependent. A path dependent design means that the effectiveness of a design is affected by the order of implementation success of the DPs. The DP that affects the most FRs has the most impact. For the design in Figure 3, DP11 affects the most FRs, then DP12, and then DP13. The knowledge of this degree of coupling does not mean that DP11 is implemented first and in isolation of DP12 and DP13. A design has not been implemented until all of the FR-DP pairs illustrated in Figure 1 and 3 are achieved. What path dependency does indicate is that it becomes impossible to effectively achieve FR12, when FR11 has not been satisfied. This knowledge provides a profound insight into the manufacturing system design problem. Namely, that costs cannot be minimized until the customer needs are satisfied. This statement is seemingly common sense. Yet, many businesses emphasize cost reduction prior to achieving the FRs that satisfy the customer. Decomposition of DP11 leads to defining FRs to provide perfect quality products FR111, on time FR112, with the shortest possible delivery time FR113, to the customer. A further discussion of the MSDD is provided in, *Decomposition Approach for Manufacturing System Design*[11].

3. Observed Performance

The plants evaluated in this paper are located in North America. Both produce similar steering gear products. Data from each plant were gathered through a series of site visits by the authors. Plant M represents a "mass" production plant. The plant produces sub-components for all of its assembly lines in large, departmental machining areas. The machines are grouped into departments based upon the manufacturing process being performed. The component assembly line studied aggregates the demand from five vehicle assembly plants. This aggregation requires the assembly line to be designed to operate at a cycle time of 12 seconds.

The management accounting approach employed by Plant M primarily focuses on the reduction of direct labor as the means to reduce manufacturing cost.[5] Plant M places a high value on reducing direct labor and increasing machine utilization. Area managers are evaluated on labor efficiency. Labor efficiency is measured by a ratio of standard labor hours divided by earned actual labor hours. Standard labor hours are calculated based on an Industrial Engineering *time standard* times the number of parts produced. Actual hours are calculated based on the number of people employed times the number of parts produced. 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.

Plant L represents "lean" production. Plant L's system design focuses on simultaneously achieving the cost, quality, delivery, and responsiveness FRs as defined by the MSDD. The MSDD states the high-level (FRs) of a manufacturing system to achieve perfect quality, predictable and responsive delivery, right quantity and mix with the lowest possible cost. Schonberger called these high-level requirements the four horsemen of production[17]. The MSDD specifically states that the right quantity and right mix of parts must be made based on customer consumption.

Plant L implemented a linked-cell manufacturing system[18] in which one final assembly cell supplies only one, or at most two, vehicle assembly plants at a standardized cycle time of 60 seconds. Likewise, the machining cell provides machined products to its customer assembly cell. The linked-cell manufacturing system design is said to be a balanced system design,[19] because each operation is designed to produce at the pace of its customer's demand. A balanced manufacturing system or (value stream) design is defined as producing at the average pace of customer demand with the same operating pattern (ie., 2 shifts, 8 hours). A balanced system design produces at the immediate customer's *takt* time.

The machining cell at Plant L has the capacity to produce at a 54 second cycle time, since allowances are factored into the takt time calculation given by equation 5. Figure 4 and Figure 5 show the high-level organization of Plants M and L, respectively.

$$\text{Takt Time} = \frac{\text{Total time/shift - (breaks \& lunches) - downtime allowances}}{\text{Average demand/shift for a given time interval } i} \quad (5)$$

i = week, quarter, etc.

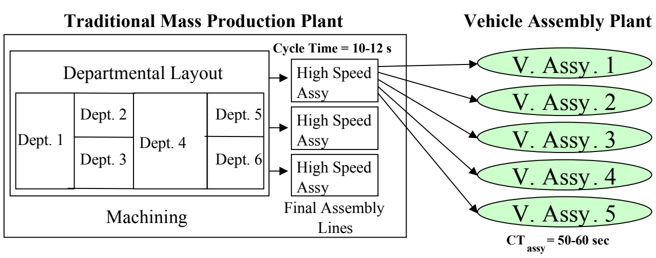


Figure 4
Organization of Plant M – Not Balanced

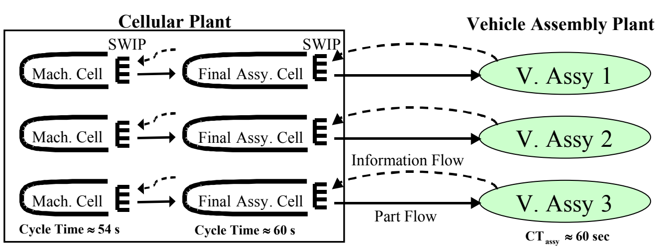


Figure 5
Organization of Plant L – Balanced

3.1 Design and Measurement Relationship

The data in Table 1 compare the assembly cell at Plant L operating at a cycle time of 60 seconds to the higher-speed assembly line at Plant M operating at a cycle time of 12 seconds.

