Proceedings of ICAD2004
The Third International Conference on Axiomatic Design
Seoul – June 21-24, 2004
ICAD-2004-28

A DECOMPOSITION BASED APPROACH TO INTEGRATE PRODUCT DESIGN AND MANUFACTURING SYSTEM DESIGN

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ABSTRACT

Early consideration of manufacturing system issues in a product development process prevents excessive product design iterations due to a failure to recognize manufacturing system constraints, as well as unnecessary manufacturing system design modification to accommodate new product designs. A structured approach to understand the interaction between product design decisions and manufacturing system design is essential to make this early consideration possible and thus, is a key for successful new product launch. In this paper, an approach to capture the interactions between manufacturing system design and product design decisions will be discussed. As a basis of the proposed approach, the manufacturing system design decomposition (MSDD) is applied. The MSDD represents a logical functional decomposition of general objectives of a manufacturing system and adopts the concept of the Axiomatic Design theory [Suh, 1990, 2001]. The use of the MSDD helps product development teams to see how their decisions affect the achievement of the manufacturing system objectives and thus, to make a right decision from the early stage of product development.

Keywords: manufacturing, system, design, product, process, decomposition

1 INTRODUCTION

Product development is a series of organized activities to realize a product concept into a finished tangible product. Product development begins with the perception of a market opportunity and ends in the production, sale, and delivery of a product [Ulrich and Eppinger, 2000]. Product design, process design, and manufacturing system design are core activities in product development. These three core activities significantly affect the success of a new product development project, which eventually shape the prosperity of a manufacturing company. Traditionally, these three core activities are conducted sequentially since it is a natural sequence – process design or manufacturing system design exists to turn a given product design into a physical product.

In today's market where competition based on 'time-to-market' is strongly dominant, however, the traditional sequential approach does not hold any more. In this market, it is a key for success to minimize the time between product concept and product realization [Ulrich and Eppinger, 2000], [Utterback, 1994], [Fine, 1998]. Therefore, many new approaches have been proposed to shorten the product development lead time. One of them is to minimize design iterations caused by downstream constraints. In order to avoid design iterations and make correct decisions in the early product development phase, well-planned coordination of the core activities is essential, along with a lively exchange of information between functional groups responsible for each core activities. A number of structured methodologies have been developed to find the most efficient way to coordinate these three activities at various abstraction levels. Some of the examples are: Concurrent Engineering (CE), Robust Design, Simultaneous Engineering (SE), Design for Manufacturing and Assembly (DFMA), and Total Quality Development (TQD). Each of these methodologies provides useful tools to coordinate the core activities and ensure the information exchange between the functional departments responsible for each of the core activities.

These methodologies, however, are limited from a manufacturing system design perspective since they often neglect or only partially consider the issues of manufacturing system design. For example, the traditional DFMA approach proposed by Boothroyd et al. [1994] focuses on process, material, and equipment issues without considering other important issues of manufacturing system design such as scheduling and changeover issues. This limitation can be critical in a complex modern manufacturing system which involves hundreds of machines and thousands of people. In other words, the modification of the manufacturing system to accommodate new product designs can be very costly and can also hurt the stability of the manufacturing system [Heragu, 1997]. Therefore, it is not only a matter of producibility of the design. It is also very important to understand how the new design affects the design and operation of the entire manufacturing system

Another example is concurrent engineering (CE) or simultaneous engineering (SE). CE or SE tries to overcome the iteration problems by building cross functional teams that facilitate communication between different functional groups. However, even in cases where manufacturing engineers participate in cross-functional product development teams as suggested by the CE or SE approach, they can only count on their own experiences and knowledge since CE or SE does not provide guidelines to manufacturing engineers against which they can review the adequateness of a product and process design from a manufacturing system viewpoint. In order to overcome the shortfalls of the existing approaches, a systematic way to understand the interactions among product design, process design, and manufacturing system design is critical. Only with clear understanding of the inter-relationship among three core activities of product development, it would be possible to reflect manufacturing system issues early in the product development processes and thus, to avoid unnecessary design modifications or manufacturing system design changes to accommodate new product or process designs.

This paper presents an approach to capture the interactions between manufacturing system design and product/process design. As a basis of the proposed approach, a recently developed manufacturing system design decomposition (MSDD) is applied. By studying how a product/process design decision affects the elements of the MSDD, the impact of the design decision on a manufacturing system can be estimated. This approach helps product development teams to see the effects of their design decisions on manufacturing systems and thus, to make a right decision in the early stage of product development.

2 PROBLEM STATEMENT

Three core activities of product development – product, process, and manufacturing system design affect one another. However, seeing the interactions among three activities in a direct way is not an easy task for several reasons. First, it is not very clear what kind of interactions should be studied. For example, the impact of a product dimension decision on equipment may be studied. Maybe the impact of process decision on operators can be studied. This approach, however, is not very structured and does not guarantee that all aspects of manufacturing system are considered for each design decision. Only part of issues can be considered with this ad-hoc approach. Second, the interface areas between the three core activities are not clearly defined. Third, it can be very case-specific depending much on the specific situation or design of a manufacturing system. A generally applicable framework, however, needs to be developed.

In order to overcome the difficulties to see the interactions among three core product development activities, two main research problems are developed:

(1) How do product/process design decisions interact with manufacturing system design?

(2) How can we systematically identify the interactions?

Since these two problems are too general to be solved, the following sub-problems are derived from the two main problems.

1) How can we represent manufacturing system design?
2) How can we represent product and process designs? What decisions in product development (especially related to product/ process design) affect manufacturing system design?
3) How can the interactions between product/process design and manufacturing system design be captured?
4) How can the new methodology be applied to a real case example? How can the existing approach be viewed with the new methodology?

Based on the solutions to the sub-problems, a comprehensive framework that can guide product development teams to see the impact of their design decisions on manufacturing systems is proposed in the later part of this paper. This framework will satisfy the following requirements:

- Clearly describes the objectives of manufacturing systems separated from the design solutions to achieve the objectives
- Presents the impact of various design decisions on the achievement of the objectives of manufacturing systems
- Provides a common platform to effectively communicate the impact across the organization
- Integrates existing tools to integrate product design and manufacturing

3 EXISTING SOLUTIONS

As is described in the introduction part of this paper, many researchers in the field of product development discussed various ways to ensure manufacturability of a product during the early product development processes. In industry, many of the methods proposed by the academia have been adopted. In this section, two important approaches in the academia to make sure that the product is designed to be producible are discussed as well as industry adoption of the approaches.

