THE SUSTAINABLE MANUFACTURING SYSTEM DESIGN DECOMPOSITION

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SYMBOLS

PFW	Purdue Fort Wayne
SE	Systems Engineering
CSD	Collective System Design
MSDD	Manufacturing System Design Decomposition
SMSSDD	Sustainable Manufacturing System Design Decomposition
SMSDDQ	Sustainable Manufacturing System Design Decomposition Questionnaire
AD	Axiomatic Design
FR	Functional Requirement
PS	Physical Solution
FRm	Measure for Functional Requirement
PSm	Measure for Physical Solution
PDCA	Plan-Do-Check-Act
CI	Continuous Improvement

ABSTRACT

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With the growing importance of the manufacturing sector, there is a tremendous demand for finding innovative ways to design manufacturing systems. Although several design methodologies are available for devising the manufacturing systems, most of the changes do not sustain for a longer period. Numerous elements contribute to issues that impede sustainability in manufacturing industries, such as the common design approach of applying solutions without understanding system requirements and appropriate thinking processes.

With a Sustainable Manufacturing System Design Decomposition (SMSDD), the precise pitfalls and areas of improvement can be well understood. The SMSDD fosters members in the organization to collectively map the customer's needs, identifying the requirements of the system design and the associated solutions. In this thesis, SMSDD is developed to design manufacturing systems for maximizing the potential of an enterprise to create an efficient and sustainable manufacturing system.

In addition to being able to design new manufacturing systems or to re-design existing manufacturing systems, the SMSDD provides a potent tool to analyze the design of existing manufacturing systems. SMSDD uses the Collective System Design Methodology steps to design a manufacturing system for leading to efficient and sustainable manufacturing system. Therefore, SMSDD can apply to a broad range of manufacturing systems. A questionnaire was developed to evaluate the existing manufacturing system design and new system designs for sustainability. The Questionnaire provides a graphical representation of the degree that requirements of the system are achieved from the viewpoint of the SMSDD.

CHAPTER 1. INTRODUCTION

Manufacturing is the production of merchandise for use of sales using labor, machines, tools, chemical, and biological processing or formation. [1] Manufacturing is the organized activity devoted to the transformation of raw materials into marketable goods. [2]. Manufacturing is the process in between customer orders and desirable outputs. The manufacturing organization is an organization that integrates the raw materials, labor efforts, technologies, machines, and other sub-systems for the ability to produce and reproduce customer ordered output products.

In the past century, the manufacturing sector has not only increased tremendously but has also contributed a vital role in the economic side. The best example of the importance of the manufacturing sector is the Gross Domestic Product (GDP) of the United States in 2013. When the manufacturing sector generated more than 34.4% of U.S. GDP. [1]. Due to the situation, the manufacturing field has gained importance, as well as competition over time which has lead industries to develop new technologies and methodologies.

Despite new technologies and disciplines, many industries struggle to be a successful manufacturing system. Some research evidence that the chief reason for struggling is because industries applying solutions to the floor without understanding the system requirements. This thesis develops the methodology for designing manufacturing systems for sustainable manufacturing system.

1.1 Definition of a Sustainable System

The manufacturing system can be viewed as a transformation process that converts a set of inputs into a set of outputs. Thomas M. Shortell refers to the system as a combination of interacting elements organized to achieve sets of purposes [3]. The inputs and outputs of a system are the main interfaces between the system and the outside world. The process is the totality of systems elements including objects and relationships. [2] The sustainable system is a system that continues fulfilling the customer's needs and keeps going over a while without interruption.

1.2 Research Objective

This thesis's primary objective is to investigate and propose a design methodology to achieve a sustainable manufacturing system with the help of Collective System Design and 7 Functional Requirements (FRs). Functional Requirement defines "what" the system must achieve to meet a customer need. Collective System Design and the 7 FRs are further discussed in detail in Chapter 2.

The specific questions that this thesis will seek to answers include:

1. What is a sustainable manufacturing system?
2. What approach should enterprise have to become a sustainable system?
3. What kind of thinking leads to sustainability in Manufacturing Systems?
4. What are the requirements for becoming a Sustainable Manufacturing System?
5. What framework is needed to design manufacturing systems?
6. What are the solutions to fulfill the system's requirements?
7. What is the common platform to effectively communicate information across the industries?

The design of manufacturing systems is a complex assignment, many industries tend to implement direct solutions without defining the system requirements. Even though many such direct solutions are useful, but often solutions are not suitable due to a lack of design framework behind it. Designing and re-designing a manufacturing system in the absence of defining requirements often leads to unsatisfactory results.

According to Dr. Cochran, G. Schmidt, and M. Hensley, less than 10% of the industries that implemented lean, can sustain changes in the system next three years. There is a need to organize, understand, educate, and collectively agree on the objectives and their solutions. [4], [5] [6].

After the success of the Toyota Production System in the 20th Century, Lean as the term became famous, and many manufacturing facilities desired to achieve the same output as the Toyota Production System. Lean Manufacturing is a given term to a broad set of management and manufacturing methods first used by Toyota to achieve a system for low-cost production of automobiles [7]. In an attempt to achieve 'Lean', those people form facilities struggle. The reason is the misconception between output and tool. People from industries see lean as a tool. Instead of the tool, lean is an output of efficient system design. Because of this misconception, industries replicate the Toyota Production System by acquiring Just-In-Time, Kanban, Poka-Yoke, Single Minute Exchange of Die (SMED), Single Piece Flow, Kaizen, 5S, Cellular manufacturing, etc. Due to this copying approach, engineers miss out on the opportunity of defining the system's requirements and their respective suitable solutions [7].

In statistical research, it is determined that ninety-five percent of the lead time is consumed waiting for the next operation or transportation time; the lead time is the amount of time that is taken from the moment a customer orders placed to the moment the product is out for delivery [8]. In remaining only five percent of the lead time, again only 30 percent of 5% lead time value-added operations are done, and rest time is consumed for non-value-added operations. Customers are willing to pay for value-added operations such as milling, drilling, painting, and forging [9]. Whereas customers are not willing to pay for non-value-added operations like transportation, loading, unloading, inspection, and rework [9]. Not having a structured designing methodology leads to the poorly designed, ineffective systems and lead to problems. Therefore is need developing a comprehensive framework that guide practitioners to design manufacturing system for sustainability.

The thesis provides a system design methodology based on the Collective System Design for sustainability, in the thesis referred to as Sustainable Manufacturing System Design Decomposition (SMSDD). Sustainable Manufacturing Design Decomposition uses axiomatic design to communicate a general set of objectives for a sustainable manufacturing system. The SMSDD integrates Flame Model, Collective System Design, the idea of the 7 Factional Requirements, and Manufacturing Design Decomposition to create a structure for relating the floor level design decisions to top-level system decisions. The research provides argument that Sustainable Manufacturing System Design Decomposition leads manufacturing system to become sustainable.

1.3 Research Hypothesis

The null hypothesis Ho: is that using the Sustainable Manufacturing System Design Decomposition (SMSDD) to design a manufacturing system does not lead Using the Sustainable Manufacturing System Design Decomposition (SMSDD) to design a manufacturing system does not lead to an efficient and sustainable manufacturing system. The alternate hypothesis of this thesis Ha: is that using the Sustainable Manufacturing System Design Decomposition (SMSDD) to design a manufacturing system does lead to to an efficient and sustainable manufacturing system. The main objective of this thesis is to provide the logical argument to reject the null hypothesis in favor of the Ha. Due to the vast topic and required a huge amount of time, no use cases were taken, instead this thesis focuses on developing the Sustainable Manufacturing System Design Decomposition and creates the SMSDD Questionnaire to attempt to provide the burden of proof to argue why the null hypothesis can be rejected in favor of the alternative.

Ho: Using the Sustainable Manufacturing System Design Decomposition (SMSDD) to design a manufacturing system does not lead to an efficient and sustainable manufacturing system. .

Ha: Using the Sustainable Manufacturing system Design Decomposition (SMSDD) to design a manufacturing system does lead to an efficient and sustainable manufacturing system.

1.4 Thesis Content

The thesis begins by addressing the importance of the manufacturing systems and the need for a sustainable manufacturing system. Chapter 2 reviews the existing design methodologies including Collective System Design (CSD), Flame Model, Axiomatic Design, Manufacturing System Design Decomposition (MSDD), and the idea of the 7 Functional Requirements (7 FRs). The second Chapter introduces some of the solutions of the Toyota Manufacturing System and provides a basic understanding of the Systems language used in the fourth chapter. Third chapter describes the importance of creating a new design decomposition by showing the limitations of MSDD and the importance of using Collective System Design with Axiomatic Design The fourth chapter describes the Application of Axiomatic Design and proposes a new design framework named Sustainable Manufacturing System Design Decomposition (SMSDD). To support the designed Sustainable Manufacturing System Design Decomposition in the third chapter, chapter fifth builds the data collection in a form of the SMSDD Questionnaire based on SMSDD.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

Chapter 2 provides a literature review to address Sustainable Manufacturing Systems. The Chapter investigates the definition of the manufacturing system, Manufacturing System Design Characteristics, Industrial revolutions, Flame Model, Collective System Design, Axiomatic Design, System Design Language, Manufacturing System Design, and 7 Functional Requirements (7 FRs) to provide the background research information for the argument made in Chapter 3 and Chapter 4.

2.2 Manufacturing System

The manufacturing system consists of multiple operations and processes (tooling, material handling, information handling, etc) and physical elements required to manufacture products. Dr. Cochran describes that the Production System consists of all enterprise activities including Sales, Marketing, distributors, suppliers, delivery, product engineers, etc that assist a Manufacturing System [10]. Below figure 2.1 illustrates the definition of a Manufacturing System . In the figure, inputs are orders, time, material, information, and energy; and output is products, services, information, and profit; in between in the process, there is work being done on inputs. Manufacturing System is closed-loop system information is fed back based on measurable outputs [10]. Please refer to figure 2.1.

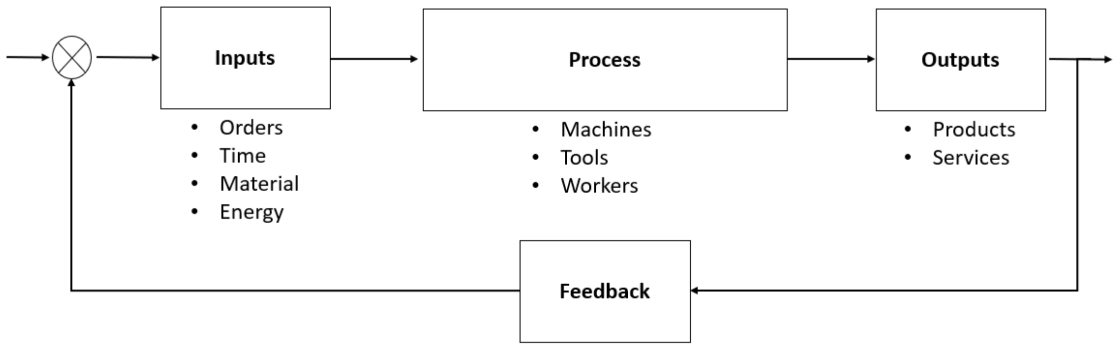

Fig. 2.1. Definition of a Manufacturing System Figure

2.3 Manufacturing System Design Characteristics

Dr. Cochran states that every Manufacturing System Design has four major characteristic elements: Flexibility, Controllability, Efficiency, and Uniqueness [10], [11]. Flexibility is the ability to change according to changes in requirements. Flexibility is defined by Black as how a manufacturing system can adapt to change [11]. Controllability is the way that information is handled in a system. Efficiency is the effectiveness of systems components to add value to the product that it manufactures and the elimination of all waste [12]. Uniqueness is the characteristic that identifies the product that the manufacturing system as able to manufacture [12].