Operational Measure	*Performance*		*Satisfied Leaf FRs*	
	Plant L	*Plant M*	*Plant L*	*Plant M*
Floor Area	1	1.1	3 of 3	0 of 3
In-cell inventory	1	2.8	9 of 9	2 of 9
WIP between machining & assembly	1	3.19	9 of 9	4 of 9
Throughput time	1	1.6	12 of 12	5 of 12
Capital Investment	1	1.3	2 of 2	0 of 2
Direct Workers	1	0.70	6 of 6	1 of 6
Indirect Workers	1	1.49	2 of 2	0 of 2
Good Parts/labor-hour (w/overtime)	1	0.99	31 of 36	12 of 36
Line returns	1	1.2	7 of 9	5 of 9
Warranty Claims	1	9.2	7 of 9	5 of 9
# of Product Models	1	0.21	5 of 5	1 of 5

Table 1
Assembly: Operational Measure – Performance and FR Relationship

The ratios in Table 1 and Table 2 were normalized by production volume to allow a comparison between the two plants. The normalizing factors were 4.80 for assembly and 8.46 for machining. This means that 4.8 assembly cells are required at plant L to produce an equivalent volume to plant M. For machining, 8.46 cells at plant L are required to produce an equivalent volume to plant M.

It is counter-intuitive to think that 4.8 assembly cells could cost less than one high-speed line or that 8.4 machining cells would cost less than the process-oriented (departmental) layout in machining of Plant M.

The volume-normalized results in Table 1 indicate that the assembly line at Plant M has fewer direct workers in the static, non-operational case. However, the design at Plant M requires more inventory, has more work in process (WIP) between machining and assembly, has a longer throughput time, requires more investment, produces more defects, has significantly higher warranty claims, cannot produce as many product varieties, and requires more indirect workers. In addition, in actual operation, the number of good parts per person-hour of operation is equivalent. According to the investment planning process used by Plant M (and company M), the cellular approach of plant L would cost *more* instead of actually costing less. The costing approach used by company M uses a unit cost calculation to drive its investment decisions. The formula rewards less direct labor. As unit cost is derived as the sum of direct labor plus material plus fixed and variable overhead divided by the number of units produced. Overhead is allocated based on direct labor time. The less the direct labor content, the less direct labor time absorption. This emphasis results in an assembly line design that had less direct labor (.72) for Plant M vs plant L (1.0) in the non-operational case. The focus on eliminating wasted motion and work in Plant L combined with the ability to produce the customer consumed quantity and mix resulted in equivalent labor performance during actual operation. This result shows that optimizing the unit cost equation did not result in superior performance for Plant M.

Operational Measure	***Performance***		***Satisfied Leaf FRs***	
	Plant L	***Plant M***	***Plant L***	***Plant M***
Floor Area	1	1.7	3 of 3	0 of 3
In-cell inventory	1	97	9 of 9	2 of 9
WIP between machining & assembly	1	1.81	9 of 9	4 of 9
Throughput time	1	117	12 of 12	5 of 12
Capital Investment	1	1.2	2 of 2	0 of 2
Direct Workers	1	0.86	6 of 6	1 of 6
Indirect Workers	1	0.72	2 of 2	0 of 2
Good Parts/labor-hour (w/overtime)	1	1.0	31 of 36	12 of 36
Internal Scrap	1	5.4	31 of 36	12 of 36
# of Product Models	1	0.35	5 of 5	1 of 5

Table 2
Machining: Operational Measure – Performance and FR Relationship

In machining, the differences are overwhelming. The data in Table 2 compare a machining cell at Plant L that produces 500 parts per shift to the batch and queue production job shop machining area at Plant M, which produces approximately 4200 parts per shift. The machining cell at Plant L supplies its customer assembly cell, while the machining area at Plant M supplies all assembly lines for the entire plant. The volume-normalized results indicate that Plant M has fewer direct and indirect workers in the non-operating case than Plant L. However, Plant M requires more floor area, significantly higher inventory (97 times) and throughput time (117 times), has more WIP between machining and assembly (1.81 times), requires more investment (1.2 times), produces more defects (5.4 times), and does not produce as many product varieties (.35 times).

Similar to the assembly comparison, during actual operation the number of good parts produced per direct labor-hour is equivalent. Fewer indirect workers are used in machining at Plant M since material is moved in larger batches and less attention is paid to cleanliness and preventive maintenance.

3.2 FR-DP Pair Analysis

One aspect of this study is to understand the extent to which Plant M's optimization of unit cost, achieves the FRs of the MSDD. The MSDD reflects the system design relationships to achieve cost, quality, delivery, and flexibility simultaneously. Systems are made up of relationships. The unit cost equation wrongly assumes that each operation's cost in the plant is independent of its affect on the other operations. The MSDD, first of all acknowledges that relationships exist; that one operation affects another.

Most importantly, the MSDD's development is based on the assertion that human beings are system designers. As system designers, the assertion is that the relationships that exist within a system can be defined *a priori* (in advance of implementation). Mass plant designs are the result of business planning and management accounting processes that are based on a worldview, which is Newtonian. This way of thinking views objects as independent of other objects. This thinking certainly can harm any business that subscribes to the business planning and management accounting processes that are derived from it.

In addition to the performance measure comparison, the MSDD was used to contrast the system design differences. The approach used determined the degree to which each plant satisfied the FRs of the MSDD. For example, when considering FR-T1, **Reduce lot Delay**, it is evident that Plant L implemented DP-T1 *Single Piece Flow***,** since the physical plant design has single-piece flow in both machining and assembly. Plant M, on the other hand, has a departmental or process-oriented layout. Parts are moved between departments using large containers. Plant L fulfills FR-T1, but Plant M does not… although plant M could be re-designed to fulfill FR-T1.