3.1 LITERATURE

Vast literature is available in the field of product development. For example, Clark and Hujimoto [1991] explain the strength of Japanese auto companies in their product development compared to their western counterparts. Phal and Beitz [1995], and Ulrich and Eppinger [2000] provide a detailed explanation of the product design processes as well as frequently used tools. Sobek [1997] compares Toyota and Chrysler in terms of their product development processes in detail and proposes the concept of set-based concurrent engineering (SBCE). Clausing [1994] proposes to use a structured and organized product development processes, and provides a step-by-step guide to world class concurrent engineering along with the tools to be used during each product development process. Meyer and Lehnerd [1997] show the advantages of applying the concept of product platform with respect to the traditional single product development approach. Wheelwright and Clark [1992] suggest a product development framework including the organization issues such as cross-functional cooperation, learning, and building of capabilities. Suh [20, 21] proposes mapping between four design domains for smooth product development. Altshuller [1988] suggests a 'theory of inventive problem solving' (TIPS or TRIZ) as a framework to find creative solutions to solve design problems.

Interestingly, most of the above-mentioned literature addresses the issues of designing a producible product that satisfies manufacturing requirements from the beginning of the product development process. It is observed that there are two major approaches to address manufacturing issues during product development. The first approach is concurrent engineering that facilitates communication between manufacturing and product development. This approach stresses the importance of organizing people from various groups within a company for close collaboration (e.g., cross-functional product development team) in order to design producible products. Authors such as Andreasen and Hein [1987], Clark and Fujimoto [1991], Wheelwright and Clark [1992], and Clausing [1994] explain different aspects of this approach in detail.

The other approach is to study how product design itself affects manufacturing or production process. For example, Nevins and Whitney [1989], and Cunningham [1998] address the issue of tolerancing and assembly. Boothroyd et al. [1994] propose several ways to estimate the cost and time of machining and assembly along with material selection issues. They also explain how to design a product to be adequate to the selected production process. O'Grady [1999] explains the concept of modularity, and Meyer and Lehnerd [1997] describe the benefits of product platforms. Both concepts contribute to maintaining a simple manufacturing system under given product variety. Suh [20, 21] proposes to link process variables with product design parameters during product design in his Axiomatic Design theory, which consequently leads to the consideration of manufacturing issues during product design. Sohlenius [2000] proposes a model for concurrent design of product, process, and manufacturing systems. In summary, the second approach tries to convey the content of issues that can arise during the transformation of conceptual product design into physical implementation.

However, manufacturing system issues are rarely addressed by these approaches even though manufacturing system design plays a significant role in the actual production of the new product..

3.2 INDUSTRY

According to the survey conducted by Kim [2002a], concurrent engineering and DFMA (design for manufacturing and assembly) approaches proposed by the academia are widely accepted in the automotive industry. The result of the survey is summarized in Table 1.

Table 1. Survey Result of Six Automotive Companies (Adopted from [Kim, 2002a])

Company	Cross functional team	Written design guideline for MFG	Info. exchange regarding mfg system design
A	Yes	Yes	Yes
B	Yes	Yes	Yes
C	Yes	Partial	Yes
D	Partial	Partial	Partial
E	Partial	No	Partial
F	Partial	No	Partial

As is shown in Table 1, the answers received from six major players in the auto industry revealed that the six companies are pursuing more or less similar goals and implementing similar tools as suggested by the academia. All of the companies stressed the importance of the communication between product design groups and manufacturing groups (including production engineering groups) in order to streamline product development activities, which results in faster introduction of new products without significant cost increase. The use of cross-functional teams or design for manufacturing guidelines is becoming a norm in the automotive industry. In addition, almost all companies claim that they encourage information exchange between manufacturing and product development groups regarding manufacturing system design issues. All respondents are aware of the disadvantages associated with the traditional 'throw-over-the-wall' approach with functional chimneys.

The question is why these six companies show different level of achievement in terms of their product development lead time in spite that they implemented more or less same tools. There can be several reasons for this but one reason may be a lack of structured framework to support the cross functional teams or information exchange between design and manufacturing, and to extend the scope of written design guidelines to manufacturing system areas. According to Condra's survey [Condra, 2001], the biggest frustration for product designers at Ford is communication gap. Simply putting product designers and manufacturing engineers together does not guarantee producible product design since they do not understand each other's point of view. This misunderstanding often leads to endless meetings, delayed launch, and meaningless blaming. Therefore, the participants to the survey agree that shared objectives between product design and manufacturing are most important. In addition, Kim [2002a] reports that one engineer at a global copy machine company confessed that it is often true for manufacturing engineers to sit at the corner of a table during a product design review meeting, doing nothing but wasting their time. Even when they raise some manufacturability issues, they cannot be sure that all issues have been addressed. Without a well-defined framework, therefore, it will be difficult for manufacturing engineers to cover entire manufacturability issues of a certain product/process design only with their personal experiences and knowledge.

4 MANUFACTURABILITY EVALUATION FRAMEWORK

In this section, by addressing the sub research problems with corresponding solutions, the ideas behind the manufacturability evaluation framework are explained.

4.1 HOW TO REPRESENT MANUFACTURING SYSTEM DESIGN

The first sub-problem of the research is how to represent manufacturing system design. . Since the main objective of the research is to develop a methodology to capture the interactions between product/process design decisions and manufacturing system design, it is important to systematically represent manufacturing system design. The systematic representation of manufacturing system design can help manufacturing engineers to cover all aspects of manufacturing system design during the product review meetings.

For this purpose, the Manufacturing System Design Decomposition (MSDD) is adopted. The MSDD has been developed by Cochran and his colleagues at MIT for the last 8 years [Cochran, et al., 2001]. The MSDD is a logical decomposition of general objectives of a manufacturing system and corresponding solutions. Some other models of manufacturing system design may be used instead of the MSDD, but the MSDD has several advantages over the other representations. Some of them are:

1. The MSDD clearly separates objectives from the means of achievements

2. The MSDD relates low-level activities and decisions to high-level goals and requirements
3. The MSDD shows the interrelationships among the different elements of a system design, and
4. The MSDD helps to effectively communicate the interrelationship information across the organization.

These advantages are gained by applying the framework of the Axiomatic Design theory. The Axiomatic Design theory clearly separates the objectives of a system (Functional Requirements, FRs) and the means to achieve those objectives (Design Parameters, DPs) while taking top-down decomposition approach that links low-level activities and decisions to high-level goals. The interrelationship among elements are defined and designed by the design matrices. In addition, the decomposition itself is a nice tool to communicate the design ideas across the organization.

In order to develop the MSDD, a variety of sources are consulted to generate adequate functional requirements and design parameters. Some of the sources consulted are: systems engineering literature, Toyota Production System (lean manufacturing) related literature, manufacturing system design literature, industrial engineering literature, and industrial projects in a variety of fields including automotive, aerospace, consumer goods, electronics, and food processing. The aim was to develop the MSDD general enough to be applicable to repetitive and discrete parts manufacturing systems in a wide range of industries.

A complete version of the Manufacturing System Design Decomposition (MSDD) is available in the Appendix. The MSDD consists of six major branches: quality, problem solving, predictable output, delay reduction, operational costs, and investment. The general structure of the MSDD is shown in Figure 1. For further explanation of the MSDD, please refer to [Cochran, et al., 2001], [Kim, 2002a], [Arinez, 2000].