2.4 Industrial Revolutions

Industrial Revolutions are the successful changes that transpired due to series of improvements made in manufacturing system design [10] [13]. The First Industrial Revolution provided a basis for manufacturing system by introducing machines, the Second Industrial Revolution introduced mass production, unclear job layout, and the moving assembly line. The Third Industrial Revolution manufacturing became low cost and high quality with help of Just In Time (JIT) [14]. Revolutions don't happen overnight [10]. Revolutions are the results of the new and different Functional Requirements and their Solutions, and in the case of Toyota Production System FRs were low cost and high quality.

The First Industrial Revolution started approximately in the late 18th century, through steam engines in textile manufacturing. Many fields transitioned from handcrafting methods to machining methods and job shops. First Industrial Revolution commenced innovations in machine designs and tools for high speed because of innovation of new technologies such as steam or water power engines and belt drive machines.

In the early 20th century, a vital role is played by the Ford Company. Ford started mass production with the because of the 98% pre-orders demand of Ford vehicles The modernisation of standardizing and interchangeability from the first Industrial Revolution supported the manufacturing sector to become a high-speed production with better quality. Competition between manufacturing sectors helped companies to understand the value of customers and began providing low-cost products, better quality, and customized products as the customer ordered. At the end of the Second World War, a variety of products and small order lots were introduced to customers [10]. To overcome small lot orders issues, variations in products and hindrances of mass productions, Toyota Production System came up up with idea of Leveling. Products at a low price, high quality, on-time delivery, produce with flexibility and consideration of customers were the goals of Toyota production System. Toyota originated the principles as Single Minute Exchange Die, Andon, Kanban, Cellular manufacturing, Poka-Yoke, Pull system, 5S, balance production, etc. These principles are explained in the next topic.

2.5 Toyota Production System

Toyota played a major role in the Third Industrial Revolution. According to the Toyota Production System, there are seven types of waste that exist in manufacturing. Seven types of waste are Overproduction, Inventory, Transportation, Processing, Motion, Waiting, and Making defects.

Overproduction occurs when a system produces excess amounts of parts of products than the number of ordered products. Overproduction causes a waste of manpower, time, material, time, and inventory waste. Having an excess inventory is seen as a symptom of having a poorly designed system. Reasons can be large lot production, long setup time, bottleneck, unbalanced system, not level production and, etc. Moving parts from one station to another place takes time, energy, and cost. Transportation is a non-value added operation. Instead of improving the techniques for transportation, a great way to deal with transportation waste is to reduce transportation or eliminate the transportation. The motion of machines, workers, and tools; motion waste occurs because the operator has to move from one place to another to search for tools, replacement of machines, doing operations, and many more. Waiting waste occurs when workers, machines, or parts are waiting for the next step. making defect waste occur when a product is found to have flaws in it after production occurs. The affected parts must be replaced or reworked completely resulting in additional costs, delays, and possible safety issues.

5 S (Sort,Set In Order, Shine, Standardize and Sustain)

5S after its alliterative core tenets—sort, set in order, shine, standardize, and sustain—the methodology originated on the Toyota assembly line, then went on to become a fundamental element of the lean manufacturing wave that swept the world in the 1980s [15]

Seiri (Sort): To clearly separate necessary things from unnecessary ones and abandon the latter.

Seiton (Set In Order): Organize, neatly arrange and identify things for ease of use. Everybody must be able to find the required tools quickly. Everything has to be in its determined place.

Seiso (Shine): Always clean up; to maintain tidiness and cleanliness.

Seiketsu (Standardize): Systematic to have workers make a habit of always conforming to rules

Shitsuke (Sustain): Sustain to have workers maintain the 3S mentioned above (Seiri, Seiton, Seiso).

2.6 Collective System Design

Dr. Cochran originated the idea of the Collective System Design methodology in the mid-2000s. Collective System Design (CSD) is an approach to have a common goal and working collectively to satisfy customer needs [16]. Cochran claims that Collective System Design attempts to create a sustainable organization to maximize the potential of an enterprise [17]. Collective System Design (CSD) is an approach that can be applied for design varieties of systems; for example manufacturing, hospital related designs, disease reversal, course Development, and organizational development and each phase of the acquisition life cycle [18], [19].

Collective System Design has a principle, as simple as its nomenclature says "Collective", Cochran recognized that collective agreement is an integral function in an organization. according to CSD, in ideal manufacturing system all department should work together, and if there is any one or more departments are not contributing to the process then, system will undergo problem with maintaining sustainability. Collective System Design is a methodology that embraces design to the logical process of "what" has to be achieved, and "how" can it be achieved. The framework of Collective System Design (CSD) consists of five elements: (1) the Flame Model of Systems, (2) the CSD Language, (3) the CSD Design Map, (4) Standard Work, and (5) the CSD Map integrated with a Plan-Do-Check-Act (PDCA) Learning Loop [20]. CSD offers systematic and chronological steps to Enterprises that should implement collectively for Continuous Improvement and successful adaptation. CSD has 12 steps as follows

1. Senior Leadership Makes A Conscious Choice to Change
2. Establish Tone and Values
3. Define Stakeholders and System Boundary
4. Identify Customer and their Needs
5. Determine Functional Requirements
6. Map the physical Solutions (PSs) to FRs
7. Define Performance Measures (FRm and PSs)
8. Define Organization Structure based on CSD Map
9. Establish Actions and Work by Continuous Improvement: Plan, Do, Check Act (PDCA)
10. Evaluate the benefit of achieving FRs
11. Prepare Resource Reallocation Plan
12. Feedback for Sustainability and Growth

CSD Methodology is the cycle of the process starting from step 1 to step 12, and reverting to step 1. Step 1 initiates the process by questioning the need for changes in the system at the senior leadership level. After a decision made by Senior leadership to change, CSD encourages leadership with all members within Enterprise to establish a positive Tone collectively (CSD step 2). After the major step of establishing tone, CSD encourages to understand the boundary of the System. In the third step, System Boundary and Stakeholders are defined. According to Suh, the components and subsystems in the system, which can be controlled are inside the system boundary, and the components that can not be controlled are the Environment [21].

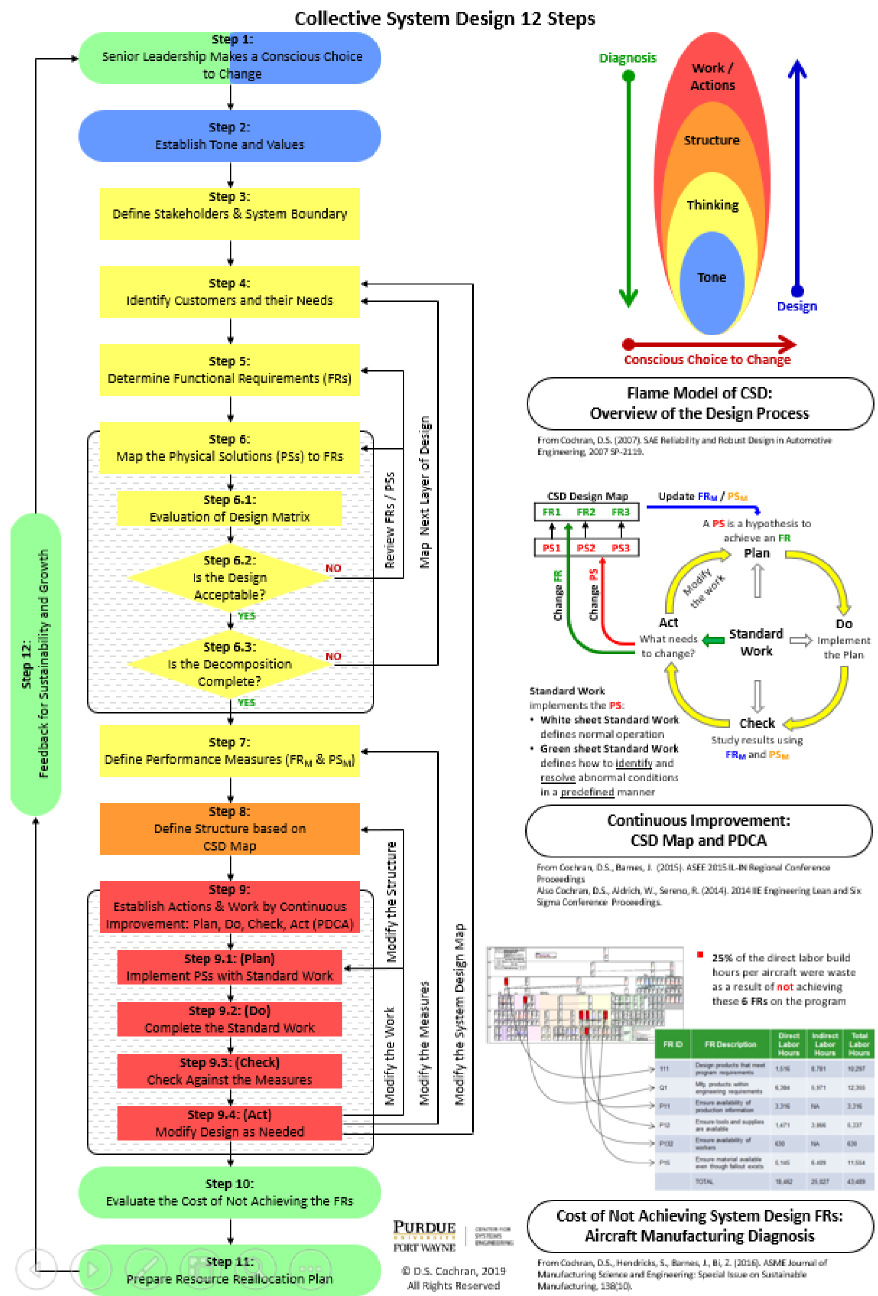

Fig. 2.2. Collective System Design Steps Flow Diagram

The third step helps to understand the system and identify Customers and their needs (CSD 4th Step). In CSD, 4th step is identifying the Customers and their needs. Identifying needs are the most vital part after Tone establishing. The fourth step creates the foundation of CSD thinking by leading towards "Determination of Functional Requirements" (CSD step 5), and then "Mapping the Physical Solutions (PSs) to FRs" (Step 6). "Evaluation of Design Matrix", "Is the Design Acceptable?", and "Is the decomposition Complete?" are the Sub-steps in step 6. Figure 2.2 is a Flow chart Diagram conveys the Collective System Design steps and Decision flows in more detail. CSD 7th Step "Define Performance Measures" is the last step of creating CSD thinking.