Tables 1 and 2 also associate the FRs of the MSDD to the performance measurement ratios. It can be seen that Plant L's achievement of the FRs stated by the MSDD is an indicator of its success with respect to the operational measures. The FRs achieved by Plants L and M are stated in the Appendix.

Figure 6 illustrates how well Plant L and Plant M have satisfied the FRs stated by the MSDD. The manufacturing system at Plant L has satisfied more of the FRs than Plant M.

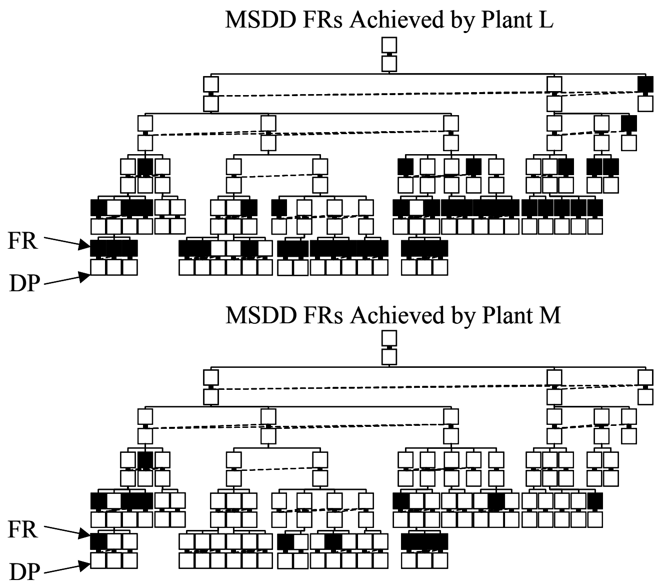


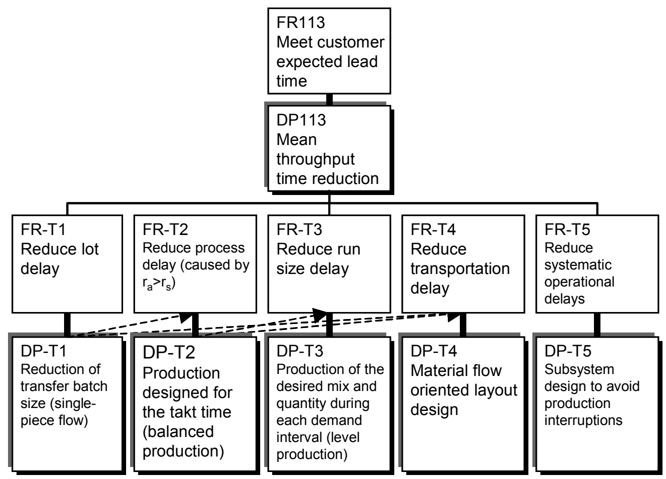
Figure 6
MSDD FRs satisfied by Plant L and Plant M

The hypothesis of this research that Plant L will achieve more FRs stated by the MSDD than Plant M appears to be supported.

4. System Design Comparison

The purpose of this section is to contrast the system design differences between the two plants. It illustrates how the thinking affects the system design. The examples will be based primarily on the delay reduction branch of the decomposition.

The delay reduction FRs are decomposed from FR113 and DP113, which address **meeting customer expected lead time** (FR113) through *mean throughput time reduction* (DP113), as shown in Figure 7. Physical implementations at each plant are evaluated to determine if the FRs illustrated by the MSDD have been satisfied.



$$\begin{Bmatrix} FR-T1 \\ FR-T2 \\ FR-T3 \\ FR-T4 \\ FR-T5 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ 0 & X & X & 0 & 0 \\ X & X & 0 & X & 0 \\ 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP-T1 \\ DP-T2 \\ DP-T3 \\ DP-T4 \\ DP-T5 \end{Bmatrix}$$

Figure 7
Decomposition of FR113

4.1 Manufacturing System Design Comparison

Plant L is able to **reduce lot delay** (FR-T1) through the *reduction of transfer batch sizes (single-piece flow)* (DP-T1). At Plant M, parts are produced in lots ranging from 250-400 pieces. This means that the first piece produced must wait for the 400th piece to be completed before it can continue to the next station where it will be processed.

Producing parts at the customer demand cycle time (or takt time) is called balanced production.[20,21] Production at Plant M is not balanced throughout the manufacturing system. Plant M aggregates demand from several customers in order to reduce direct labor costs and to maximize machine utilization (Figure 4). The result is that one assembly line is designed to meet the aggregate demand from five vehicle assembly plant customers. This practice prevents the assembly line from operating at one customer's takt time and requires the assembly lines to have very fast cycle times. The aggregation of demand results in a line cycle time of 12 seconds (Figure 8).

Automated machines are designed for high speed and the work content at manual stations is small. An operator must remain at each manual station while the line is running. If demand drops, the number of workers cannot be reduced since the line is designed so that one operator is tied to one station. Separating a worker from a station is not cost effective in this case since the line cycle time is so short (12 seconds).