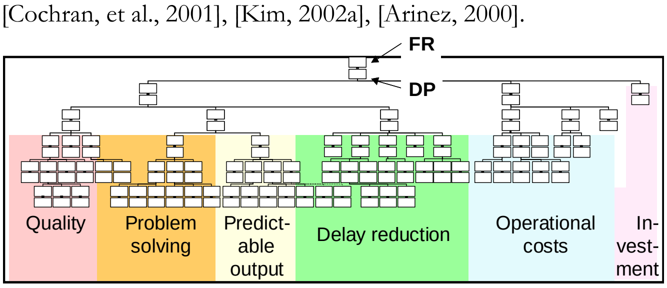


Figure 1. The General Structure of the Manufacturing System Design Decomposition (MSDD)

The MSDD has been successfully applied in various disciplines. For example, Arinez [2000] discusses the use of the MSDD for equipment design. Duda [2000] presents the use of the MSDD to link strategy, performance measurement, and manufacturing system design. Notably, Linck [2001] tries to validate the usefulness of the MSDD by applying the questionnaire to several different industry cases. He provides evidences that the MSDD effectively reflects the elements of lean manufacturing and is useful in assessing the level of 'leanness' of a plant.

4.2 HOW TO REPRESENT PRODUCT DESIGN

The second research sub-problem is how to represent product development and what types of product/process design decisions affect manufacturing system design while product development involves various activities, the proposed approach does not consider such areas of product development as marketing, customer relations, and distribution, since the aim of the proposed approach is to provide a way to see the interactions among the decisions of product design, process design, and manufacturing system design. In addition, the proposed approach does not try to model the entire product/process design. The proposed manufacturability evaluation framework identifies the general elements of product/process design that significantly affects manufacturing systems. This is because it is very difficult to model the product and process design. For example, product/process design is very case-specific and it involves a creativity of human beings. Different product and process designs are prepared for different products and they can be all new to the world. In order to make the proposed approach generally applicable, general elements of product and process design should be identified as well as their interrelationships, which can be very difficult. Product design process or process design steps can be generalized but the contents of product/process design can't. Therefore, instead of modelling the entire product/process design, product/process design decisions that affect manufacturing systems are identified.

A thorough review is given to several models of product development and the elements of product/process design that affect manufacturing systems are identified. The models reviewed include: Phal and Beitz [1995], Ulrich and Eppinger [2000], Wheelwright and Clark [1992], Bocagnegra [2001], Dobbs [2001], and Lenz and Cochran [2000]. As a result, six different groups of product/process design elements are identified to affect manufacturing systems. They are: 1) product variety, 2) product architecture, 3) purchasing decision, 4) material selection, 5) process selection, and 6) detailed design.

4.3 HOW TO SEE THE INTERACTION BETWEEN PRODUCT/PROCESS DESIGN DECISIONS AND MANUFACTURING SYSTEM DESIGN

The third research sub-problem is how to see the interaction between product design decisions and manufacturing system design. Since a general decomposition model of a manufacturing system (MSDD) and product/process design decision categories are available at this point, the interactions between manufacturing system design and product/process design can be captured by reviewing how each category of product/process design decisions affects the FRs and DPs of the MSDD. For example, it can be reviewed how a product variety decision affect FR-Q111 and DP-Q111 in the quality branch of the MSDD. FR-Q111 states to 'ensure operator has knowledge of required tasks' and this is achieved by DP-Q111, 'training program.' The product variety decision can affect the achievement of FR-Q111 by changing the amount of knowledge on tasks to be performed by operators. Therefore, when a product variety decision is made, its impact on required operator knowledge should be reviewed and considered for a better achievement of quality. This reviewing process can be repeated to other FRs and DPs of the MSDD so that a complete map of the interactions of each category with the FRs and DPs of the MSDD can be developed.

The reason that both the FRs and DPs of the MSDD are considered in the reviewing process is that the DPs stated in the MSDD are believed to be a reasonable way to satisfy the FRs. Therefore, it is believed to be beneficial to check whether product/process design decisions are appropriate from the point of view of the suggested DPs. In addition, the decomposition itself cannot be completed without specifying the DPs and thus, it is necessary to include DPs in the reviewing process.

The results of the reviewing process for the product variety category of product/process design are presented in Figure 2. The FRs and DPs of the MSDD that can be affected by product variety decisions are highlighted. In the reviewing process, all leaf FRs and DPs of the MSDD are primarily considered. However, since the MSDD assumes product design and process design as given, high level FRs and DPs are considered whenever necessary to reflect product/process design issues.

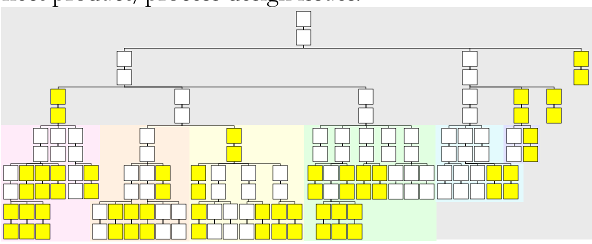


Figure 2. The FRs and DPs of the MSDD that can be ffected by a Product Variety Decision

As is shown in Figure 2, product variety affects manufacturing systems in various ways. It is directly related to the required flexibility of the manufacturing system, which is closely linked to operating costs and investment, which is shown by highlighted boxes in the cost and investment branches of the MSDD. In addition, product variety decisions heavily affect quality, identifying and resolving problems, predictable output, and delay reduction branches.

The same process can be repeated to the product architecture, purchasing, material selection, process selection, and detailed design categories, to develop a map like Figure 2, for each category. For further detailed explanations of the general interactions between the six categories and manufacturing systems and the FRs and DPs of the MSDD, please refer to [Kim, 2002a]. The result of this mapping process can be summarized in a matrix form, which is shown in Figure 3. As is shown in Figure 3, there are various manufacturing system requirements that are affected by product/process design decisions other than quality. Quality branch are significantly affected by design decisions but other branches such as identifying & resolving problems, predictable output, delay reduction, cost, and investment branches are also significantly affected. Therefore, these factors should be considered during the product development processes. Interestingly, there are certain FRs and DPs that are not affected by product/process design decisions. For example, FR P122, ‘ensure availability of workers’ and DP P122 ‘perfect attendance program’ in the predictable output branch are not affected by product/process design.

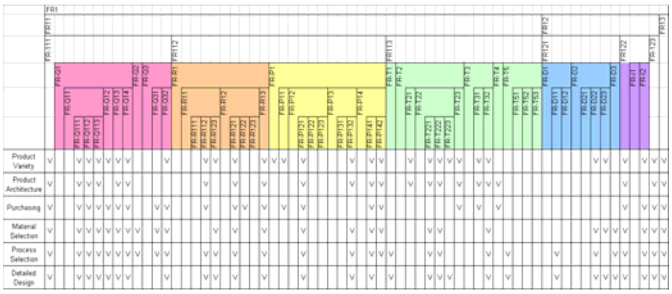


Figure 3. The Matrix of the FRs and DPs of the MSDD that can be affected by Six Design Categories

4.4 MANUFACTURABILITY EVALUATION PROCESS

The manufacturability evaluation process guides the conflict resolution between product/process design and manufacturing system design. It starts from identifying FRs and DPs of the MSDD that are affected by a product/process design decision. Manufacturability evaluation framework that is presented 4.1~4.3 is used in this stage. Then it is identified if there is any FR and DP that are negatively affected by a product/process design decision. If there is any, the conflict between product/process design and manufacturing system design is resolved either by product/process design change or manufacturing system design change. In this way, the manufacturability of a product is ensured during product development. For detailed explanation on each step of manufacturability evaluation process, please refer to [Kim, 2002a].