In the 8th step of CSD "Define Organization Structure based on CSD Map", all potential Physical Solutions of respective Functional Requirements are collectively obtained from the CSD thinking Map. These lower lever Physical Solutions are drawn to the Physical layout of the organization and help to design a physical structure of the Organization. In the 9th step, Work/ action is established by the PDCA cycle (Plan Do Check Act Cycle) on the floor of the enterprise.

In the Plan phase of the PDCA cycle, Potential Physical Solutions are planned to implement with the assist of the Standard work (cite is needed). Subsequently, all plans to implement PSs must be needed to execute, then need to check against the measures, and then act according to a needed modified design. At the end of the cycle, this feedback needed to update the CSD Thinking map for better performance to meet customer needs and their Functional Requirements. (these steps loops are shown in Figure 2.2). Evaluation of the benefits of Achieving Functional Requirements is the 10th CSD step. The author believes that the "10th step encourages stakeholders and internal customers to perceive the positive outcomes of the implemented steps, and continually motivated to maintain the CSD step cycle.

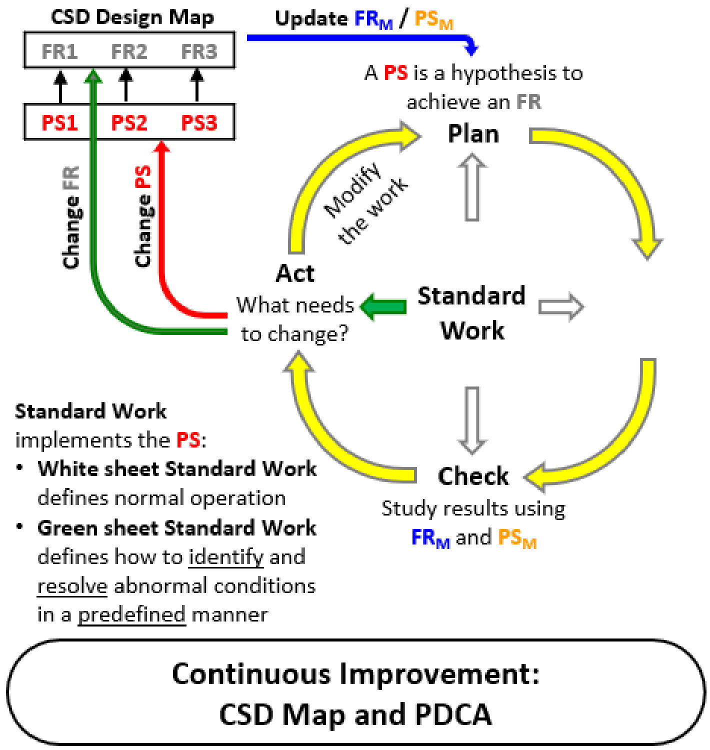

Fig. 2.3. PDCA Cycle

2.7 FLAME Model

Cochran and Smith describe the Flame model as the hierarchy of essential elements of the system: Tone, Thinking, Structure, and work/ Actions. These key elements are present in all the systems and each element has an effect on each other, which causes the state of the system [22]. Work and Actions is the outermost layer of the Flame model. This layer can be easily diagnosed and observed. The further inner layer of the Flame model is Structure, followed by thinking and tone is the innermost layer.

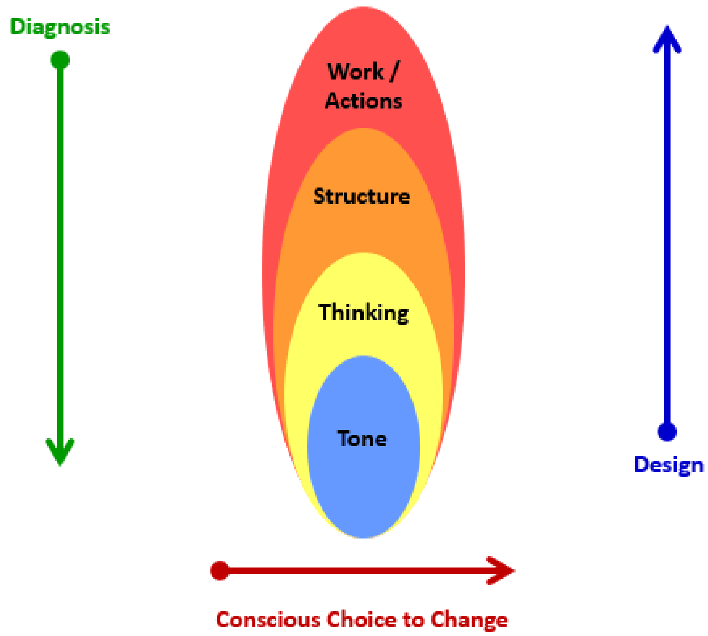

Fig. 2.4. Flame Model

Cochran and Barnes state, “As with the colors of a flame, the model represents that the parts of the system are not separable from the whole. Often the Work / Actions and the enterprise structure (Physical System) are the only parts considered in the design because they are more easily observable. However, the thinking and organizational tone are at the core of the Flame Model" [23]. While the Tone and Thinking are harder to diagnose, therefore CSD methodology suggests tone and thinking should be the base for the enterprise designing process. Establishing the tone and the thinking is done by determining what the system should achieve through the collective agreement of everyone within the system [24].

2.7.1 Diagnosis of the System

Following the Flame Model figure illustrates the way to Diagnosis the system in Figure 2.4. The diagnosis of the system starts with understanding and observing the Work /Actions on the floor. Diagnosis of Work Actions layer is advocates to go on the Gemba Walk, Gemba walk helps to identify problems on the floor. After identifying problems, it is necessary to find the root cause of the issues [25]. According to the literature survey, 95 % of the time, the problems in the systems are faults due to the system itself than the operator's faults. The structure is the next layer to diagnosis after the Work /Actions. Next in the Thinking layer, Functional Requirements and Physical solutions of the systems are identified. At the end, the Tone of people working in the system is evaluated. In retrospect, the diagnosis follows the path towards Tone through Work /Actions, Structure, and Thinking.

2.7.2 Designing of the System

The Flame model illustrates the way of designing the system starting from the Tone, Thinking, Structure, and Work /Actions. Designing phase comes after a diagnosis of the system in the Flame model.

Tone

Once the problems are accepted and understood, it starts with a need for change in the tone of the enterprise. Senior leaders need to have a positive tone. The positive tone should consist of a respectful environment, realize faults are in a system rather with the people, the involvement of all indirect and direct labors for the process of improving the system, and understand the problems are an opportunity for Continuous Improvements. A positive tone encourages attain internal customer's needs that create high morale on the floor and results in meeting external needs [22]. Internal customers are the customers who are inside of the Systems boundary. Deming defines

External customers as the customers who lie outside of the boundary of the system (Systems Environment) [26].

Thinking

Thinking starts after the successful creation of a positive tone, As discussed in the CSD section, thinking has the identification of customers and their needs. Deming categorizes customers into two types: Internal Customers and External Customers [26]. Direct operators and indirect operators within the enterprise are Internal Customers and end customers are the External Customers.

In thinking layer Design Decomposition is created, where Functional Requirements are identified from Customer needs and potential Physical Solutions is collectively decided to fulfill respective Functional Requirements. Design decomposition maps solutions and requirements for better visualization and an easy understanding of the design. Rules for creating Design Decomposition are in depth explained in the next section System Design Language.

Structure

The structure is how the stations are placed on the floor, the organization of the team (Enterprise System Design) [22], and the value stream of the facility. The structure is also dealt with a hierarchy of positions holding up in the system.

Work/ Actions

Work/ Actions is the result of Tone, Thinking, and Structure. Standard work plays an important role in work action because Standard work defines action and implementation of the complete design [22]. Standard Work is defined as organized Haman actions that are efficiently created in chronological sequence to avoid waste (Muda). It is made up of three elements: Takt time, working sequence, and standard in-process inventory. [27]. For Continuous Improvement, PDCA Cycle is required to be implemented at work stations.

2.8 System Design Language

In CSD thinking, a standardized common language is needed for communicating, designing systems structures collectively, sharing concepts, associating knowledge without changing the context, Developing collective skills, and storing information.

2.8.1 Axiomatic Design

The purpose of Axiomatic design is to create a scientifically-based system, to improve design activities by providing the designer with a theoretical foundation based on logical and thought processes and tools.

In the system design process, "What" and "How" are the main questions, Suh defined Axiomatic Design as "Continuous interplay between what we want to achieve and how to achieve it" [28]. Axiomatic Design is a design theory based on two fundamental axioms. The first axiom is to maintain the independence of functional requirements and, the second is to minimize the information content of the resulting design solution [29], [28]. Axiomatic Design is remarked by Suh as "the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through the mapping between functional Requirements (FRs) and Physical Solutions (PSs) [29], [28]".

Functional Requirement is defined as the minimum set of independent requirements that completely characterizes the design goal [28]. Physical Solutions are defined as the solutions of "how to achieve it?" in the form of Physical Solutions Domain that satisfies the specified FRs [28].

Design Domains

In system design language, there are following three domains: Customer Domain, Functional Domain, and Physical Domain. The following Figure 2.5 illustrates the design Domains.

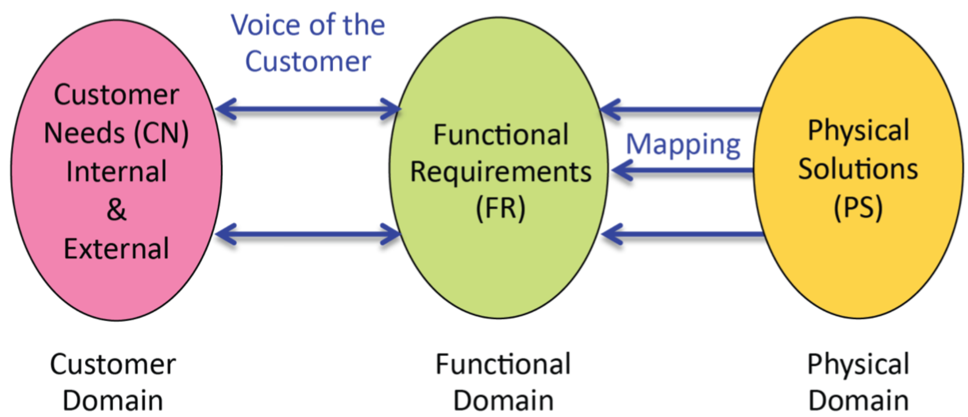

Fig. 2.5. Design domains

The designing process starts with understanding customers and identifying their needs. What customers desire is called Customer Needs. Voice of customers (Customer Needs) must be collectively mapped to the functional domain, where the customer needs are translated into a set of Functional Requirements (FRs). A functional requirement is a customer need that the system should achieve. Functional Requirements should always start with verbs and be solution neutral [23].

Physical Solution is the solution to achieve the respective Functional Requirement. In other words, Physical Solutions deal with "how" to achieve the FRs. Physical Solutions always start with nouns. Figure 2.6 is an example of a design relationship.