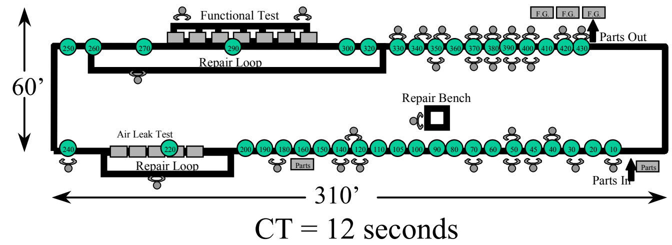


Figure 8
Assembly line at Plant M

Machining at Plant M is performed in large departments that make parts for all of the assembly lines. Each of these departments produces only one type of part. Figure 9 illustrates the layout of the machining department studied at Plant M. The capacity of the entire department is set to satisfy the aggregated demand from all of the assembly lines that the area supplies. The planning process calculates the number of machines in each department from Equation 6.

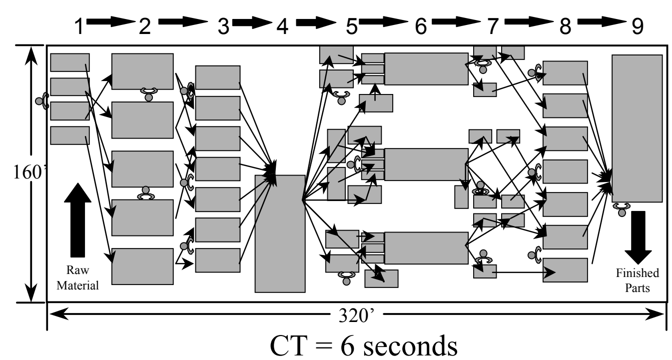


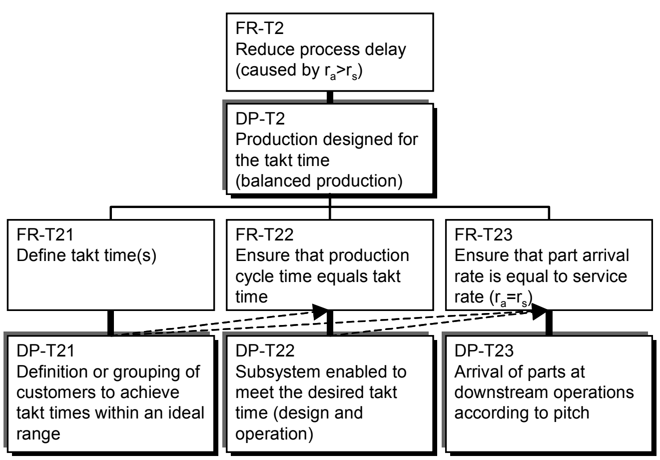
Figure 9
Machining area at Plant M

$$\text{Number of machines in a department} = \frac{Y}{X} \qquad (6)$$

Y is the aggregate demand for the department multiplied by the cycle time of the machines in the department. X is the available operating time for the department.

The machines in these departments must produce at high speeds to reduce unit labor cost. This condition results from the assumption that one person operates only one or a limited number of machines. Large, high-speed machines (or processing islands) are designed for high speed. One person is typically tied to a load station.

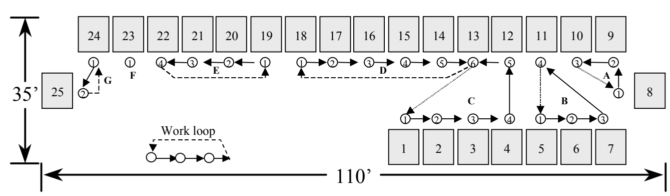
The machining department supplies seven assembly lines as an aggregate group. The machining department operates for three shifts, while the assembly lines operate for one or two shifts. Output from the machining department must meet the combined consumption rate of all of the assembly lines. The average output cycle time is approximately 6 seconds.



$$\begin{Bmatrix} FR-T21 \\ FR-T22 \\ FR-T23 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP-T21 \\ DP-T22 \\ DP-T23 \end{Bmatrix}$$

Figure 10
Decomposition of FR-T2

The MSDD illustrates that three FRs must be satisfied in order to achieve balanced production. Figure 10 shows the decomposition of FR-T2 and the corresponding design matrix. Before the assembly and machining cells at Plant L were built, Plant L **defined the takt times** (FR-T21) of the cells by *defining* [each cell's] *customers to achieve takt times within an ideal (cycle time) range* (DP-T21). After defining the takt time, Plant L **ensured that the production cycle time equaled the takt time** (FR-T22) with *subsystems that are enabled to meet the desired takt time* (DP-T22). The assembly cell shown in Figure 11 and the machining cell shown in Figure 12 are able to operate at various customer demand cycle times that are greater than 30 seconds. In both of these designs, the worker is separated from the machine. Therefore, labor cost is no longer coupled with the speed of the machine. In contrast to Plant M, if customer demand decreases, the number of workers operating the cell may be decreased.