5 CASE EXAMPLE

In this section, it is presented how the manufacturability evaluation framework can be used to solve a design problem of a part supplier in automotive industry. In addition, the usefulness of a systematic approach to resolve design and manufacturing conflict is discussed.

5.1 BACKGROUND INFORMATION OF PLANT A

Plant A produces anti-lock braking systems (ABS) for OEM companies in the automotive industry. This plant produces three types of ABS. The first type is ordinary ABS. The second one is ASR (Acceleration Slip Regulation) and this type provides additional function that prevents wheels from slipping when accelerating vehicles to the ordinary ABS. The third one is VDC (Vehicle Dynamics Control) and this type provides vehicle control capability in addition to the ASR functions (it automatically prevents too much turn or too little turn by applying breaking forces on the wheels).

The production process starts from machining of aluminum forged blocks. This machining process is to make breaking fluid channels on the block and thus, is basically drilling process. All machining is done by a machining center or two machining centers depending on the type of ABS. Then finished blocks are moved to deburring machines to remove burrs, and washing and visual inspection processes are followed. Machined blocks are then moved to the assembly line where electric valves are inserted to the block. In this case example, the primary focus of the research is given to the machining area.

The machining centers used in the machining area are supposed to perform as many operations as possible in one load to save manual loading/ unloading time. They are high-precision and high-speed machining centers equipped with over 100 tools to achieve this purpose. However, finishing a part cannot be done in one load because all faces must be processed. Due to this constraint, ABS housings, for example, have to be manually unloaded from one position (clamping A in Figure 4: left) in a fixture and then loaded to another position (clamping C in Figure 4: left), so that a total of 4 motions to load and unload are required to finish a part. Tombstone fixtures are applied to produce as many parts as possible in one load. Each fixture holds 12 parts at a time. The fixtures used here are shown in Figure 4.

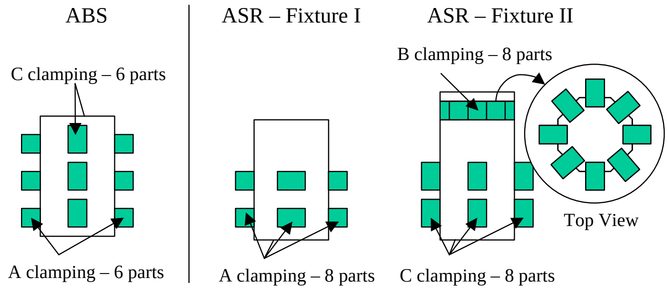


Figure 4. A Schematic View of Fixtures for ABS (Left) and ASR/VDC (Right)

In the case of ASR/VDC housings, the machining process becomes trickier than that of ABS housings. ASR/VDC housings have four angled fluid channels that cannot be handled with the existing fixture for ABS housings (see Figure 5).

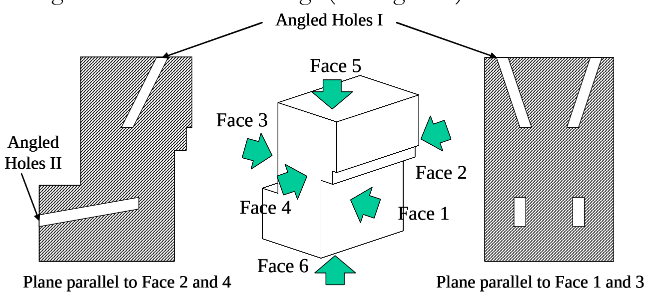


Figure 5. Angled Fluid Channels in the ASR/VDC Housings.

Therefore, new fixtures are designed as shown in the right side of Figure 4. In a new fixturing system, two different fixtures are used and each fixture is located on a machine respectively. Therefore, two machines are grouped together to produce ASR/VDC housings. The fixture I type shown in Figure 4 has A type clamping and holds eight fresh housing blocks. The fixture II type has newly designed B type clamping on top of it as well as C type clamping. Each clamping position can hold eight parts and thus, fixture II type can hold sixteen parts in one cycle. Parts are moved from the position A to B and then moved again from the position B to C. The fixture I type holds only eight parts even though it can hold up to twelve parts because clamping B can only hold up to eight parts due to the space limitation. Parts are moved without buffers between clamping positions (A, B, and C) and thus, the number of parts held by each clamping position should be same.

5.2 Design and Manufacturing Conflicts in Plant A

Compared to ABS housing production, several problems can be identified with the production of ASR/VDC housings. First, two machining centers need to be dedicated to process ASR/VDC housings since two fixtures are required for the production of ASR/VDC housings. In addition, it takes about a day to change the fixtures for ASR/VDC housings to the fixture for ABS housing due to the high precision requirement. This deteriorates the mix flexibility of the plant to the demand fluctuation. Furthermore, both fixture types of I and II should have the capability of rotating in one degree scale while the rotational capability in 90 degrees is enough for the fixtures for ABS housings. Another problem is quality. For example, sometimes defective parts are produced due to chips in the spindle. If defective parts were found after the machining operations and they were made during the processing in the clamping B position, a total of eighteen parts are likely to be scrapped. Six finished parts along with twelve parts in the fixture type II in the run are likely to be defective.

It is noteworthy that all troubles are caused by two fluid channels in unique angles that cannot be handled by the existing fixture, combined with the manufacturing strategy of incorporating as many operations as possible in one load of the parts to the machining center. Then, two uniquely angled fluid channels are a result of lack of communication between manufacturing and product design. If the holes with unique angles were eliminated through extensive communication between manufacturing and product design, there would be no need for new fixture design and consequent separate operation of machining centers dedicated to ASR/VDC housings. Ironically, this company is company C in Table 1 who said that concurrent engineering and extensive information exchange between manufacturing and product/process design is the norm.

This problem is also different from traditional DFMA problems. There is a DFMA rule saying that angled drilling is bad because it is difficult to keep required tolerances due to tool deformation such as tool bending or tool slippery. However, for a global company like this company who has a very advanced level of machining technology, this general DFMA rule does not matter so much in terms of process capability. Rather, as is described earlier, the angled holes caused manufacturing system problems such as limited production flexibility, dedication of machines, and high rotational capability of fixture.

