# EQUIPMENT EVALUATION TOOL BASED ON THE MANUFACTURING SYSTEM DESIGN DECOMPOSITION

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## ABSTRACT

This paper presents an evaluation tool that can be used to determine how well the physical characteristics of a particular piece of equipment (or set of machines) satisfy the functional requirements of the manufacturing system design. This evaluation tool for equipment is based on the Manufacturing System Design Decomposition v5.1 (MSDD). The MSDD identifies a series of goals for a manufacturing organization called Functional Requirements (FRs) and how each one of these helps to achieve the high-level business goals. The requirements from the MSDD that affect equipment design and operation have been identified, and the evaluation tool presented here can be used to evaluate how well a particular piece or set of equipment conforms to these requirements. This evaluation tool can be used to ensure that equipment designs better align with overall manufacturing system objectives. The tool can also be used to identify problems with existing equipment and to set goals for the equipment to be improved to better satisfy the requirements placed on it by the MSDD.

**Keywords**: Equipment Design, Machine Design, Cell Design, Production System Design Decomposition, Lean Production

## INTRODUCTION

Competitiveness in today's business environment requires the use of a structured approach to ensure that its manufacturing system is designed to achieve the business objectives. The connection between every aspect of the manufacturing system and how it helps to achieve the business goals must be established. The lack of such a connection can place the manufacturing enterprise at risk of engaging in practices that lead to waste in the form of poor quality and poor ability to trace problems, excessive inventory, long throughput times, poor ergonomics (wasted motions of operators), etc. An effective approach to establish the connection between the elements of a manufacturing system and the business objectives of an enterprise is the Manufacturing System Design Decomposition v5.1 (MSDD) [Production System Design Laboratory, 2000], which is briefly introduced below. The MSDD is based on the Axiomatic Design methodology [Suh, 1990]. Axiomatic Design is a process of making decisions about *what* a design intends to achieve and *how* it intends to achieve it. The MSDD identifies this thought process and these decisions for the design of a manufacturing system. A manufacturing system designed using the MSDD will achieve the principles of the Toyota Production System (TPS) [Monden, 1993 and Shingo, 1989], which are also commonly known as the principles of *lean* manufacturing.

A very important aspect of any manufacturing system is its equipment, regardless of whether a company's equipment consists of complicated automated machinery or simple hand tools. The design and selection of equipment is a critical factor that can determine the capability of a manufacturing system to meet high-level business goals. Whether a company designs and builds or buys its equipment, it is important that the equipment be designed to follow a prescribed set of requirements to achieve the business enterprise goals. A subset of the requirements identified in the MSDD influences the selection, design and operation of equipment. The connection of these requirements to the business goals is clearly stated in the decomposition. The specific Functional Requirements that affect equipment design and operation are identified below [Arinez and Cochran, 1999]. This paper presents an Evaluation Tool that can be used to determine how well a particular piece or set of equipment conforms to those Functional Requirements associated with equipment design and operation that are identified by the MSDD.

## MOTIVATION

Since the equipment is such an integral part of any manufacturing system and it can determine the way that a system performs, it is important to ensure that the equipment will enable the achievement of the enterprise goals. The MSDD identifies a series of Functional Requirements (FRs) for the design of a manufacturing system, and a subset of these requirements influences the design and operation of equipment. To ensure that the equipment conforms to the FRs established in the MSDD, one must know what the physical attributes of the equipment are to fulfill such FRs. The Equipment Evaluation Tool presented here is intended to provide the connection between the physical attributes of a machine and how those attributes fulfill the FRs from the MSDD.