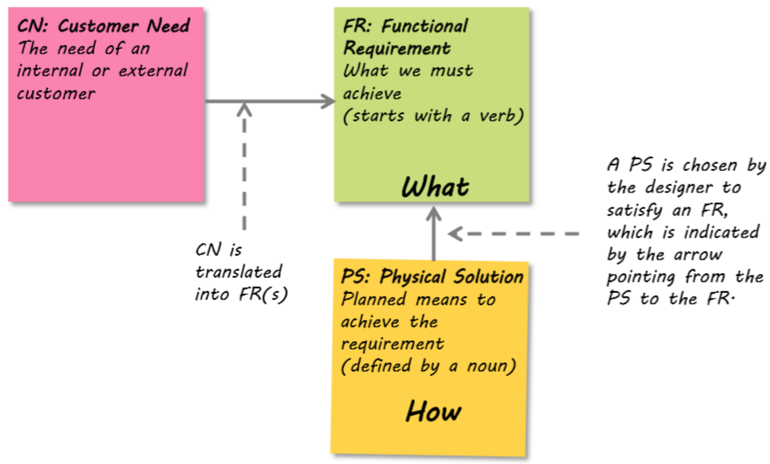

Fig. 2.6. Example of Design Relationship

Performance Measurement

Finding performance measurements is the next step of Collective System Design after establishing FRs and PSs. The addition of measurements on both FRs and PSs. FRm is quantitative information about the required performance of the respective functional requirement. It helps to distinguish whether an FR is satisfied or not. PSm checks whether applied PS is correct or not. This assists the validity of customer needs fulfillment and makes the design process more effective [23].

There are some exceptions cases when FRs and PSs are not measurable and have binary forms. In such cases, FRm and PSm are not required.

System Design Decomposition

The System Design Decomposition is the visual representation of CSD thinking, where Physical Solution and Functional Requirements are mapped with the rules of axiomatic design. FRs and PSs mapping makes the current system easy to understand, helps to design the system collectively, aids to track the impact of a chosen

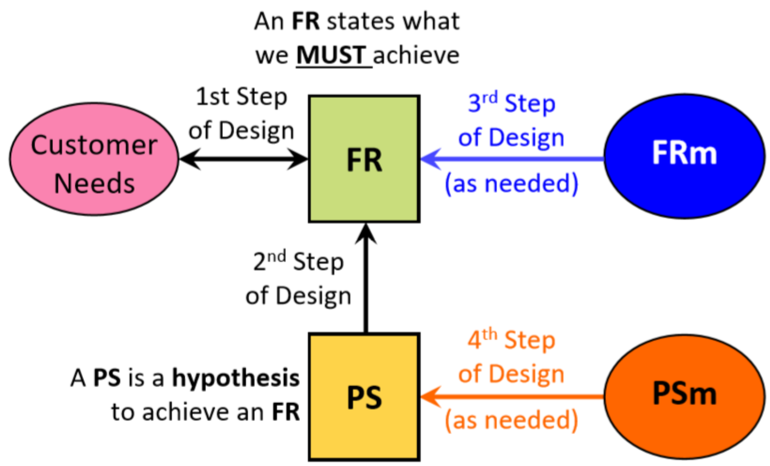

Fig. 2.7. System Design Language

solution to the system, and identifies the scope of the improvements. System Design Decomposition plays an important role in CSD steps 4, 5, 6, and 7.

Steps to create System Design Decomposition

1. Map Customer Needs to Functional Requirements.
2. Choose Physical Solutions to satisfy Functional Requirements.
3. Check for interactions/coupling among the PSs and FRs at the current level.
4. Define a performance measure for the FRs (abbreviated FRm) when applicable.
5. Define a performance measure for the PSs (abbreviated PSm) when applicable.
6. Decompose the design to the next level.

The above steps are used to create System Design Decomposition, the initial four steps are explained earlier in sections Design domain and performance measurements.

Path dependency in the system design is defined as the phenomenon of change in Physical Solution that will affect the achievement of another left-sided Functional

Requirement within the same respective level. Path dependency in decomposition are presented by an arrow drawing from PS to affecting FR, refer to following figure 2.8 Note: In I level, as there is only FR is present, so coupling at the level I is impossible.

The design must be decomposed to the next level, after checking the couplings and interactions. Decomposition can be continued to the next level, only if the design is Path Independent or Path Dependent. In the case of Coupled Design, Redundant Design, and Incomplete Design; design can not proceed for the next decomposition level.

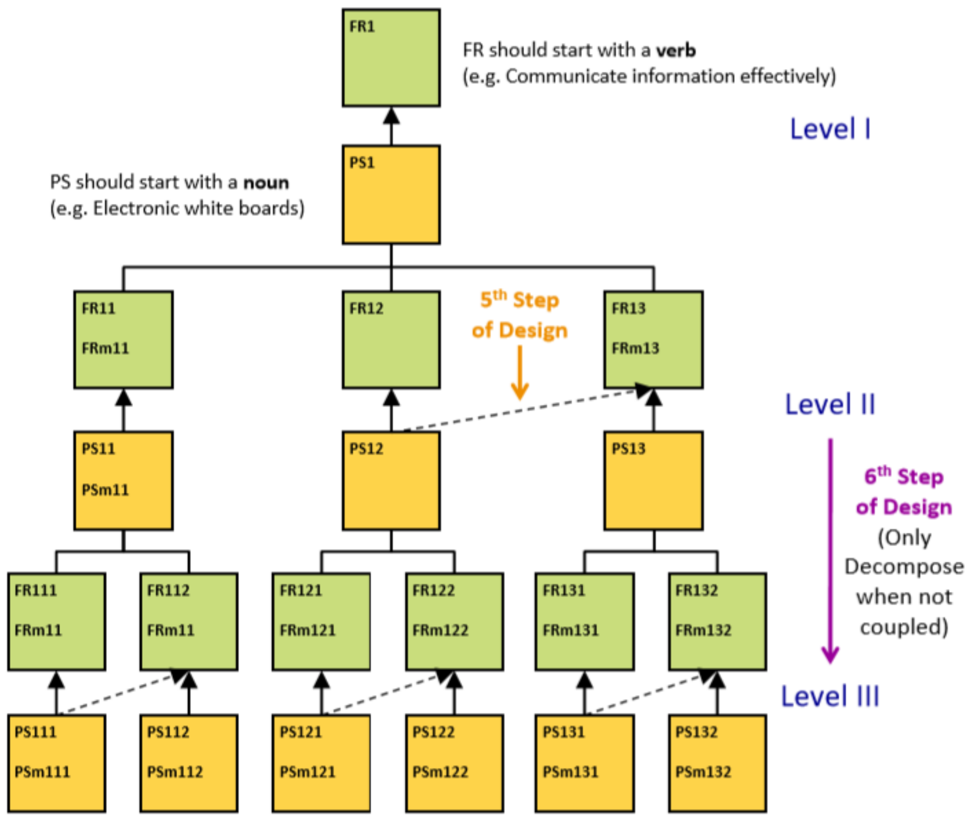

Fig. 2.8. Example of the System Design Decomposition

2.8.2 Types of Design

Uncoupled Design (Path Independent)

In Uncouple Designs, the change of Physical Solutions does not influence other Functional Requirements at the respective level. The outcomes of such uncoupled designs are predictable. Equation 1 represents the design equation for the relationship between FRs and PS within a branch.

$$FRi = [Aij]PSj$$

Where FRi and PSj matrices are Functional Requirements and Physical Solutions respectively, and Aij Matrix is the design relationship the matrix at the specific level of design decomposition.

$$\begin{vmatrix} FR1 \\ FR2 \\ FR3 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{vmatrix} \begin{vmatrix} PS1 \\ PS2 \\ PS3 \end{vmatrix}$$

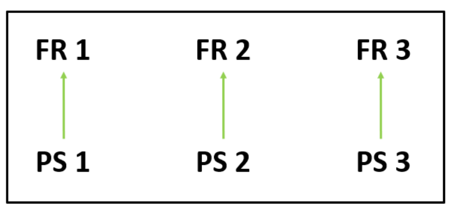

Fig. 2.9. Uncoupled Design

The design with a diagonal matrix is called an uncoupled design [28].

Path Dependent Design (Partially Coupled)

In the Path Dependent Design, a single PS can meet respective FR as well as one or more FRs on right-sided FRs of decomposition to forms a triangular matrix. Path dependency is shown in the following figure 2.10, where PS1 achieves FR 1 and the sets of FRs on the right sides (FR 2, FR3). Suh refers to Path dependent design as a Decoupled design [28]. This design also serves predictability.

$$\begin{vmatrix} FR1 \\ FR2 \\ FR3 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{vmatrix} \begin{vmatrix} PS1 \\ PS2 \\ PS3 \end{vmatrix}$$

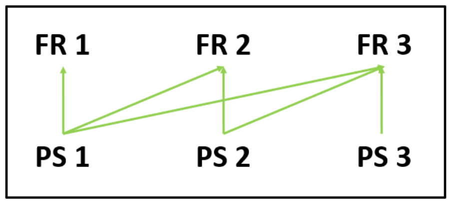

Fig. 2.10. Path Dependent Design

Coupled Design

Coupled design is the design in where PS meets multiple FRs in a crossed manner and forms a complex design as shown in figure 2.11. In the Following example, PS 1 and PS 2 both fulfill FR 1 and FR 2. Such designs do not have predictability. Because of the coupling, it does not allow the system to decompose further, so it is unacceptable at the upper level of decomposition.

$$\begin{vmatrix} FR1 \\ FR2 \\ FR3 \end{vmatrix} = \begin{vmatrix} X & X & 0 \\ X & X & 0 \\ 0 & 0 & X \end{vmatrix} \begin{vmatrix} PS1 \\ PS2 \\ PS3 \end{vmatrix}$$

The following designs are not acceptable and considered as incomplete decomposition.

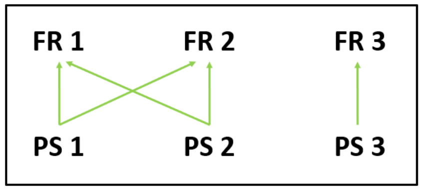

Fig. 2.11. Coupled Design

Redundant Design

$$\begin{vmatrix} FR1 \\ FR2 \\ FR3 \end{vmatrix} = \begin{vmatrix} X & X & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{vmatrix} \begin{vmatrix} PS1 \\ PS2 \\ PS3 \end{vmatrix}$$

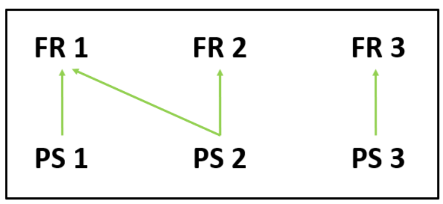

Fig. 2.12. Redundant Design

Incomplete Design

$$\begin{vmatrix} FR1 \\ FR2 \\ FR3 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & X \end{vmatrix} \begin{vmatrix} PS1 \\ PS2 \\ PS3 \end{vmatrix}$$

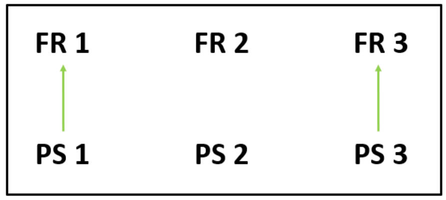

Fig. 2.13. Incomplete Design

2.9 Manufacturing System Design Decomposition

Joachim Linck and Cochran developed the Manufacturing System Design Decomposition (MSDD) at MIT in 2001. The idea behind MSDD was to create the design for a wide range of repetitive and discrete part manufacturing systems [30]. The purpose of MSDD is to (1) separate objectives from the means of achievement, (2) relate low-level activities and decisions to high-level goals and requirements, (3) state the inter-relationships among the different elements of a system design, (4) provide a common platform to effectively communicate this information across the organization.