In the next generation of the ASR/VDC, all fluid channels are designed to be perpendicular to the faces of the housings in order to prevent the same problem from occurring again. This is only one solution to the problem, however, and more options to solve this problem may be found. For example, manufacturing system design may be changed to accommodate the angled fluid channel design without causing a lot of manufacturing problems. Instead of incorporating as many operations as possible in one load of housings, lean cellular manufacturing approach may be taken to minimize the impact of angled fluid channels on manufacturing system. In any case, the manufacturability of the design decision can be checked with the manufacturability evaluation framework proposed in section 4 of this paper. The proposed framework will show what elements of manufacturing system design are affected by each solution option and thus, provide the motivation for searching for new solutions.

5.3 APPLICATION OF MANUFACTURABILITY EVALUATION FRAMEWORK TO THE PROBLEM

The angled fluid channel design belongs to the detailed design category. From a detailed design perspective, two angled fluid channel design affects the FRs and DPs of the MSDD in a way shown in Figure 6 if the ABS housing machining is assumed to be given. The gray colored blocks show the FRs and DPs of the MSDD that are relevant to the category but not significantly affected by the given design decision. The black colored blocks indicate the FRs and DPs that are directly related to the design decision in consideration.

In the quality branch, the most important impact of the angled fluid channel design is that the angled fluid channels cannot be machined with the fixture that is used for ABS housing production (FR-Q12). To solve this conflict, new fixtures are developed as is shown in Figure 4. However, the new fixtures do not completely meet the FR-Q12 since the new fixture design does not solve the quality problem caused by loading multiple parts per each cycle of the machining. When chip-in-spindle problem occurs, for example, all of the loaded parts should be scrapped, which deteriorates the quality level. From this sense, the existing solution is just ad-hoc modification of the ABS housing machining operations in order to produce ASR housings.

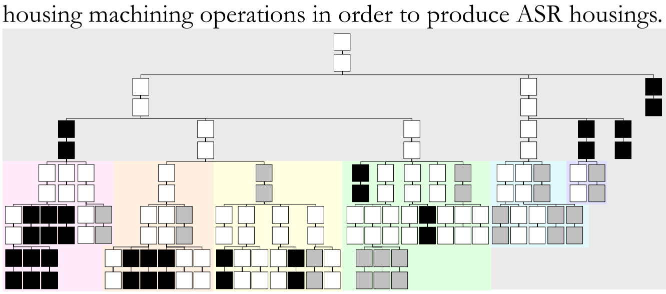


Figure 6. The Impact of Angled Fluid Channel Design on the FRs and DPs of the MSDD from the Detailed Design Perspective.

As is explained before, the operation steps to machine the ASR housings are different from the steps for the ABS housings due to the new fixture developed to machine the angled fluid channels and other machining requirements such as increased number of fluid channels and the increased size of the housings. Therefore, the operators need to be trained on the new required tasks (FR-Q111) and new standard work methods (FR-Q112) should be developed. Training of the operators or developing the new standard work methods should not be difficult since the machining of the ASR housing is not very different from that of the ABS housing in a fundamental way. Some mistake proof devices can be developed to prevent the operators' mistakes caused by the introduction of the new fixture and the operational change (FR-Q113).

The angled fluid channel design may be linked to the method assignable causes (FR-Q13) or material assignable causes (FR-Q14). The location and direction of the angled fluid channels relative to the other fluid channels may be reviewed to see if machining processes are adequate to make those fluid channels. In a similar way, the incoming material property may be checked if the material property supports the design. With regard to the FR-111, the angular tolerance of the angled fluid channels needs to be controlled in addition to the design specifications on the geometry of the housing. The angular tolerance may greatly affect the location of the end of fluid channels and additional efforts should be made to keep the angular tolerances.

In the identifying and resolving problems branch, it should be first checked if the introduction of the new fixture and the consequent new operation pattern deteriorates the simplicity of the material flow paths within the existing manufacturing system (DP-R112). The ABS housing machining area is not designed to keep the material flow paths simple and thus, no significant difference arises after the introduction of the new fixture. The introduction of the new fixture and the new operational steps may lead to new types of production disruptions and the new production disruptions should be reflected to the feedback system (DP-R113), which is overlooked in the existing system. In addition, new supportive resources to solve the disruptions related to the new fixture (FR-R121). This factor is not thoroughly considered in the current system.

In the predictable output branch, new standard methods to ensure repeatable processing time may need to be developed due to the new operational pattern caused by the introduction of the new fixtures (FR-P121). Even though the machining operations are automated, loading and unloading are conducted by the operators and the operators are required to load and unload parts from three clamping positions, A, B, and C. The complexity involved may lead to variation in task completion time of the operators (FR-P121). In addition to this factor, current preventive maintenance programs in use should be reviewed and modified as necessary to accommodate the introduction of the new fixture (FR-P122). FR-P141 and FR-P142 are not much affected by the introduction of the new fixture because the manufacturing system designed for ABS production does not have SWIP and the scheduling is done based on forecasting and MRP (material requirement planning) system. Instead of SWIP, a large number of inventories are kept to ensure the parts availability. Proper timing of part arrivals (FR-P142) is not necessary to ensure material availability even though fallout exists (FR-P14) since the fallouts are compensated by inventories.

In the delay reduction branch, improvement is made on the lot size of the process. The lot size of the ABS machining is twelve parts but that of the ASR machining is eight. The lot size of the ASR machining is decreased to eight since the clamping position B can hold only eight parts. This reduces the lot delay. However, this lot delay reduction is minimal since the CNC machining centers in use have three spindles and thus, can process three parts in parallel, which minimizes the lot delay. This capability contributes to the large investment made to procure the existing CNC machining centers.

FR-T221, FR-T222, and FR-T223 that are related to the takt time are not affected by the introduction of the new fixture caused by the angled fluid channels. This is because the manufacturing system design for ABS housing machining is not operated according to the takt time.

The FR that is most significantly affected by the introduction of the angled fluid channels is FR-T32. Within the ABS housing family, the changeover time is less than 5 minutes since it is only a matter of changing machining programming. However, to change over from ABS family to ASR family, it takes more than a day since huge tombstone fixtures need to be exchanged and complex calibrations are required. In addition, two fixtures need to be exchanged since two fixtures attached to two machining centers respectively work as a group to produce ASR housings.

In the operating cost branch, FR-122 may be affected by the introduction of the new fixtures that are developed because of the angled fluid channels. This is because two more types of fixtures are added to the fixture for the ABS housing and thus, indirect labor requirement to maintain the fixtures may be increased. In addition, the changeover from ABS to ASR requires indirect labor, which would not be necessary if the same fixture could be used for both ABS and ASR housings. Facilities cost may be also increased since more fixtures need to be managed and this may require more space. In the investment branch, the investment made to develop the fixtures for the ASR housing would not be necessary if the fixture for the ABS housing could be used for the ASR housing.

There can be many ways to resolve the conflicts caused by the angled fluid channels. One way is to replace the angled fluid channels with the fluid channels that are perpendicular to the face of the housing. In this case, the special fixtures for ASR housings are not necessary and the same fixture can be used for both ABS and ASR housing machining, which eliminate the conflicts identified through the manufacturability evaluation process. The FRs and DPs that are affected by new design is shown in Figure 7. The total number of FR and DP pairs that are affected by product design is reduced from 18 (angled fluid channel design) to 4 (all-perpendicular fluid channel design).