CT = 60 seconds

Figure 11
Assembly cell at Plant L

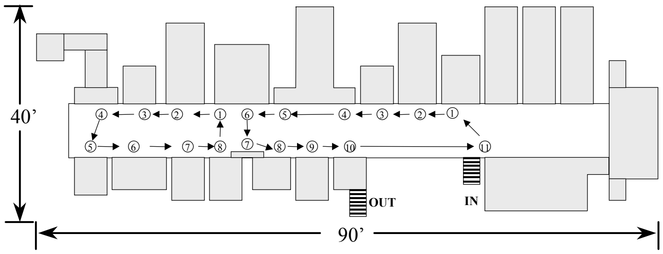


Figure 12
Machining cell at Plant L

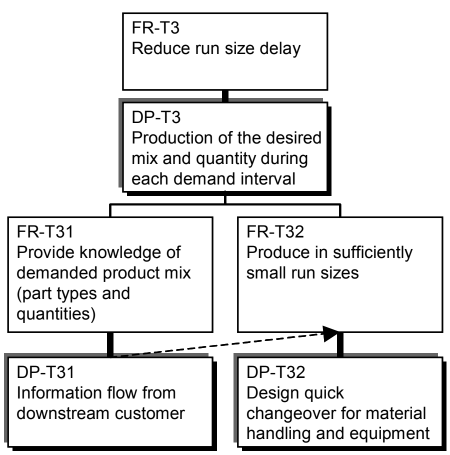
The benefit is that when customer demand for a product changes, workers can be added to or removed from the assembly and machining cells. This approach changes the output cycle time of the cells to scale the production rate with the demand rate. When workers are added, work loops are shortened, resulting in less work content per worker and a faster production rate. Removing workers lengthens the work loops, increases the work content per loop, and decreases the production cycle time (time per part… not throughput time or flow time). Operating cost is more effectively controlled, since the overall number of products per labor-hour remains roughly the same, independent of demand. Figure 11 and Figure 12 illustrate one configuration of work loops in an assembly cell and a machining cell, respectively.

In a balanced system, several benefits result from each cell being linked to only one or two vehicle assembly plants. Production can be focused on fewer customers or one. The balanced system design enables the lowest possible inventory level. And a decreased inventory results in shorter response and throughput times, allowing immediate feedback and enabling faster problem resolution. The assembly cell shown in Figure 11 is linked to only one customer and supplies parts at the customer’s takt time.

Level production is a way to **reduce the run size delay** (FR-T3) that results from manufacturing the same part for long periods of time. Level production *requires production of the desired mix and quantity* [of each part type demanded] *during each demand interval* (DP-T3). This practice eliminates the need to store large quantities of inventory to meet customer demand.[20] Production can be leveled over different periods of time: a month, a week, a day, or an hour; the shorter the time interval, the smaller the run size. The smaller the run size, the lower the inventory. When inventory is lowered, the response time to detect and resolve quality problems decreases. In addition, the manufacturing system is able to adapt to change more quickly.

Plant M uses a “push” system to try meeting its customers’ demand.[22] Weekly production schedules, based on customer demand, are divided into daily requirements. The assembly lines and machining departments are given a daily production schedule that is based on forecast demand from the downstream customer. When the schedule is not met, the unmade parts are added to the next day's schedule.

In the machining departments, production is scheduled at the input end (e.g. the first set of operations) of the department. The high level of inventory, the large number of part-flow combinations, and the long time intervals between defect creation and identification all lead to unpredictability in the output. The assembly lines are often limited to running parts based upon what parts are available, thus causing production to deviate further and further from schedule.



$$\begin{Bmatrix} FR-T31 \\ FR-T32 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP-T31 \\ DP-T32 \end{Bmatrix}$$

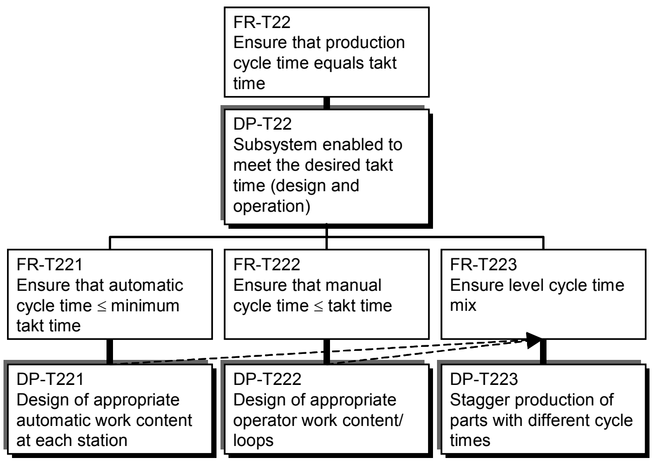
Figure 13
Decomposition of FR-T3

Further decomposition of FR-T3 is shown in Figure 13. In order to **provide knowledge of the demanded product mix** (FR-T31) from a customer or downstream operation, a company must have *information from the downstream customer* (DP-T31). Plant L uses a "pull" system to communicate customer consumption or demand information within its manufacturing system. Only a small standard inventory, called the Standard Work in Process (SWIP), of finished goods is maintained. (When the run size is lower, the SWIP may be lowered.) When parts are removed from the finished goods inventory, a signal is sent to the assembly cell to replenish the same quantity and type of parts that were removed. The assembly cell withdraws the parts it needs from the machining cell's SWIP shown in Figure 5. This withdrawal signals the machining cell that it should produce the components that were removed. This approach coordinates production and ensures that the right quantity and right mix of parts are made when they are needed.

Every time an operator passes a machine in his work-loop at Plant L, he/she moves a part from one machine to the next. This method of advancing one part at a time **reduces transportation delay** (FR-T4) because a *material flow oriented layout design* (DP-T4) was selected when designing the machining cell. At Plant M, even after a bin has been filled with parts, it may be minutes or hours before a forklift operator comes by to transport the parts to the next station.