The Equipment Evaluation Tool identifies the FRs that affect equipment design and operation and then describes the physical attributes that equipment must have to satisfy these FRs to different levels of achievement. Six levels of accomplishment have been identified, from failure-to-achieve (Level 1) to full-achievement (Level 6) of the Functional Requirements from the MSDD. A rationalization of each one of the six levels of achievement and which systems typically fall into each level will be provided below. The important point to note is that the Equipment Evaluation Tool can be used to assess a particular piece or set of equipment to test how well it satisfies the FRs from the MSDD. The user can simply compare the physical attributes of the equipment with those described on the different levels of achievement presented in the evaluation tool. This immediately establishes the connection between the attributes of the equipment and the goals of the manufacturing system. Based on the comparison of physical attributes of a machine against those described on the Equipment Evaluation Tool, a particular equipment design can be evaluated according to the following objectives:

1. Evaluate the current status of the design and operation of equipment by evaluating how well it satisfies the FRs from the MSDD.
2. Identify areas for improvement where the current equipment does not fully satisfy the FRs from the MSDD, and therefore focus the efforts to improve the manufacturing system on the areas that need it the most.
3. Indicate how equipment can fully satisfy the FRs from the MSDD, and therefore set the objectives to be achieved by the equipment design and improvement efforts.
4. Provide a method to track the progress of improvements in terms of equipment design and operation.
5. Align equipment design with the business objectives identified by the MSDD.

## THE MANUFACTURING SYSTEM DESIGN DECOMPOSITION

Production systems have traditionally been designed in isolation from business objectives through a process in which individual subsystems are optimized independent of each other and of the overall system [Cochran, Kim and Kim, 2000]. The resulting systems often are difficult to control and do not meet the enterprise's objectives. The design of manufacturing systems using a comprehensive and coherent methodology has traditionally been practiced only very rarely.

One recent approach to the design of manufacturing systems is the Production System Design (PSD) framework [Cochran, 1999 and Carrus and Cochran, 1998]. The centerpiece of the PSD framework is the Manufacturing System Design Decomposition (MSDD) shown in Figure 1. The MSDD uses the Axiomatic Design methodology [Suh, 1990] to develop a design of a production system that satisfies the ideals of the Toyota Production System. Axiomatic design is a methodology that establishes two fundamental axioms to be followed throughout the design process: maintain the independence of the functional requirements and minimize the information content of the design. The first axiom emphasizes that to the extent possible each design parameter should satisfy only one functional requirement, and the second axiom seeks to produce as simple a design as possible. Using axiomatic design and its two fundamental axioms to design production systems can lead to simple, easy to operate systems that achieve business objectives.

The MSDD uses axiomatic design methodology to identify high-level Functional Requirements (FRs) for a manufacturing enterprise. Also, in the MSDD a Design Parameter (DP) is chosen for each FR as the physical implementation that best satisfies it. The quantitative relationship between the FRs and the DPs is derived using design matrices. Once the relationship has been

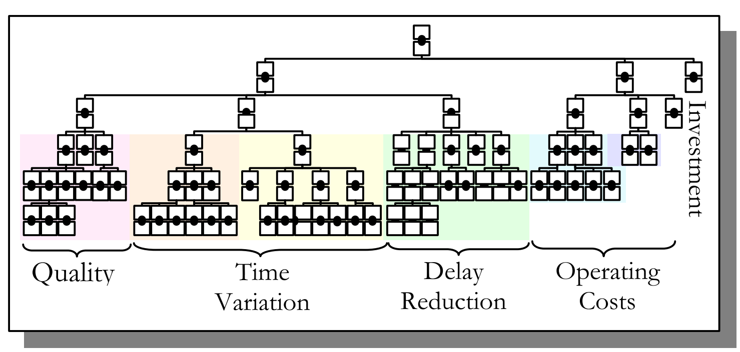


**Figure 1: Manufacturing System Design Decomposition**

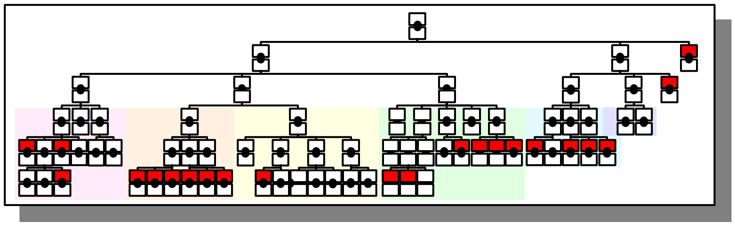

**Figure 2: FRs from MSDD that Affect Equipment Design and Operation**

established at one level, FRs are decomposed into as many lower level requirements as needed. Following this process repeatedly and comprehensively produces a series of FRs and DPs that identifies the thought process behind the design of each subsystem within the manufacturing enterprise. The importance of the MSDD is not only that it establishes FRs and DPs for the design of each subsystem, but also that it clearly links those FRs and DPs (through design matrices) with the high-level objectives of the enterprise.