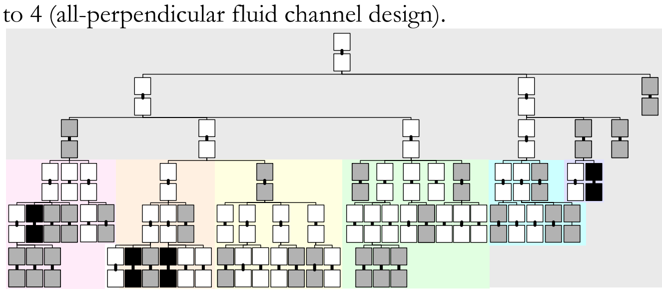


Figure 7. The Impact of All-Perpendicular Fluid Channel Design on the FRs and DPs of the MSDD from the Detailed Design Perspective.

FR-Q12 still needs to be checked since even new product design does not completely solve quality problems such as chip-in-spindle problem. DP-R112 (simplified material flow path) also needs to be checked since the introduction of new ASR/VDC precuts will change the material flow paths in the existing plant. FR-R122 to minimize delay in contacting correct support resources is another FR to be checked with the introduction of ASR/VDC housing. New contact person should be assigned for ASR/VDC housing machining problems, if necessary. FR-I2 to eliminate information disruption and DP-I2 that is seamless information flow needs to be checked to accommodate the introduction of ASR/VDC housings to the existing plant.

5.4 CASE CONCLUSION

In this section, the plant C case is presented. It is shown that the overlook of product designers on the manufacturability of their design from the manufacturing system's perspective can lead to serious inefficiency in manufacturing.

The proposed manufacturability evaluation framework has several benefits. First, the framework allows product designers and manufacturing engineers to see the consequences of the design decision on the existing manufacturing system. Therefore, two groups can easily communicate the problems and possible solutions in a systematic way. In the plant C case, product designers must have certain intents with the angled fluid channel design. Manufacturing engineers, on the other hand, saw the angled fluid channel design as a challenge to overcome using their manufacturing expertise. The unique fixtures dedicated to ASR/VDC housings are the result of the manufacturing engineer's pride that is "you design anything, we make whatever you design." However, these new fixture caused inefficiency in the existing manufacturing system. Instead of solving conflicts with 18 FR-DP pairs of the MSDD shown in Figure 6, product designers and manufacturing engineers can use the proposed manufacturability evaluation framework and come up with a new product design, which may never be thought if ad-hoc consideration of manufacturing systems is made by manufacturing engineers. This new design allows them to solve conflicts with only four FR-DP pairs by relatively minor modification of manufacturing system.

Second, the proposed framework can be used to ensure the traceability of a design decision in terms of its impact on manufacturing system design. By seeing the impact of a design decision on the FRs and DPs of the MSDD, it can be traced how manufacturing responds to the design decision – either by changing manufacturing system itself or by asking product design changes. Third, the proposed framework serves as a starting point to compare two design options, which can lead to a serious trade study. Using the manufacturability evaluation framework, two design options can be compared in terms of their conflicts with the FRs and DPs of the manufacturing system. Then further research can be made to seriously analyze the impact of two design options on manufacturing systems in details, if necessary.

6 CONCLUSION

In this paper, an approach to capture the impact of product design decision on manufacturing systems is proposed. The proposed manufacturability evaluation framework does this by showing how a product/process design decision affects the FRs and DPs of the MSDD, which represents general objectives of a manufacturing system and means to achieve the objectives. The manufacturability evaluation framework is developed by answering four research sub-problems presented in section 2 that are derived from two main research questions: 1) how product development decisions interact with manufacturing system design and 2) how we can systematically identify the interactions. The manufacturability evaluation process is suggested to guide conflict resolution between product/process design and manufacturing system design. In addition, a case study example is presented to show the usefulness of the manufacturability evaluation framework.

The manufacturability evaluation framework, however, only provides a framework to evaluate the manufacturability of a design decision from a manufacturing system's perspective. Its content is subject to changes as the requirements for manufacturing systems change and our knowledge on the interactions between product/ process design and manufacturing is accumulated. Therefore, efforts to reveal the interrelationship between product/process design and manufacturing should be continued in order to enrich the contents of the proposed approach.

The real strength of the proposed approach is that it can be used together with other solutions such as concurrent engineering and traditional DFMA methods. The manufacturability evaluation framework expands the traditional DFMA methods from the manufacturing process level into the manufacturing system level. It also provides contents that can be used at the communication meetings of concurrent engineering. For example, product/ process design groups and manufacturing groups under concurrent engineering environment can easily communicate the possible problems of a product/process design on manufacturing by using the proposed framework. In addition, the conflicts identified by using the proposed framework may be solved by applying DFMA techniques.

All benefits of the manufacturability evaluation framework can be achieved since the framework is based on the MSDD representing general requirements of a manufacturing system and investigates how product/process design decisions affect the achievement of these requirements. The manufacturability of a product/process design decision should be understood as how well the design decision contributes to the achievement of the objectives of manufacturing systems that are represented by the MSDD. Without a clear understanding of interaction between various aspects of manufacturing system design and product/ process design decisions, true concurrent engineering cannot be achieved. Instead of thinking about manufacturing problems in an ad-hoc way, the manufacturability evaluation framework enables systematic identification of the manufacturing system problems during product development.

7 ACKNOWLEDGMENTS

The author would like to thank Dr. Taesik Lee and Mr. Jongyoon Kim for their kind assistance to develop the manufacturability evaluation framework idea. The author had a lot of discussions with them on the manufacturability evaluation framework idea, which significantly contributed to the contents of this paper.

8 REFERENCES

[1] Altschuller, G., *Creativity as an Exact Science – the Theory of the Solution of Inventive Problems*, Gordon and Breach Science Publishers, New York, NY, 1988.

[2] Andreasen, M. and Hein, L, *Integrated Product Development*, Springer-Verlag, New York, NY, 1987.

[3] Arinez, J., "An Equipment Design Approach for Achieving Manufacturing System Design Requirements," *Doctoral Thesis*, MIT, Cambridge, MA, 2000.

[4] Bocanegra, C., "Design and Implementation of Product Development Design Decomposition (PD^3)," *M.S. Thesis*, MIT, Cambridge, MA, 2001.

[5] Boothroyd, G., Dewhurst, P., and Knight, W., *Product Design for Manufacture and Assembly*, Marcel Dekker, New York, NY, 1994.

[6] Clark, K. and Fujimoto, T., *Product Development Performance: Strategy, Organization, and Management in the World Auto Industry*, Harvard Business School Press, Boston, MA, 1991.

[7] Clausing, D., *Total Quality Development: A Step-by-Step Guide to World-Class Concurrent Engineering*, ASME Press, New York, NY, 1994.