MSDD is based on Axiomatic Design, Where the top prime Functional Requirement is "FR1: Maximize long term return of investment", and Physical Solutions is " PS1: Manufacturing System Design". PS1 "Manufacturing system Design" is further decomposed till level 6th and resulted in the distinction of six main objectives for manufacturing systems: quality, identifying and resolving problems, predictable output, delay reduction, reduction of operational costs, and investment efficiency. Refer to the following figures 2.14 and 2.15. MSDD is not a tool, but MSDD provides thinking by guiding the need for objective and recognizing the respective Solutions. For example, MSDD discusses waste reduction at direct operations. First, the need for reducing waiting of operators on the machine is notified, and then PS: Human-Machine separation is referred, As shown in figure 2.15

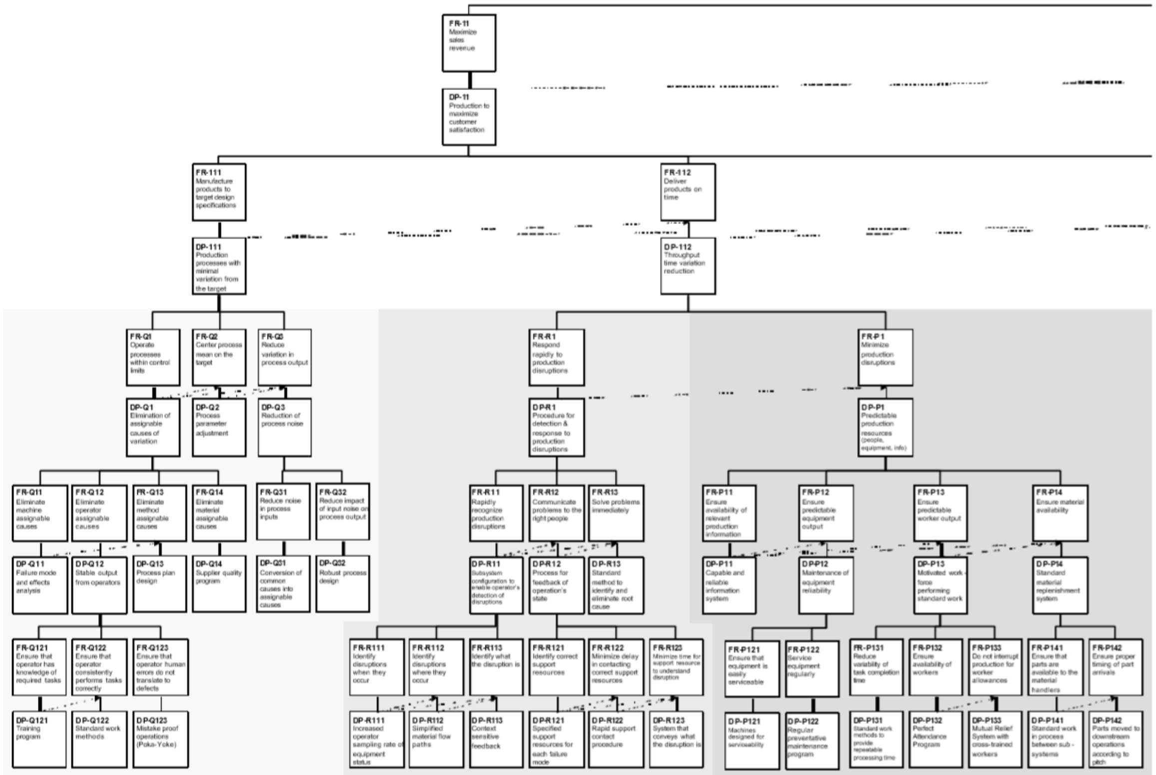

Fig. 2.14. Manufacturing System Design Decomposition

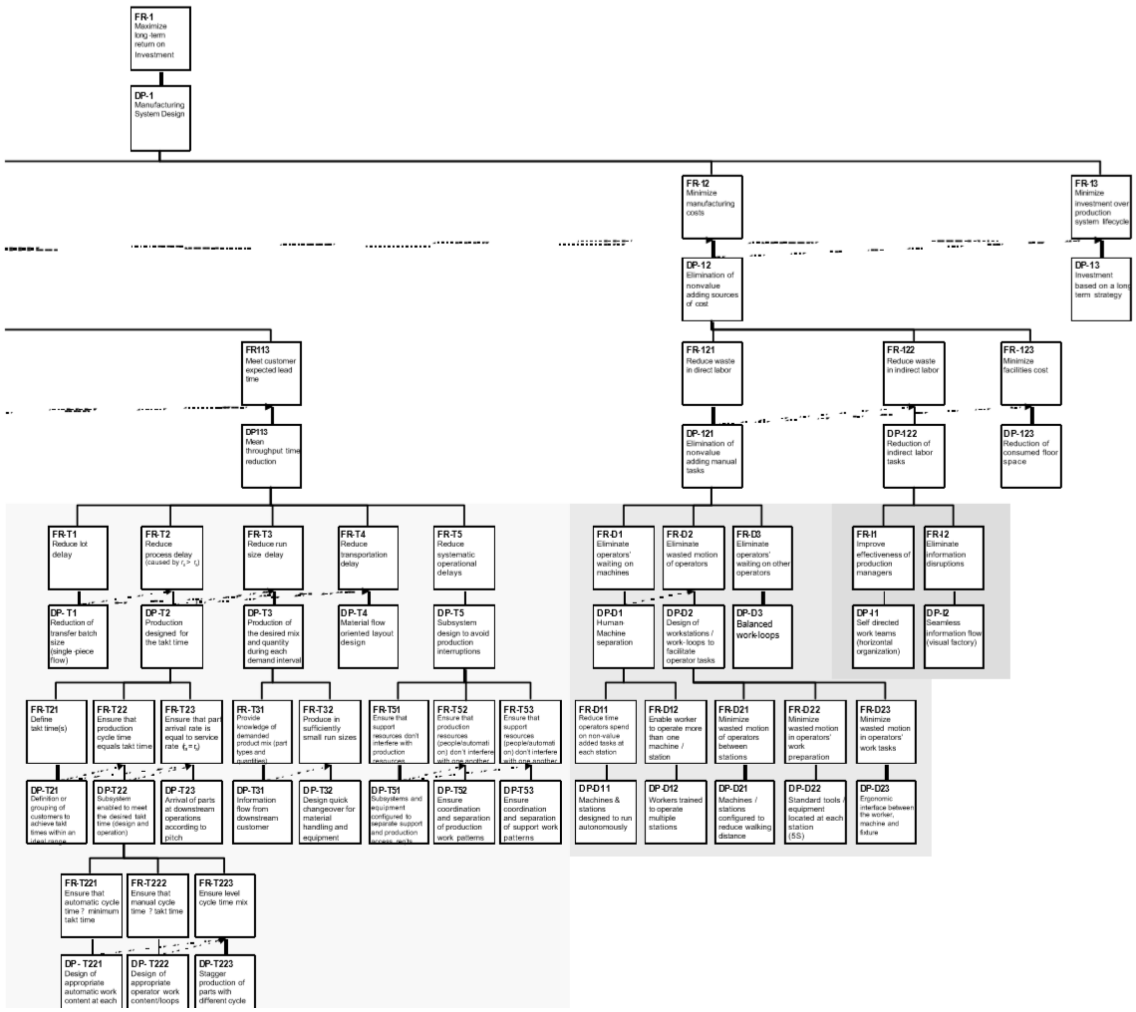

Fig. 2.15. Manufacturing System Design Decomposition

2.9.1 7 Functional Requirements

Every manufacturing system needs to achieve certain sets of Functional Requirements. As the system varies, it does also varies the Functional Requirements. Cochran tossed the term of creating a set of FRs which are needed to every manufacturing plant to transform into sustainable manufacturing system. 5 FRs are derived from MSDD and 2 FR is added from a safety point of view and Continuous Improvements as showed in the following figure 2.16, those collections of necessary FRs are called 7 FRs.

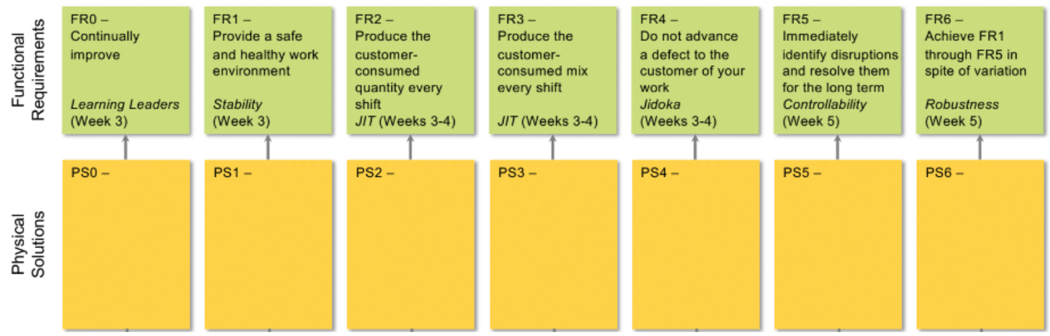

Fig. 2.16. 7 Functional Requirements

Manufacturing System Design decomposition, addition of CSD, and flame prospective to FRs list, these are the following 7 Functional Requirements that are needed to achieve for all manufacturing to become effectively sustainable.

1. FR0 : Continually Improve
2. FR01 : Provide a safe and healthy work environment
3. FR02 : Produce the customer consumed quantity every shift
4. FR03 : Produce the customer consumed mix every shift
5. FR04 : Do not advance a defect to the customer of your work
6. FR05 : Immediate identify the abnormal conditions and resolve them for the long term controllability
7. FR06 : Achieve FR01 through FR05 in spite of the variation

2.10 Summary of the Chapter

In the retrospect of Chapter 2 provides information about the manufacturing System, Manufacturing System Design Characteristics, and Industrial Revolution Toyota Production System for the understanding of the manufacturing sector's design history and the need for the designing framework.

The next half chapter reviews the Collective System Design, Flame Model, System Design language, Manufacturing Systems Design Decomposition, and 7 Function Requirements to acquaint with all designing languages and methodologies information represented in the next chapters.

CHAPTER 3. MOTIVATION FOR SUSTAINABLE MANUFACTURING SYSTEM DESIGN DECOMPOSITION

Current Chapter presents the argument based on literature survey why new design decomposition is should be developed.

3.1 The need for new Design Decomposition

As Collective System Design explained in the literature review, CSD is the right approach to design various types of systems (manufacturing system, health care system, product development, service development, etc). CSD steps are an appropriate method for designing systems, and for manufacturing systems, more detailed and specific steps will be easy for engineers and workers to understand and implement.