4.2 Equipment Design Comparison

This section of the paper illustrates how machine design is affected by achieving the FRs of the MSDD. Machines should not be designed as stand alone operations, which are isolated from the rest of the manufacturing system.[20]



$$\begin{Bmatrix} FR-T221 \\ FR-T222 \\ FR-T223 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP-T221 \\ DP-T222 \\ DP-T223 \end{Bmatrix}$$

Figure 14
Decomposition of FR-T22

The MSDD illustrates that equipment design is important to **ensure that the production cycle time equals takt time** (FR-T22). Decomposition of FR-T22 is shown in Figure 14. To achieve the goal of producing to takt time, selecting the appropriate manufacturing process becomes critical. In order to **ensure that the automatic cycle time ≤ the minimum takt time** (FR-T221), engineers must *design the appropriate automatic work content at each station* (DP-T221). For example, Plants L and M both use a tempering process to improve toughness and to stress relieve the same type of part. Tempering is a heat treatment process that is a function of time and temperature. To achieve a desired thermal effect, temperature is logarithmic as given by the Larson-Miller equation.[23]

$$\begin{aligned} &\text{Thermal effect} = T(\log t + 20)(1/10^3) \\ &T \text{ is temperature (Rankin)}, t \text{ is hours} \end{aligned} \tag{7}$$

Plant M tempers parts with a large draw furnace. The parts are heated at a lower temperature than at Plant L. The throughput time is two hours, which means that hundreds of parts are resident in the machine at any given time. Plant L designed a machine that induction tempers one part at a time at a higher temperature to achieve a cycle time of 54 seconds. The machine was designed with a second spindle to allow two parts to be tempered at a time to achieve takt times between 26 and 54 seconds (see Figure 15).

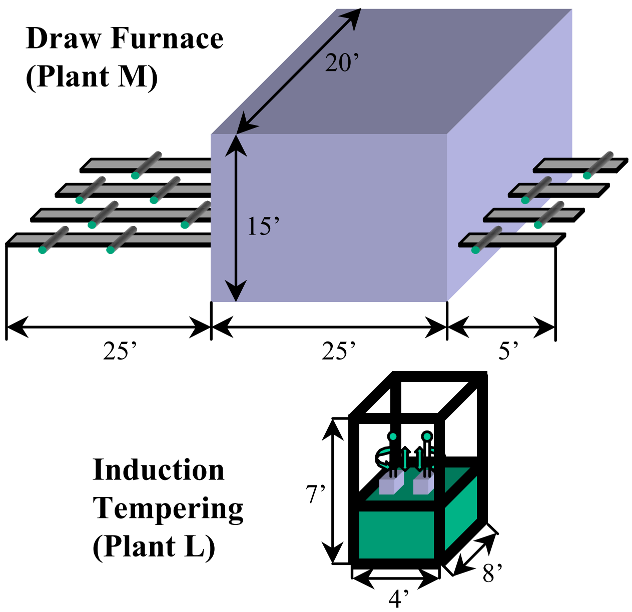


Figure 15
Methods used for Tempering at Plants L and M

When the takt time cannot be met by manufacturing process selection, several options exist: to sub-divide the processing into multiple steps, add a second station or spindle within the machine, or add another machine that parallel processes the part. Parallel processing is a last resort because it makes tracing problems difficult and increases the complexity of the operator’s work pattern.

For a series of tests performed by both Plant L and Plant M, Plant L split the tests into several machines on its assembly lines to meet the minimum takt time. Plant M on the other hand built an elaborate gating and control system to route parts to one of seven identical parallel processing stations that have integrated the multiple testing operations.

Figure 13 shows that achieving level production requires **producing in sufficiently small run sizes** (FR-T32). Smaller run sizes require faster, more frequent changeovers. This means that plants must *design quick changeover for material handling and equipment* (DP-T32.) Both plants in this paper can perform setups in less than 10 minutes for individual machines on the assembly lines.[24] Only Plant L can perform machine setups in less than 10 minutes for machining. Broach changeover at Plant M takes from 3 to 5 hours. Broach changeover at Plant L requires the simple flip of a switch due to its turret design. Sketches of both broaches are shown in Figure 16.