[8] Cochran, D., Arinez, J., Duda, J., and Linck, J., "A Decomposition Approach for Manufacturing System Design," *Journal of Manufacturing Systems*, Vol. 20, No. 6, 2001a.

[9] Condra, K., "Managing the Product Development and Process Engineering Interface" *M.B.A Thesis*, MIT, Cambridge, MA, 2001.

[10] Cunningham, T., "Chains of function delivery: a role for product architecture in concept design," *Doctoral Thesis*, MIT, Cambridge, MA, 1998.

[11] Dobbs, D., "Development of An Aerospace Manufacturing System Design Decomposition," *M.S. Thesis*, MIT, Cambridge, MA, 2001.

[12] Duda, J., "A Decomposition-Based Approach to Linking Strategy, Performance Measurement, and Manufacturing System Design," *Doctoral Thesis*, MIT, Cambridge, MA, 2000.

[13] Fine, C., *Clock Spped: Winning Industry Control in the Age of Temporary Advantage*, Perseus Books, Reading, MA, 1998.

[14] Heragu, S., *Facilities Design*, PWS Publishing, Boston, MA, 1997.

[15] Kim, Y-S., "A Decomposition-Based Approach for the Integration of Product Development and Manufacturing System Design," *Doctoral Thesis*, MIT, Cambridge, MA, 2002a.

[16] Kim, Y-S., "A Decomposition-Based Approach to Design for Lean Manufacturing System," International CIRP Design Seminar, *CIRP-DS '02*, Hong Kong, May 16-18, 2002b.

[17] Lenz, R. and Cochran, D, "The Application of Axiomatic Design To the Design of the Product Development Organization," The First International Conference on Axiomatic Design, *ICAD '00*, Cambridge, MA, June 21-23, 2000.

[18] Linck, J., "A Decomposition-Based Approach for Manufacturing System Design," *Doctoral Thesis*, MIT, Cambridge, MA, 2001.

[19] Meyer, M. and Lehnerd, A., *The Power of Product Platforms: Building Value and Cost Leadership*, The Free Press, New York, NY, 1997.

[20] Nevins, J. and Whitney, D., *Concurrent Design of Products and Processes*, McGraw-Hill, New York, NY, 1989.

[21] O'Grady, P., *The Age of Modularity: Using the new world of modular products to revolutionize your corporation*, Adams and Steele Publishers, Iowa City, IA, 1999.

[22] Pahl, G. and Beitz, W. *Engineering Design*, 2nd edition (translated by Wallace, K. M.), Springer-Verlag, London, 1995.

[23] Sobek II, D., "Principles that Shape Product Development Systems: A Toyota – Chrysler Comparison," *Doctoral Thesis*, University of Michigan, Ann Arbor, MI, 1997.

[24] Sohlenius, G., *The Manufacturing System: Our Motor of Welfare*, in preparation for publication, ISSN 1650-1888, KTH, Stockholm, Sweden, 2000.

[25] Suh, N., *The Principles of Design*; Oxford University Press, New York, NY, 1990.

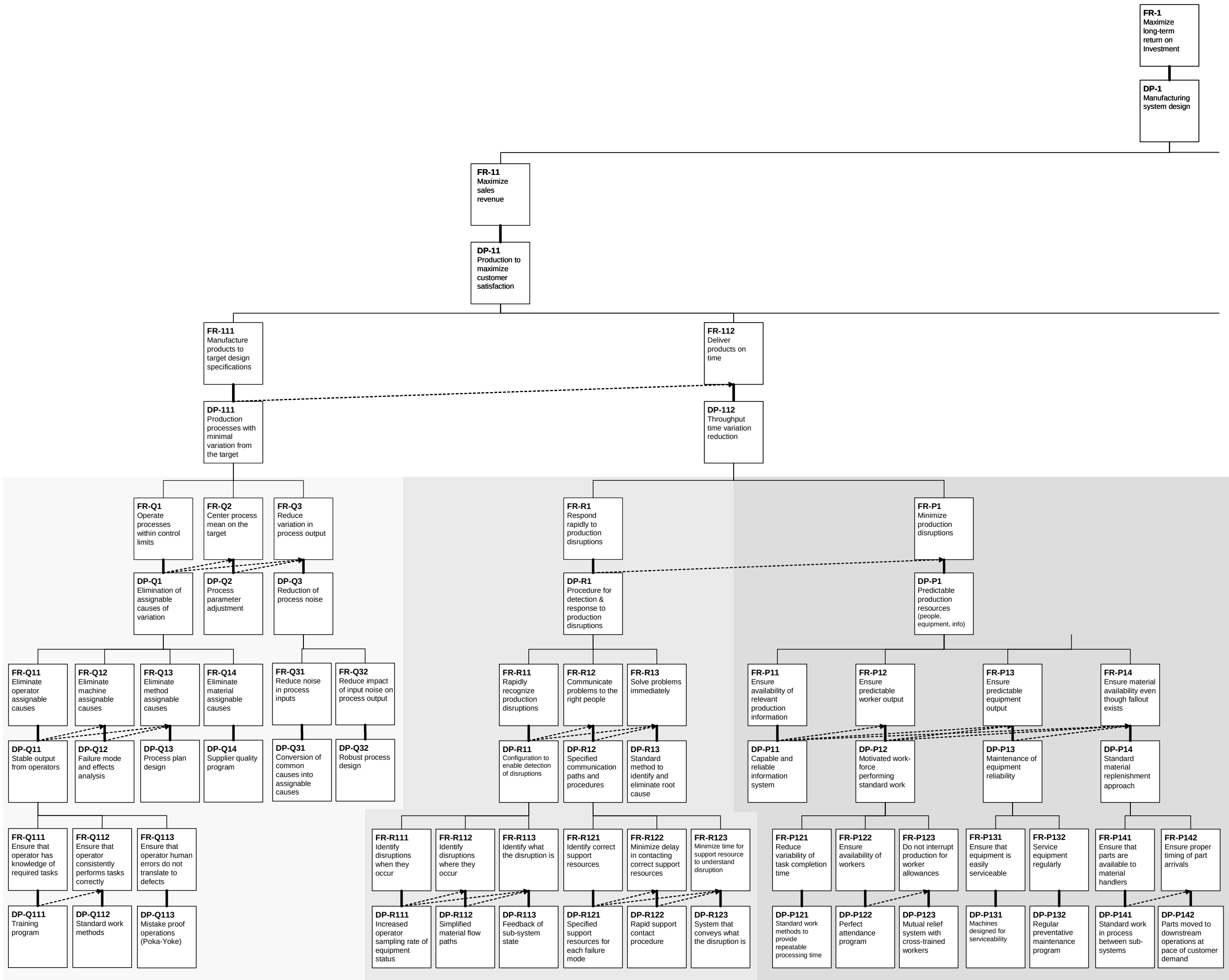
[26] Suh, N., *Axiomatic Design – Advances and Applications*, Oxford University Press, New York, NY, 2001.