The axiomatic design methodology is scientifically based to design by providing designers a theoretical foundation based on logical and thought processes. MSDD is created based on the Axiomatic design approach. Dr. Cochran claims MSDD works effectively for designing manufacturing systems, but the author claims some additions are required to the MSDD design decomposition. In the next section, limitations of the Manufacturing System Design Decomposition are explained. The motivation for the new design decomposition is to minimize the limitations of the MSDD and include the CSD methodology.

3.2 Limitations of the Manufacturing System Design Decomposition

The limitations of the Manufacturing System Design Decomposition are stated below:

1. The Manufacturing System Design Decomposition is created to satisfy the topmost Functional Requirement, FR 1: "Maximize the long-term return on investment" which is the prime goal of the MSDD. For designing a sustainable manufacturing system the topmost FR should be FR1 "Design Sustainability for Manufacturing Industry."

2. Manufacturing Systems Design Decomposition is decomposed until the specific solutions. Those specific solutions narrow down the application in industries.

3. The MSDD is completely decomposed till the bottom levels. Therefore a fully decomposed design decomposition does not allow engineers and workers to design their system. If people from the system are aware of FRs behind PSs, it successfully implements PSs for long-term sustainability.

4. Note that the focus of the PSs and subsequently of the complete decomposition is on the manufacturing aspects of an enterprise. While other areas such as marketing and product development positively influence the return on the enterprise's investment, the MSDD limits attention to core aspects of manufacturing.

5. MSDD was developed on assumption that all required resources are available in the system, it is pre-assumed that the product design and production machines are the at best condition. Manufacturing System Design Decomposition stands on the assumptions made with product and production machine resources that may cause hurdles and future management problems. It is needed to update the MSDD and add Product design and machine resources design aspects to deal with these issues.

6. To increase the number of sales, MSDD does not cover product designing. However, product design is as equally responsible as manufacturing to increase customer satisfaction.

7. MSDD was created before the CSD methodologies. Hence the Safety, Tone, And Continuous improvement of such essential elements are not covered by MSDD.

8. MSDD does cover the manufacturing system's thinking side but misses how to implement the solutions on the floor.

9. Methods and training workers are well explained in MSDD. Nevertheless, the selection of workers is not mentioned.

3.2.1 Need to Define System Boundary as Functional Requirement

According to the definition of the manufacturing system and production system (stated in chapter 2), the Manufacturing system consists of machines, tools, inventory, materials, maintenance team, direct labors, manufacturing engineers, quality engineers, time investment, Standard Work instructions, and sets of operations. The production system includes sales, supplier and purchasing team, product engineering, shipping, administration, and other sectors for supporting Manufacturing [10]. For collective designing, it must to participate in all departments from the enterprise, instead of only the manufacturing department. The below figure renders all major departments of the enterprise.

In Collective System Design, step 2 is "Define Stakeholders and System Boundary". All sub-systems in the boundary share the common prime goal and support the cooperative working principle. However, the manufacturing subsystem is a huge part of the system, and actual production occurs in the manufacturing subsystem. Therefore, most engineers and administrators concentrate on the Manufacturing subsystem.

In System Architecture, the view is "A representation of a complete system from the perspective of sets of concerns." And, Viewpoint is "the conventions of the system from a specific set of concerns." While in this process designers miss out on the remaining subsystems and lose a collective working principle.

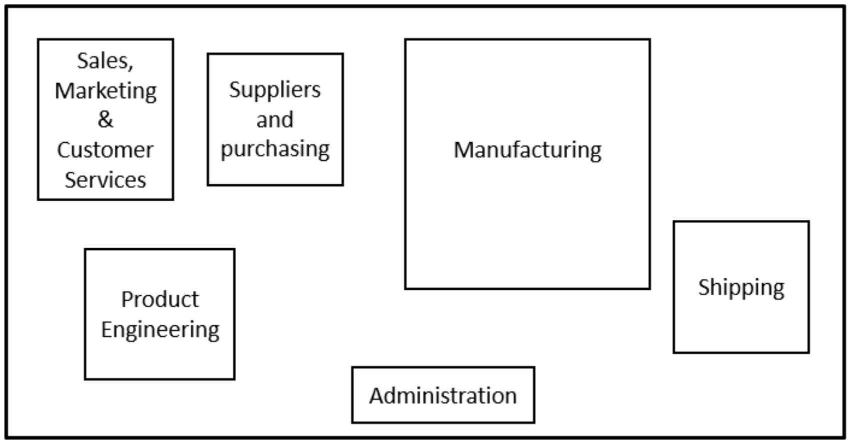

Fig. 3.1. System Boundary

The resulting design created from viewpoints does not cover the connections between subsystems. For example, sale affects suppliers and manufacturing, where product design and manufacturing affects sale, respectively.

To maximize sales, product design, sales department, and manufacture department contribute too. All departments work together for the same higher goal. In this way, it is more crucial to have a collective agreement of all departments.

3.2.2 Importance of Functional Requirements

The new design decomposition should more emphasis on FRs than PSs. There can be multiple possible PSs for a single Functional Requirement, and designers must identify the most suitable solutions according to the system's point of view. From those top-level PSs can vary and depending upon suitable PSs selection bottom FRs vary. The author makes the argument that PS is essential, but Upper-level FRs are more common for all manufacturing. Engineers must understand to create a system design according to respective system boundaries and conditions. The following figure 3.2 shows the lean production framework, and Physical Solutions implemented in Toyota. In 1999, Suzuki of TRW to design a lean manufacturing plant, Suzuki came

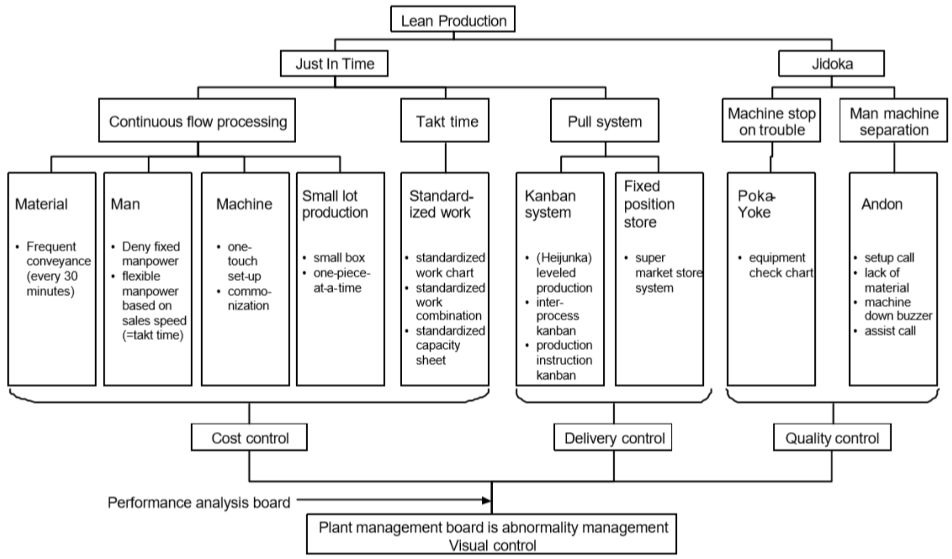

Fig. 3.2. Lean Production Framework (Suzuki, 1999)

up with the above framework shown in figure 3.2. According to Suzuki's framework, Lean production can be attained or achieved by the successful implementation of Just In Time and Jidoka. To design Just In Time, in-plant continuous flow, small-lot production, Takt time, pull system; are needed to apply. Moreover, for the successful achievement of Jidoka, Poka-Yoke and Andon have to be implemented. [31]

Toyota House model figure shown in 3.3, illustrates the design system towards stability, Robustness, and contractility of the manufacturing system [32]. Factors in the Toyota House model is similar to the Lean Production Framework by Suzuki.

The above figures (3.2, and 3.3) depict Physical Solutions of sustainability and waste elimination, and most of the Solutions from MSDD are the same as those shown in the above diagram. The only difference in MSDD is that design decomposition shows the Function Requirements behind those physical solutions. In the MSDD, the bottom level PSs are the output of the top Functional Requirements.

Therefore it is necessary to understand the FRs behind the chosen PSs for sustaining in enterprise for the long term.

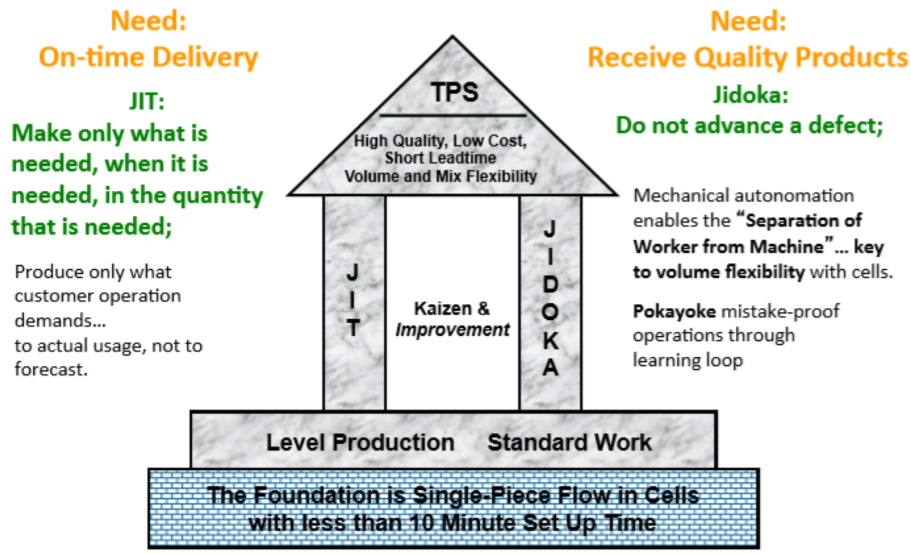

Fig. 3.3. Toyota House Model

3.3 Summary of the chapter

This chapter describes the importance of creating a new design decomposition by showing the limitations of MSDD and the importance of using Collective System Design with Axiomatic Design. MSDD has most FRs, and PSs are focused on manufacturing rather than the whole Enterprise. If all departments share the same goal and are connected, designing the Collective System is necessary. This heroin makes the argument that for sustainability and to achieve the function requirements, system boundaries are needed to expand.

CHAPTER 4. DESIGN FOR SUSTAINABLE MANUFACTURING SYSTEM

This chapter represents the Sustainable Manufacturing System Design Decomposition (SMSDD) inspired by Manufacturing System Design Decomposition. SMSDD uses the FLAME model, CSD Steps and Axiomatic Design. The development of the SMSDD is based on design methodology of axiomatic design.

The need for Sustainable Manufacturing System Design Decomposition

Most of the changes implemented in industries do not sustain until the next 3 years of implementation, and very few changes remain in the system; This is a common phenomenon that occurs due to blindly accepting or implementing Physical solutions. If the new Physical Solutions are implemented by understanding the Function Requirements behind them, it helps sustain the changes and aids in changing culture.