## FUNCTIONAL REQUIREMENTS FROM MSDD THAT AFFECT EQUIPMENT DESIGN AND OPERATION

The MSDD, in addition to serving as a general tool for the design of production systems, also provides a method to effectively communicate design requirements to subsystems like the equipment, the information system, etc. Of particular interest in the context of this paper is the equipment used in the manufacturing enterprise as a subsystem of the production system. In the process of conveying the requirements for the design of a manufacturing system, the MSDD has identified a series of FRs that affect the design and operation of equipment. Figure 2 highlights the FRs from the MSDD that influence the design and operation of equipment in a production system.

The specific Functional Requirements that affect equipment design and operation are listed below:

- FR-Q11 Eliminate machine assignable causes (of variation).
- FR-Q13 Eliminate method assignable causes (of variation).
- FR-Q123 Ensure that operator human errors do not translate to defects.
- FR-R111 Identify disruptions when they occur.
- FR-R112 Identify disruptions where they occur.
- FR-R113 Identify what the disruption is (when one occurs).
- FR-R121 Identify correct support resources (to resolve a disruption when one occurs).
- FR-R122 Minimize delay in contacting correct support resource (to resolve a disruption when one occurs).
- FR-R123 Minimize time for support resource to understand disruption (when one occurs).
- FR-P121 Ensure that equipment is easily serviceable.
- FR-T221 Ensure that automatic cycle time is less than or equal to the minimum takt time.
- FR-T222 Ensure that manual cycle time is less than or equal to the minimum takt time.
- 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-D11 Reduce time operators spend on non-value added tasks at each 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.
- FR123 Minimize facilities cost.
- FR13 Minimize investment over production system lifecycle.

## EQUIPMENT EVALUATION TOOL

The objective of the equipment evaluation tool is to assess how well the physical attributes of a particular piece or set of equipment satisfy the FRs from the MSDD that affect equipment design and operation. The previous section identified the FRs from the MSDD that relate to the equipment, and those will be used as the evaluation criteria in the Equipment Evaluation Tool. However, in the spirit of reducing the information content of the evaluation tool without sacrificing its effectiveness, some of the criteria were consolidated to reduce the overall number of FRs to be considered. The rationale used to consolidate the FRs was: when all (or at least most) of the sub-FRs of a particular FR affect equipment design, then the evaluation tool will use the parent FR as the evaluation criteria instead of using all of its sub-FRs. The use of this rationale allows us to reduce the number of criteria to be evaluated from 22 FRs that influence Equipment design (from the previous section) to only 13 FRs, without sacrificing the effectiveness of the evaluation. Figure 3 illustrates how the FRs that affect equipment design were consolidated into a smaller number of evaluation criteria using the rationale described above. It also shows how these criteria appear in the Equipment Evaluation Tool and how each of the criteria relates to the FRs from the