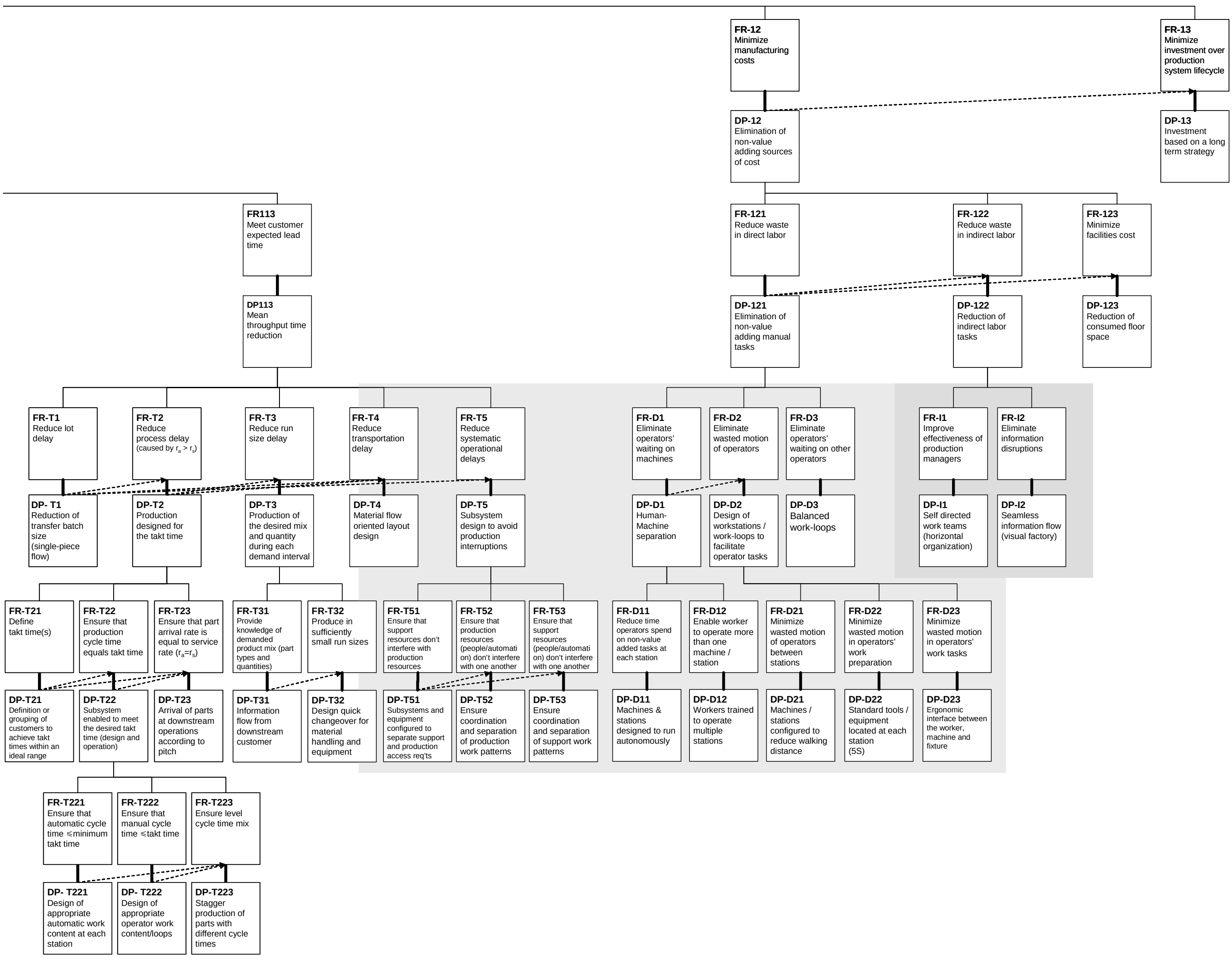
[27] Ulrich, K. and Eppinger, S., *Product Design and Development*, Irwin McGraw-Hill, New York, NY, 2000.

[28] Utterback, J., *Mastering the Dynamics of Innovation*, Harvard Business School Press, Boston, MA, 1994.

[29] Wheelwright, S. and Clark, K., *Revolutionizing Product Development: Quantum Leaps in Speed, Efficiency, and Quality*, The Free Press, New York, NY, 1992.

9 APPENDIX – THE MANUFACTURING SYSTEM DESIGN DECOMPOSITION




FR-12 Minimize manufacturing costs
FR-13 Minimize investment over production system lifecycle
DP-12 Elimination of non-value adding sources of cost
DP-13 Investment based on a long term strategy
FR113 Meet customer expected lead time
DP113 Mean throughput time reduction
FR-121 Reduce waste in direct labor
FR-122 Reduce waste in indirect labor
FR-123 Minimize facilities cost
DP-121 Elimination of non-value adding manual tasks
DP-122 Reduction of indirect labor tasks
DP-123 Reduction of consumed floor space
FR-T1 Reduce lot delay
FR-T2 Reduce process delay (caused by $r_a > r_s$)
FR-T3 Reduce run size delay
FR-T4 Reduce transportation delay
FR-T5 Reduce systematic operational delays
FR-D1 Eliminate operators' waiting on machines
FR-D2 Eliminate wasted motion of operators
FR-D3 Eliminate operators' waiting on other operators
FR-I1 Improve effectiveness of production managers
FR-I2 Eliminate information disruptions
DP- T1 Reduction of transfer batch size (single-piece flow)
DP-T2 Production designed for the takt time
DP-T3 Production of the desired mix and quantity during each demand interval
DP-T4 Material flow oriented layout design
DP-T5 Subsystem design to avoid production interruptions
DP-D1 Human-Machine separation
DP-D2 Design of workstations / work-loops to facilitate operator tasks
DP-D3 Balanced work-loops
DP-I1 Self directed work teams (horizontal organization)
DP-I2 Seamless information flow (visual factory)
FR-T21 Define takt time(s)
FR-T22 Ensure that production cycle time equals takt time
FR-T23 Ensure that part arrival rate is equal to service rate (r_a=r_s)
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-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
DP-T21 Definition or grouping of customers to achieve takt times within an ideal range
DP-T22 Subsystem enabled to meet the desired takt time (design and operation)
DP-T23 Arrival of parts at downstream operations according to pitch
DP-T31 Information flow from downstream customer
DP-T32 Design quick changeover for material handling and equipment
DP-T51 Subsystems and equipment configured to separate support and production access req'ts
DP-T52 Ensure coordination and separation of production work patterns
DP-T53 Ensure coordination and separation of support work patterns
DP-D11 Machines & stations designed to run autonomously
DP-D12 Workers trained to operate multiple stations
DP-D21 Machines / stations configured to reduce walking distance
DP-D22 Standard tools / equipment located at each station (5S)
DP-D23 Ergonomic interface between the worker, machine and fixture
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
DP- T221 Design of appropriate automatic work content at each station
DP- T222 Design of appropriate operator work content/loops
DP-T223 Stagger production of parts with different cycle times