4.1 Application of Axiomatic Design for the Creating Sustainable Manufacturing System Design Decomposition

Followings are the steps of creating SMSDD:

1. Identification of the supreme need
2. Conversion of the need into Functional Requirement
3. Determination of the Functional Requirement
4. Collection and Analysis of possible Physical Solution
5. Selection of suitable Physical Solutions

6. Clarification of relationships between the PSs and FRs to determine the design matrix

7. Continuation of decomposition till it is required

Design decomposition starts with considering designing a sustainable system, then converting Needs into Functional Requirement and Selection of suitable Physical Solutions. In creating design decomposition, once FR is identified, there can be multiple PSs that can help fulfill the respective Functional requirement. Therefore it is questioned that "is the matrix coupled?" If the matrix is coupled, then another possible PS is considered, based on the PS, which does not couple the matrix and satisfies the FR that PS is selected as suitable Physical Solution. These steps are continued till final PSs are refined and can not be further decomposed.

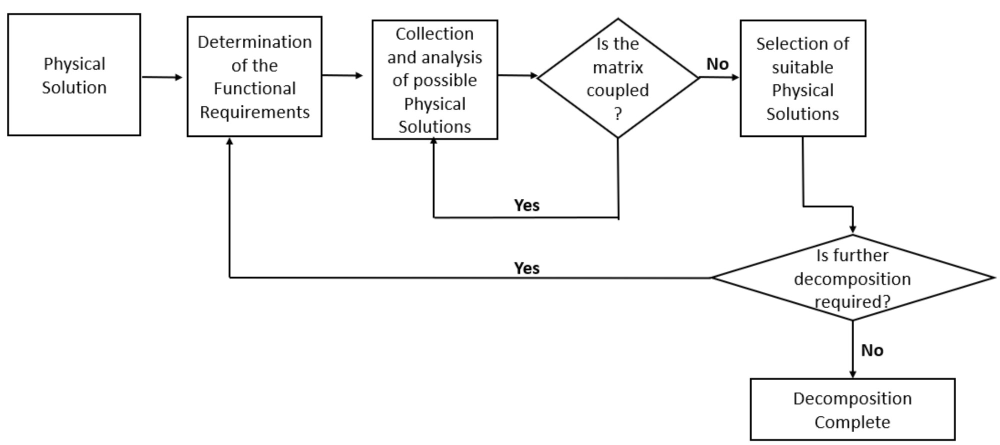

Fig. 4.1. Design steps for further decomposition of bottom most Physical Solutions

The above diagram 4.1 renders the design steps for are taken for creating Sustainable Manufacturing System Design decomposition of the bottom most Physical Solutions.

4.2 Sustainable Manufacturing System Design Decomposition

SMSDD and 7 FRs Concept inspire sustainable Manufacturing System Design Decomposition (SMSDD). The SMSDD is created to provide the framework for a large variety of manufacturing facilities. SMSDD covers all factors including understanding the current system, Tone, safety, resource planning, quality, on-time delivery, production despite variations, and eliminating non-value-added operations.

The outcome of Sustainable Manufacturing System Design Decomposition includes six significant factors: Understand the current system, Tone, thinking map, organization structure, and implementing physical solutions as shown in 4.2. The six areas provide key elements of SMSDD and are discussed further in detail in the next sections.

The SMSDD is designed for a wide range of manufacturing systems. Hence, most of the bottom level PSs are not decomposed completely. The reason is as the system varies, then respectively, Physical Solutions also changes. Moreover, incomplete decomposition allows the organization members to participate in the design process and derive their own more convenient physical solutions.

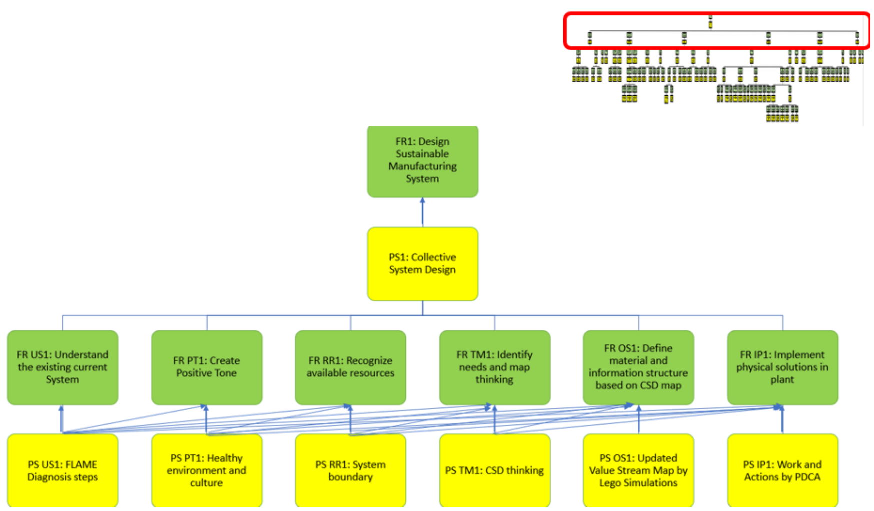

Fig. 4.2. Top Level of Sustainable Manufacturing System Design Decomposition

4.2.1 Top-Level Decomposition

The first and topmost functional Requirement is FR1: “Design Sustainability for Manufacturing Industry” shown in Figure. FR 1 is the prime and most crucial Functional requirement in SMSDD. PS1: “Collective System Design” is a determined physical solution for successfully a compliment of FR1. As mentioned in the literature review, the Collective System Design methodology is adequate for manufacturing system designing. Note that in SMSDD, a collective system is considered as the most suitable Physical Solution, and all below levels are based on (CSD) methodology.

The second level of SMSDD is derived from Collective system design steps: FR US1: “Understand the existing current system,” FR PT1: “Create positive Tone,” FR RR1: “Recognize available resources,” FR TM1: “Identify needs and map thinking,” FR OS1: "Define material and information flow structure based on CSD map,” and FR IP1: “Implement Physical Solutions on the plant.” These 6 FRs are derived from 12 steps of CSD methodology. Each FR has a corresponding PS as shown in 4.2, PS US1: "FLAME Diagnosis steps," PS PT1: "Healthy environment and Culture," PS RR1: "System boundary," PS TM1: CSD Thinking," PS OS1: "Updated Value Stream Map by Lego Simulations," and PS IP1: "Work and Actions by PDCA" Respectively.

In figure 4.2, it can be seen that there are arrows from left-sided PSs to right-sided FRs; these arrows represent the path dependency. Path dependency shows PS affects the FR. for example, "PS US1: FLAME Diagnosis steps" influences all rest FRs. Without having a proper FLAME diagnosis of the current system, the process of creating tone, recognizing resources, mapping thinking, designing the structure, and implementing solutions become critical. Similarly, figure 4.2 renders "PS PT1" affect FR RR1, FR TM1, FR OS1 and, FR IP1. The design matrix makes path dependency looks clear.

The design matrix is as follows:

$$\begin{vmatrix} FRUS1 \\ FRPT1 \\ FRRR1 \\ FRTM1 \\ FROS1 \\ FRIP1 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 & 0 \\ X & X & X & 0 & 0 & 0 \\ X & X & X & X & 0 & 0 \\ X & X & X & X & X & 0 \\ X & X & X & X & X & X \end{vmatrix} \begin{vmatrix} PSUS1 \\ PSPT1 \\ PSRR1 \\ PSTM1 \\ PSOS1 \\ PSIP1 \end{vmatrix}$$

Each 6 PSs are further decomposed in detail in the following sections. Onward the second level of the SMSDD, FRs, and PSs are labeled in a way as Two alphabets followed by digits to trace back to their root CSD step. US represents Understanding the System, PT for Positive Tone, RR for Recognize Resources, TM for Thinking Map, OS for Organization Structure, and IP for Implement Physical Solutions; the unique number helps to track their levels and the positions of the FRs and PSs in the decomposition.

It is a common argument that "Which PS is important in decomposition?" Path dependency answers the question, it can also be seen in the following Design matrix. Leftmost PSs are more influential and affect rest FRs. For example, figure 4.2 renders "PS US1" affects FR PT1, FR RR1, FR TM1, FR OS1 and, FR IP1, and rest PSs affect right-side FRs. Hence left PSs are essential. Note that it is only applicable for path dependant decomposition. In the case of the path independent matrix, all PSs are equally important.

4.2.2 Understand the System

Understand the currently existing system is the first branch of SMSDD, it focuses on the understanding of the existing current system as per FLAME diagnosis steps. Understand the System branch is decomposed in the following Figure 4.3.

According to CSD methodology, it is necessary first to understand the existing system for designing any manufacturing system, it can be achieved by FLAME diagnosis steps. There are four layers in the Flame Model: Work / Action, Structure,

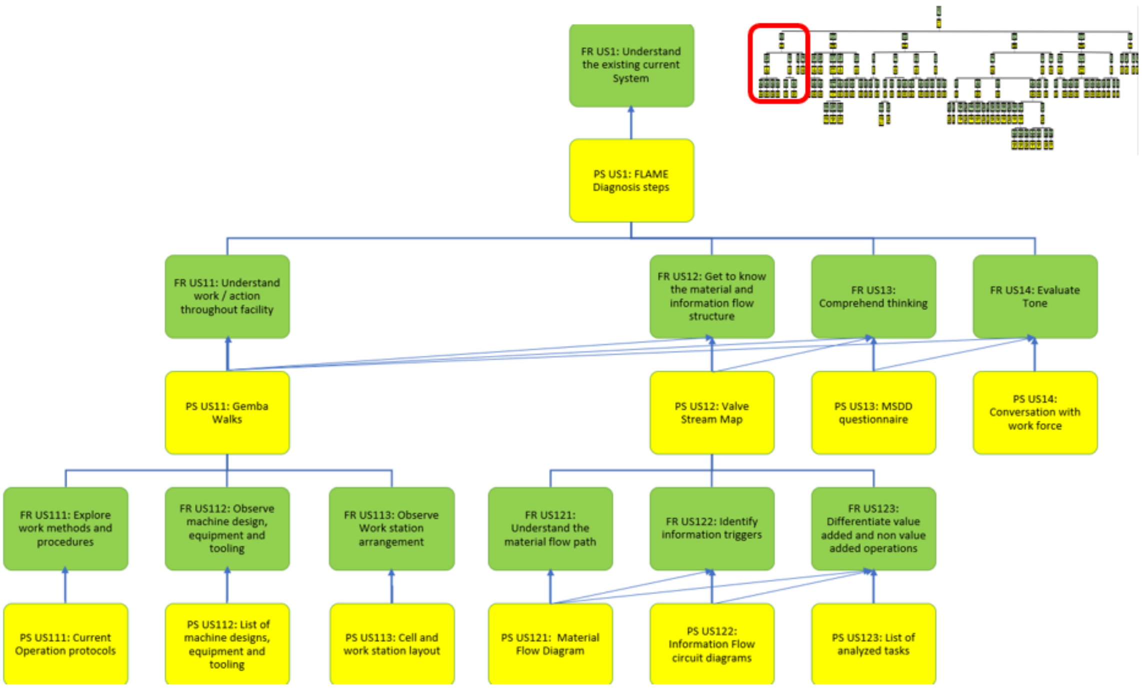

Fig. 4.3. Sustainable Manufacturing System Design Decomposition Understand System

Thinking, and Tone. The diagnosis process starts from the outermost layer of the flame model to the innermost layer. Therefore, to accomplish PS US1: "FLAME Diagnosis steps," understanding each layer is necessary.