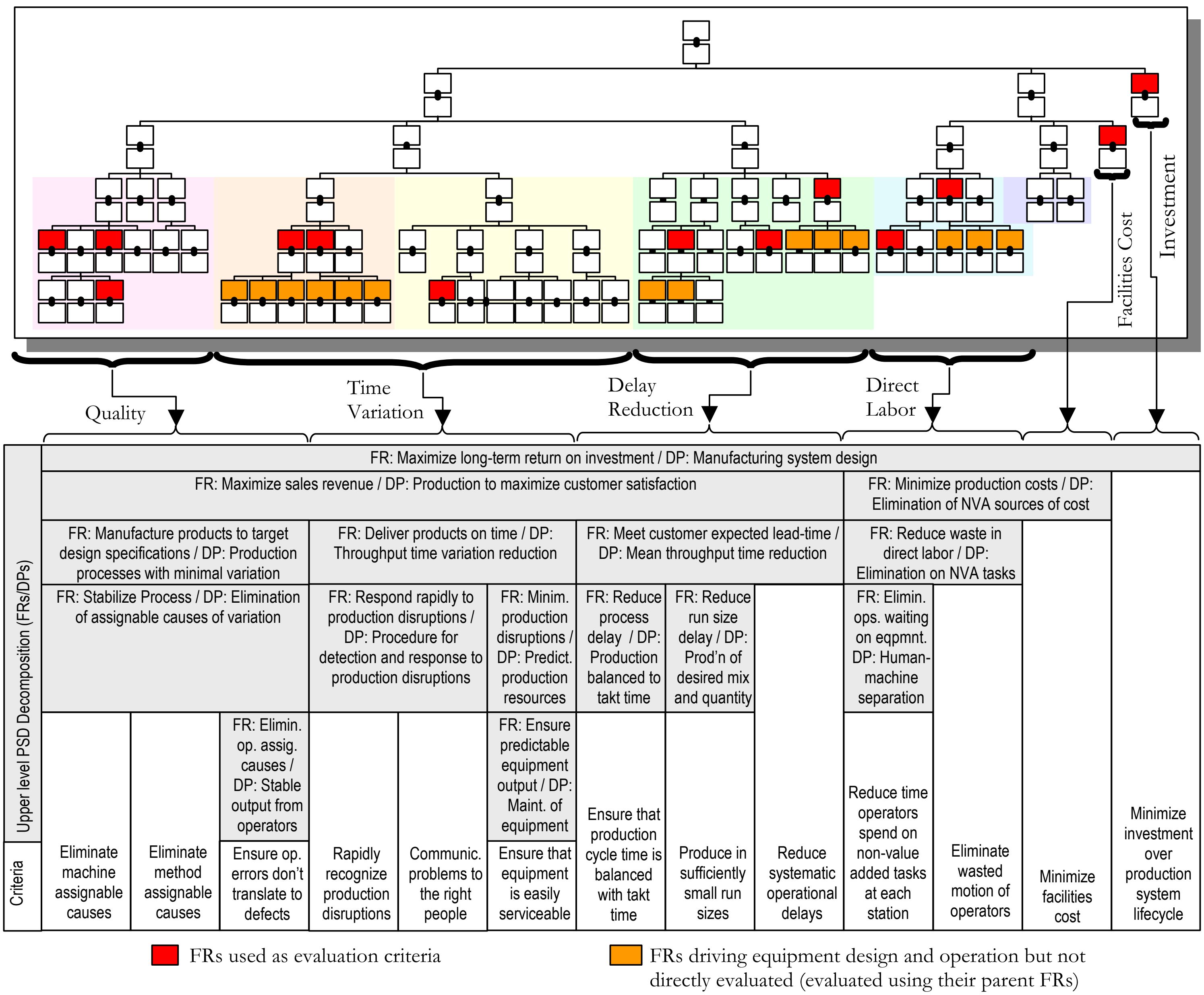


**Figure 3: Derivation of Criteria for Equipment Evaluation Tool from MSDD**

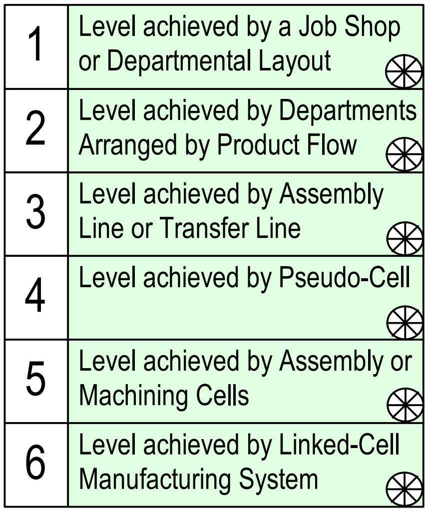


**Figure 4: Evaluation Scheme for Equipment Evaluation Tool**

MSDD.