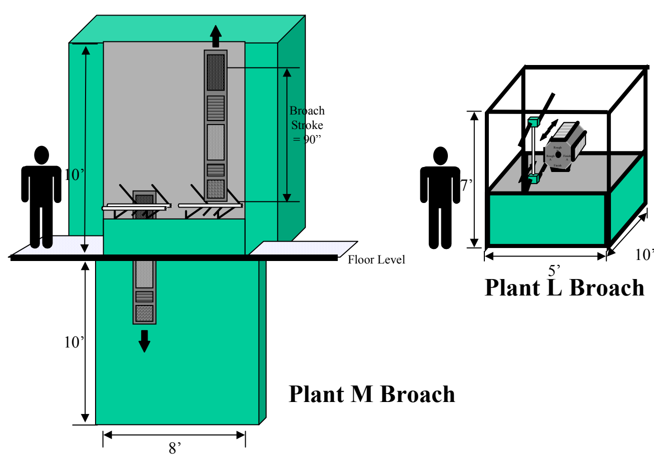
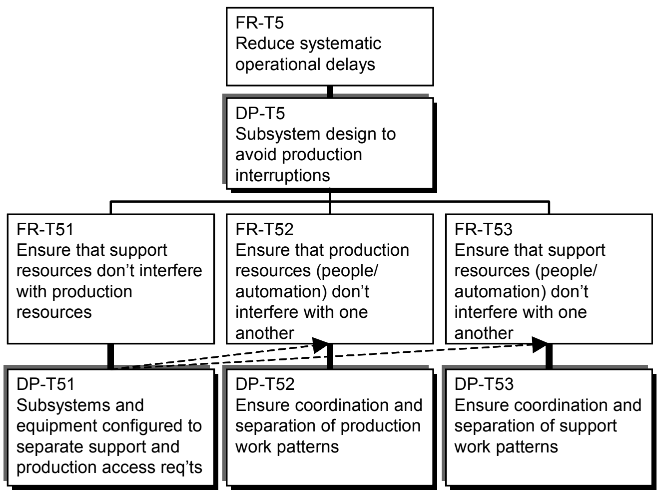


Figure 16
Broach Designs at Plants L and M

Necessary functions, such as equipment maintenance, chip removal, and material supply, can increase a manufacturing system’s response time if these functions are allowed to disrupt manufacturing processes. Instead of accepting these disruptions, companies should **reduce systematic operational delays** (FR-T5) through *subsystem design to avoid production disruptions* (DP-T5). Decomposition of FR-T5 is shown in Figure 17.



$$\begin{Bmatrix} FR-T51 \\ FR-T52 \\ FR-T53 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & 0 & X \end{bmatrix} \begin{Bmatrix} DP-T51 \\ DP-T52 \\ DP-T53 \end{Bmatrix}$$

Figure 17
Decomposition of Eliminate Common Cause Disruptions

One way to **ensure that support resources don't interfere with production resources** (FR-T51) is by designing *subsystems and equipment* [that are] *configured to separate support and production access requirements* (DP-T51). Plant L has implemented DP-T51 in several ways. By making controls and systems accessible from the rear of the station or machine (and not the side of the machine), a worker can do many preventive maintenance tasks without getting in the way of workers who are working inside of the manufacturing cell. Chips are fed to the back of machines, so that the chips may be collected without any disruption to production. Finally, material is fed from the outside to the inside of a cell at the point where the parts are needed. This practice prevents the material handler from interfering with the assemblers inside of the cell.

Plant M is not consistent in following these aspects of the MSDD. Some controls and systems are accessible from the rear of stations, but others require entering the line and stopping production for adjustments. Chips are fed through the center of machines down to in-floor removal systems. This design makes moving machines at a later time difficult, but does satisfy FR-T51 by not stopping production to remove chips. At the assembly lines, containers of materials are typically stacked up near the line. Workers must stop working in order to retrieve parts and place the parts where they are needed.

5. Summary

This paper found that Plant L achieves more of the FRs outlined by the MSDD than Plant M. It also illustrated how equipment must be designed to achieve the FRs of the manufacturing system that it supports.

On average, Plant L satisfied 96% of the FRs while Plant M only satisfied 23%. Plant M was developed to optimize the unit cost equation, which is focused on optimizing the cost of individual operations in the plant. The business planning process and the management accounting process used by Plant M are derived from this thinking. This viewpoint assumes that minimizing the sum of the individual operating costs reduces total cost.

The Manufacturing System Design Decomposition (MSDD) illustrates that the system design used by Plant L performs better than Plant M in a side-by-side comparison. This result challenges the assumption that lower cost is the result of optimizing the sum of the individual operation costs. In addition, the linked-cellular manufacturing system can accommodate volumes as high as the "mass" plant, by simply replicating the linked-cell value streams.

The MSDD allows system designers to see and understand the interrelationships that exist in manufacturing systems. Plant L's superior operational performance and achievement of most of the FRs stated by the MSDD, suggests that a design decomposition approach may be used to design plants with superior performance. This finding provides additional understanding that a science base for system design can be truly realized, which was Suh's original statement of the need for developing axiomatic design.

Plant M illustrates the problems that occur when sub-elements are optimized independently of the whole. The MSDD provides a framework for understanding the requirements and means that are necessary to design effective manufacturing systems. It forms the basis for designing, controlling, and communicating the web of interrelationships that exist in any manufacturing system, without the use of buzzwords and superficiality.

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Biographies

Prof. David Cochran is an Associate Professor of Mechanical Engineering at MIT. He founded the Production System Design Laboratory, an initiative within the Laboratory for Manufacturing and Productivity, to develop a comprehensive approach for the design and implementation of production systems. He is a recipient of the "Shingo Prize for Manufacturing Excellence." He has taught over 30 manufacturers the implementation and underlying principles of production system design. Dr. Cochran serves on the Board of Directors of the Greater Boston Manufacturing Partnership and the AMA. Prior to joining MIT, Dr. Cochran worked with Ford Motor Company. He holds a Ph.D. and B.S. degrees from Auburn University, and a M.S. degree from the Pennsylvania State

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Daniel Dobbs recently completed dual master's degrees in the Mechanical Engineering department and the Technology and Policy Program at the Massachusetts Institute of Technology. His research focused on the design and development of new manufacturing systems in existing industries. He is now working as a manufacturing engineer at Texas Instruments in Attleboro, MA.