Notice that the FRs being considered as evaluation criteria in the Equipment Evaluation Tool do not all correspond to a particular level in the MSDD because the FRs that affect equipment design appear throughout all levels of the decomposition. It would be unrealistic to try to evaluate the equipment by selecting FRs at a particular level since the equipment design and operation affects various parts of the system that are defined at different levels of the MSDD. Also, it is important to note that a single machine or piece of equipment can, and generally will, be affected by several different FRs from the MSDD. Physical attributes to achieve different FRs can be combined (physical integration) and still achieve separate FRs (functional independence). The distinction between physical integration and functional independence is an important one in Axiomatic Design methodology and applies thoroughly when designing equipment using the MSDD.

### *Qualitative Evaluation*

To evaluate a piece or set of equipment, the FRs have already been identified based on the discussion above and in Figure 3. The evaluation and grading scheme is now developed. Consistent with the evaluation approach used for the Production System Design Evaluation Tool [Chu and Cochran, 2000], the Equipment Evaluation Tool defines six levels of achievement for each FR being considered. For each FR in the Equipment Evaluation Tool, the descriptions at the six levels of achievement are consistent with a mental model of a system design as illustrated by Figure 4. Figure 4 shows a gradient of six levels of DPs corresponding to six levels of achievement relative to a given FR.

Level 1 represents a traditional manufacturing system, characterized by a job shop or departmental layout and not designed from a system perspective. Level 2 represents a system characterized by a departmental or product flow layout. Level 3 represents a system consisting of assembly and transfer lines. Level 4 represents a system where cells have started to be implemented in certain areas of the plant but they are still not designed to fully achieve the FRs from the MSDD. Level 5 represents a system characterized by the presence of cells in a majority of the areas. Level 6 represents the ultimate level of achievement of a manufacturing system designed based on the MSDD, characterized by linked cells.

In order to evaluate a piece or set of equipment, the actual physical characteristics are matched to the descriptions under each category of the Evaluation Tool. Since it is unlikely that all machines or stations in a set of equipment will have uniform characteristics that all fall within the same level of achievement, it may be necessary to score part of the equipment being considered in one level and another portion of it at another level. The pie charts provide a method in which a portion of the equipment can score at a high level of achievement and another portion can score at a low level for a particular FR. For each FR, or column, the scores from the pie charts at all six levels should add up to 100%. Figure 4 shows the pie charts used in this scoring method. By using this approach, it is immediately evident which percentage of the equipment being evaluated has a high level of achievement and which percentage has a low level of achievement.

### *Quantitative Evaluation*

In addition to the qualitative evaluation just described, the Equipment Evaluation Tool also allows a quantitative evaluation of the criteria being considered. For each FR evaluated, a performance metric has been identified that allows a quantitative evaluation of that particular FR. This set of performance metrics is shown in Figure 5. The figure also shows the performance metrics for the higher level FRs, up to Return on Investment (ROI), which is the highest level metric, as a way to demonstrate the connection between the FRs being evaluated and the enterprise-wide objectives. Notice that no target values have been set for any of the performance metrics indicated here since they may vary widely between industries and

<table>
<tr><td rowspan="6">Metrics</td><td rowspan="2"># of defects per n parts assignable to equipment</td><td rowspan="2"># of defects per n parts assignable to the process</td><td># of defects per n parts caused by human error</td><td rowspan="2">Time between occurrence of disruption and identification of what the disruption is</td><td rowspan="2">Time between id of what the disruption is and support resource knowing what it is</td><td>Time required to service equipment</td><td rowspan="2">Production cycle time - takt time</td><td rowspan="2">Actual run size - target run size. Ratio of changeover time to takt time</td><td rowspan="3">Production time lost due to interference among resources</td><td rowspan="2">% of operators' time spent on NVA tasks while waiting at a station</td><td rowspan="3">% of operators' time spent on wasted motions</td><td rowspan="4">Facilities Cost</td><td rowspan="5">Investment over production system lifecycle</td></tr>
<tr><td># of defects per n parts assignable to operators</td><td>#, length of unplanned equipment downtime</td></tr>
<tr><td colspan="3"># of defects per n parts with an assignable cause</td><td colspan="2">Time between occurrence and resolution of problems</td><td>#, length of disruptions</td><td>Inv. due to process delay</td><td>Inv. due to run size delay</td><td>% of time waiting on equipment</td></tr>
<tr><td colspan="3">Process Capability</td><td colspan="3">% on-time deliveries</td><td colspan="3">Difference between mean throughput time and customers' expected lead-time</td><td colspan="2">% of op. time spent on NVA motions and waiting</td></tr>
<tr><td colspan="9">Sales revenue</td><td colspan="3">Production Costs</td></tr>
<tr><td colspan="13">Return on Investment</td></tr>
</table>

**Figure 5: Performance Metrics for the Equipment Evaluation Tool**

even between different applications within the same system, setting the targets is left to the user considering the particular application.

### *Structure of the Equipment Evaluation Tool*

The complete Equipment Evaluation Tool is shown in Figure 6 in a reduced view to present its format and structure. Notice that the Equipment Evaluation Tool consists of 13 columns, each one corresponding to one of the evaluation criteria, and they are used to assess the level of achievement of the 22 FRs from the MSDD that relate to the equipment. Each column describes the physical characteristics of equipment at each of the six levels of achievement. The document also has a comments section to clarify the purpose and scope of each column, as well as

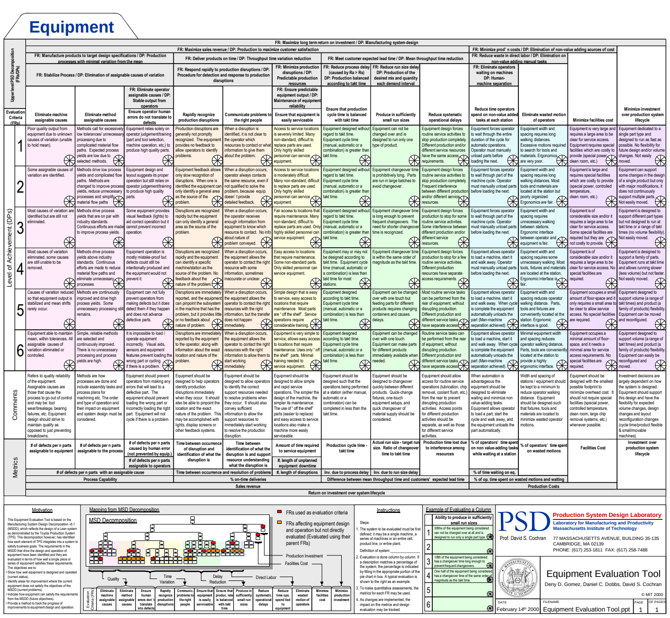


**Figure 6: Equipment Evaluation Tool**

the performance metrics for each FR to allow a quantitative evaluation. Finally, the Equipment Evaluation Tool includes the motivation, the derivation of the FRs being evaluated from the MSDD and the instructions and example of evaluating a column, to make it a self-contained document.

### *Quality*

The 3 FRs from the quality branch on the MSDD that affect equipment design are:

- **FR-Q11 Eliminate machine assignable causes:**

Refers to the quality reliability of the equipment. Assignable causes are those that cause the process to go out of control and may be: tool wear/breakage, bearing failures, etc. Equipment design should strive to maintain the quality of the output, as opposed to just preventing breakdowns.

- **FR-Q13 Eliminate method assignable causes:**

Methods are how processes are done and include assembly tasks and process plans for machining, assembly etc. This FR ensures that the impact of the types of operations selected and their order on the design of the equipment and system is considered. Ideally the methods are simple and allow for equipment with no unnecessary processing and high process yields.

- **FR-Q123 Ensure that operator human errors do not translate to defects:**

Equipment should prevent operators from making any errors that will lead to a defective part. The equipment should prevent loading the wrong part or incorrectly loading a part. Equipment will not cycle if there is a problem.

### *Time Variation*

The 3 FRs from the time variation branch on the MSDD that influence equipment design are:

- **FR-R11 Rapidly recognize production disruptions:**

Equipment should be designed to help operators identify production disruptions immediately when they occur. Equipment should also be able to pinpoint the location and the exact nature of the problem. Lights, display screens and other feedback systems help to recognize production disruptions rapidly.