Appendix A: MSDD Leaf FRs* Satisfied by Plant L and Plant M

Quality Branch FRs

Plant L	Plant M
FR-Q2: Center process mean on the target	FR-Q2: Center process mean on the target
FR-Q11: Eliminate machine assignable causes	FR-Q11: Eliminate machine assignable causes
FR-Q13: Eliminate method assignable causes	FR-Q13: Eliminate method assignable causes
FR-Q14: Eliminate material assignable causes	FR-Q14: Eliminate material assignable causes
FR-Q121: Ensure that operator has knowledge of required tasks	FR-Q121: Ensure that operator has knowledge of required tasks
FR-Q122: Ensure that operator consistently performs tasks correctly	
FR-Q123: Ensure that operator human errors do not translate to defects	

Identifying and Resolving Problems Branch FRs

Plant L	Plant M
FR-R13: Solve problems immediately	
FR-R111: Identify disruptions when they occur	
FR-R112: Identify disruptions where they occur	
FR-R122: Minimize delay in contacting contact support resources	

Predictable Output Branch FRs

Plant L	Plant M
FR-P11: Ensure availability of relevant production information	FR-P121: Ensure that equipment is easily serviceable
FR-P121: Ensure that equipment is easily serviceable	FR-P132: Ensure availability of workers
FR-P122: Service equipment regularly	
FR-P131: Reduce variability of task completion time	
FR-P132: Ensure availability of workers	
FR-P133: Do not interrupt production for worker allowances demand interval	
FR-P141: Ensure that parts are available to the material handlers	
FR-P142: Ensure proper timing of part arrivals	

* Leaf FRs are terminal FRs that are not further decomposed within the MSDD

Delay Reduction Branch FRs

Plant L	Plant M
FR-T1: Reduce lot delay FR-T4: Reduce transportation delay FR-T21: Define takt times FR-T23: Ensure that part arrival rate is equal to service rate FR-T31: Provide knowledge of demanded product mix (part types and quantities) FR-T32: Produce in sufficiently small run sizes FR-T51: Ensure that support resources don't interfere with production resources FR-T52: Ensure that production resources (people/automation) don't interfere with one another FR-T53: Ensure that support resources (people/automation) don't interfere with one another FR-T221: Ensure that automatic cycle time ≤ minimum takt time FR-T222: Ensure that manual cycle time ≤ takt time FR-T223: Ensure level cycle time mix	FR-T52: Ensure that production resources (people/automation) don't interfere with one another FR-T21: Define takt times FR-T221: Ensure that automatic cycle time ≤ minimum takt time FR-T222: Ensure that manual cycle time ≤ takt time FR-T223: Ensure level cycle time mix

Direct Labor Branch FRs

Plant L	Plant M
FR-D3: Eliminate operators' waiting on other operators FR-D11: Reduce time operators spend on non-value added tasks at each station FR-D12: Enable worker to operate more than one machine / station FR-D21: Minimize wasted motion of operators between stations FR-D22: Minimize wasted motion in operators' work preparation FR-D23: Minimize wasted motion in operators' work tasks	FR-D23: Minimize wasted motion in operators' work tasks

Indirect Labor Branch FRs

Plant L	Plant M
FR-I1: Improve effectiveness of production managers FR-I2: Eliminate information disruptions	

Facilities and Investment FRs

Plant L	Plant M
FR123: Minimize facilities cost FR13: Minimize investment over production system lifecycle	

Leaf FRs not Satisfied or Not Known for Plant L

Functional Requirement	Reason not satisfied
FR-Q2: Center process mean on the target	Not evaluated
FR-Q31: Reduce noise in process	Not evaluated
FR-Q32: Reduce impact of input noise on process output	Not evaluated
FR-R113: Identify what the disruption is	Machines stop, but do not always communicate nature of problem
FR-R123: System that conveys what the disruption is	Alert system does not convey the nature of disruptions

Calculation of Leaf FRs Satisfied by each Plant

Performance Measurement	***Equation***
Floor Area	FR123 + FR-T4 + FR-D21 (achieved) of (total possible)
In-cell Inventory	FR-P13 leaf FRs, FR-T1, FR-T3 leaf FRs, FR-T5 leaf FRs (achieved) of (total possible)
WIP Between Machining & Assy	FR-P14 leaf FRs, FR-T1, FR-T2 leaf FRs, FR-T4
Throughput Time	FR113 leaf FRs (achieved) of (total possible)
Capital Investment	FR13, FR123 (achieved) of (total possible)
Direct Workers	FR121 leaf FRs (achieved) of (total possible)
Indirect Workers*	FR122 leaf FRs (achieved) of (total possible)
Good Parts/labor-hour (w/overtime)	FR111 leaf FRs, FR112 leaf FRs, FR113 leaf FRs (achieved) of (total possible)
Internal Scrap	FR111 leaf FRs, FR112 leaf FRs, FR113 leaf FRs (achieved) of (total possible)
Line Returns	FR111 leaf FRs (achieved) of (total possible)
Warranty Claims	FR111 leaf FRs (achieved) of (total possible)
# of Product Models	FR-T223, FR-T3 leaf FRs, FR-D22, FR-13 (achieved) of (total possible)

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