- **FR-R12 Communicate problems to the right people:**

Equipment should be designed to allow operators to identify the correct support resources needed to resolve problems when they occur. Equipment should also convey sufficient information to allow the support resources to immediately start working to resolve the production disruption.

- **FR-P121 Ensure that equipment is easily serviceable:**

Equipment should be designed to allow simple and rapid service operations. Ideally, equipment should be designed to be as simple as possible, since the simpler the design of the machine, the simpler its maintenance. Also, equipment should strive to use "off the shelf" parts (easier to replace) and easy access to service locations to make it more easily serviceable.

### *Delay Reduction*

The 3 FRs from the delay reduction branch on the MSDD that affect equipment design are:

- **FR-T22 Ensure that production cycle time is balanced with takt time:**

Equipment should be designed such that the operations being performed at a station (either manual, automatic or a combination) can be completed in less than the takt time.

- **FR-T32 Produce in sufficiently small run sizes:**

Equipment should be designed to enable small run sizes; therefore it should changeover quickly between different products. Quick-change fixtures, one-touch equipment setups, and quick changeover of material supply should be considered to reduce the changeover time.

- **FR-T5 Reduce systematic operational delays:**

Equipment should allow access for routine service operations (lubrication, chip removal, coolant flush, etc.) from the rear of the station to prevent disrupting production activities. Access points for different production activities should be separate.

### *Direct Labor*

The 2 FRs from the direct labor branch on the MSDD that influence equipment design are:

- **FR-D11 Reduce time operators spend on non-value added tasks at each station:**

When automation is advantageous the equipment should be designed to prevent tying the operator to the station waiting for an automatic cycle to be completed. The equipment should allow the operator to load a part, start the cycle and walk away, and the equipment will unload the part automatically when finished.

- **FR-D2 Eliminate wasted motion of operators:**

The width and spacing of stations/equipment should be kept to a minimum to reduce the operators' walking distance. Equipment should be designed such that fixtures, tools and materials are located to minimize wasted operator motions.

### *Facilities Cost and Production Investment*

The 2 FRs from the facilities cost and production investment branches on the MSDD that affect equipment design are:

- **FR123 Minimize facilities cost:**

Equipment should be designed with the smallest possible footprint to minimize overhead cost. It should not require special facilities (special power, controlled temperature, clean room, large chip removal systems, etc.) whenever possible.

- **FR13 Minimize investment over production system lifecycle:**

Investment decisions are largely dependent on how the system is designed. Equipment should support the system design and have the flexibility for expected volume changes, design changes and layout reconfiguration changes (cycle time/product flexible and small/movable machines).

## SUMMARY

This paper presented an Equipment Evaluation Tool that can be used to assess how well the design and operation of equipment within a manufacturing enterprise supports the manufacturing system design. The Equipment Evaluation Tool is based on the Manufacturing System Design Decomposition v5.1 (MSDD). It identifies which requirements from the MSDD affect equipment design and operation and which physical characteristics the equipment should have to satisfy these requirements. The Equipment Evaluation Tool allows a qualitative evaluation of the equipment in a gradient of 6 levels of achievement by comparing the physical attributes of the equipment to the descriptions under each one of the levels. The Equipment Evaluation Tool also allows a quantitative evaluation by using the performance metrics for each FR being assessed.

The Equipment Evaluation Tool can be very valuable to a manufacturing enterprise since it serves as a measure of how well the current design and operation of equipment supports the manufacturing system design. The tool can also be very useful in providing a guideline or set of objectives for the improvement of current equipment or the design of new equipment. Another application is to track the progress of a system as the equipment design changes.

It is important to note that although the authors have made every attempt to make the concepts and descriptions in the Equipment Evaluation Tool general in nature, they might not apply exactly to every industry or every manufacturing operation. When using the Equipment Evaluation Tool it might be useful to alter some of the descriptions and/or metrics to suit the particular industry or system under evaluation.

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