FR US1: "Understand work/action throughout facility" gives the understanding of work action layer, FR US2: "Get to know the material and information flow structure" aids to the analysis of structure layer, FR US13: "Comprehend thinking" helps to understand the thinking layer and in the end FR US14: "Evaluate Tone" focuses on the understanding of the tone of the existing system. Corresponding Physical Solutions are PS US11: "Gemba Walk," PS US12: "Value Stream Map," PS US13: "MSDD questionnaire," and PS US14: Conversion with work force."

Design Matrix from Understand the system level 3 is path-dependent as shown bellow. Because of flame layers has to be analyzed sequentially from outer layer to innermost. Therefore PSs affects the rest of right-sided FRs automatically.

$$\begin{vmatrix} FRUS11 \\ FRUS12 \\ FRUS13 \\ FRUS14 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & X & X & 0 \\ X & X & X & X \end{vmatrix} \begin{vmatrix} PSUS11 \\ PSUS12 \\ PSUS13 \\ PSUS14 \end{vmatrix}$$

Gemba walks denote the action of going to see the actual process on the actual work floor, understand the work, ask questions, and learn [25]. The Gemba Walk gives opportunities to walk through the workplace and identify wasteful activities. While exploring a work/action by Gemba walks, the current work operations protocols must be seen to explore the working methods and procedures (FR-PS pair US111); List of machine design, equipment, and tooling must be gathered properly to observe machine design, equipment, and tooling (FR-PS pair US112); and study of cell and workstation layout should be done to obverse workstation arrangement (FR-PS Pair US113). FR PS pairs US111 to US113 are the example of a path independent design matrix. There are no effects of PSs on each others FRs.

$$\begin{vmatrix} FRUS111 \\ FRUS112 \\ FRUS113 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{vmatrix} \begin{vmatrix} PSUS111 \\ PSUS112 \\ PSUS113 \end{vmatrix}$$

PS US12 "Value stream map" is further decomposed into three PR-PS pairs to evaluate the material and information path flow. Firstly, material flow diagrams must be analyzed to understand the material flow path (FR-PS US121 pair); Secondly, information flow circuit diagrams have to be seen to identify the information triggers (FR-PS pair US122). After having the material flow diagrams and information flow diagrams, it is necessary to differentiate between value-added operations and value-added operations(FR US123). The PS US123: "List of analyzed tasks" helps to satisfy the FR US123. All three FR-PS pairs are path dependant as shown in figure 4.3 and shown in the design matrix:

$$\begin{vmatrix} FRUS121 \\ FRUS122 \\ FRUS123 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{vmatrix} \begin{vmatrix} PSUS121 \\ PSUS122 \\ PSUS123 \end{vmatrix}$$

4.2.3 Positive Tone

Positive Tone is the second branch of SMSDD, and the first step towards the designing System. The tone is the soul of the manufacturing system, this branch help to the innermost layer of the Flame model. A Healthy environment and culture is the solution (PS PT1) to create a Positive Tone (FR PT1), As shown in figure 4.4 PS PT1 is decomposed further into five elements: FR PT11: "Allow all working members to participate in the design process", FR PT12: "Understand the need for change", FR PT13: "Provide Safety," FR PT14: "Sustain positive tone," and lastly FR PT15: "Define good Tone."

FR PT11 is the essential Functional Requirement; the Collective agreement environment (PS PT11) empowers the employee by enabling all members to take decisions. PS PT11 affects FR PT12-PT14. Continuous Improvement (PS PT12) is a must for understanding the need for change; Sustainability is a long-term process, and PS PT12 initiates the process of improvement in all aspects. CI pushes the designing procedure to make it more efficient and successful. Awareness of safety (PS PT13) should be acknowledged to provide safety (FR PT13). The satisfaction of achieving goals and good outcomes always helps to keep employee's tone positive. For that reason, FR PT14: Sustain positive tone can be achieved by PS PT14: Satisfaction of achieving goals (FRs). Ruiz's four agreements (PS PT 15) enquired is a must for the definition of good tone (FR PT15). The design matrix is as followed:

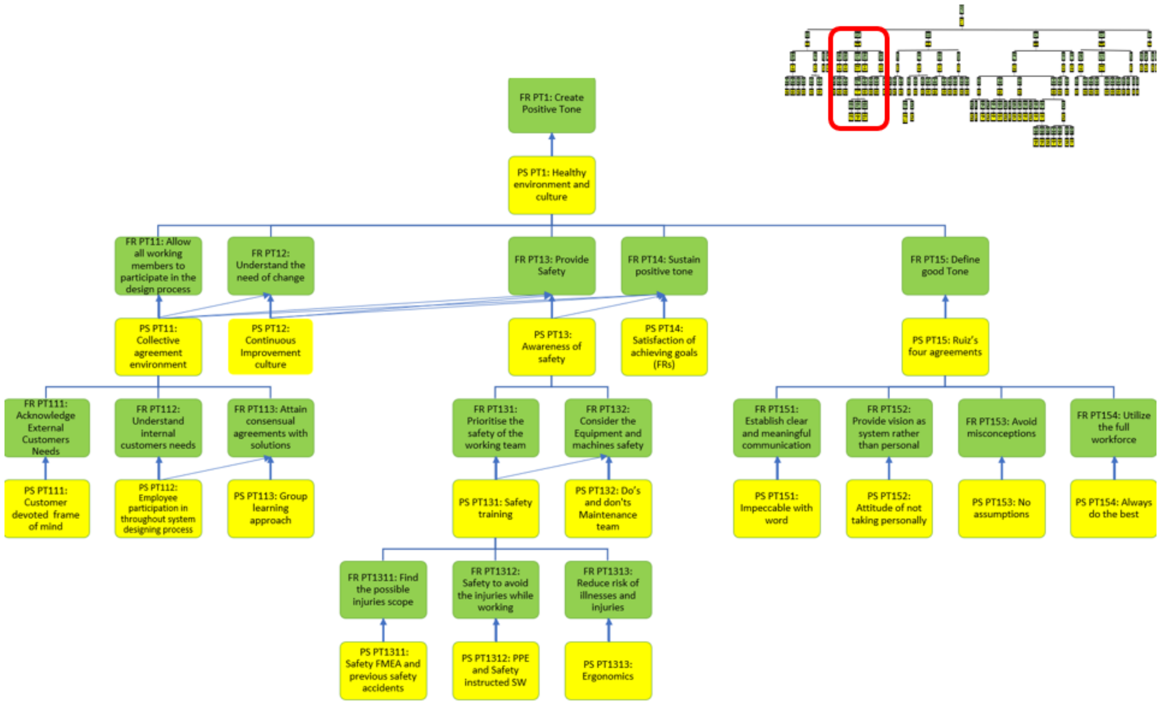

Fig. 4.4. Sustainable Manufacturing System Design Decomposition Positive Tone

$$
\begin{vmatrix} FRPT11 \\ FRPT12 \\ FRPT13 \\ FRPT14 \\ FRPT15 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ X & X & X & 0 & 0 \\ X & X & X & X & 0 \\ 0 & 0 & 0 & 0 & X \end{vmatrix} \begin{vmatrix} PSPT11 \\ PSPT12 \\ PSPT13 \\ PSPT14 \\ PSPT15 \end{vmatrix}
$$

Three requirements are defined to achieve a collective agreement environment (PS PT11) as shown in figure 4.4: Acknowledge External Customers Needs (FR PT111) by adapting the customer devoted frame of mind (PS PT111); Understand internal customers needs (FR PT112) by considering internal worker's voice and participating in the designing process (PS PT112); Attain consensual agreements with output solutions by acquiring group learning approach (PS PT113). PS PT 112 affects the FR PT113, this can be seen in the following design matrix:

$$\begin{vmatrix} FRPT111 \\ FRPT112 \\ FRPT113 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & X & X \end{vmatrix} \begin{vmatrix} PSPT111 \\ PSPT112 \\ PSPT113 \end{vmatrix}$$

Safety

Safety is one of the Functional Requirements from the 7 FRs, FR1- "Provide a safe and healthy work environment". The safety concern is part of the tone and output of Internal customer's needs (PT12). SMSDD is built in such a way that the safety area comes under the tone branch. Creating a positive tone covers every mindset and attitude of a complete system altogether, and safety awareness is a must for a healthy environment.

Figure 4.4 represents PS PT13: "Awareness of safety" has two elements: Safety of workers (FR PT131) and safety of machines with equipment (FR PT132). Respective Physical solutions are PS PT131: "Safety training" and PS PT132: "Do's and don'ts list from Maintenance team." The safety training is further decomposed into three Functional Requirements: FR PT1311, FR PT1312, and FR 1313 (Please refer to 4.4). Safety training should be designed in such a way that safety FMEA and previous safety-related reports discover the possible injuries in future (FR-PS pair PT1311); identified injuries has to avoided by using PPE and instructed Standard worksheets (FR-PS PT1312); Ergonomics updates on the work floor will reduce the illness injuries(FR-PS PT1313). 'FR PS' Pairs are path-dependent as the design matrix is shown below:

$$\begin{vmatrix} FRPT1311 \\ FRPT1312 \\ FRPT1313 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{vmatrix} \begin{vmatrix} PSPT1321 \\ PSPT1312 \\ PSPT1313 \end{vmatrix}$$

PS PT15: "Ruiz's four agreements" is further decomposed into four elements, as shown in figure 4.4. According to Miguel Ruiz, there are four agreements: Impeccable with the word, Attitude of not taking it personally, No assumptions, and Always do the best. Impeccable with the word (PS PT151) having this attitude is must to satisfy the FR PT151: Establish clear and meaningful communication within members of the system; Attitude of not taking personally (PS PT152) is must for achieving the vision as the system rather than personal vision (FR PT152); No assumptions (PS PT153) should be made to avoid the misconceptions or misunderstanding (FR PT153), and frame of mind to always do the best (PS PT154) is a must for use all workforce power (FR PT154). The design matrix is as below:

$$\begin{vmatrix} FRPT151 \\ FRPT152 \\ FRPT153 \\ FRPT154 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{vmatrix} \begin{vmatrix} PSPT151 \\ PSPT152 \\ PSPT153 \\ PSPT154 \end{vmatrix}$$

4.2.4 Recognizing the Resources

Recognizing resources is the third branch of SMSDD inspired by Collective System Design Step 3- Define Stakeholders and System Boundary 2.2. The recognizing resources FR aims to support the next upcoming thinking mapping, structure material information flow path, and implement PSs on the floors branches; by providing the idea of defining the available resources. PS RR1 system boundary is further decomposed as shown in figure 4.5.

The decomposition of FR RR1: "Recognize available resources" and it's respective PS RR1: "System boundary" is shown in figure 4.5. To accomplish PS RR1: "System boundary," System boundary must be defined (FR RR11), resources have to be chosen with respective the needs (FR RR12), Flexibility with variable needed to improved (FR RR13) and lastly available time must be utilized (FR RR14). The associated Physical Solutions are "System Boundary diagram" (PS RR11), "Resource Recruitment plan" (PS RR12), "System boundary expansion" (PS RR13), and "Time Management" (PS RR14). The path dependencies follow the logic that must be firstly

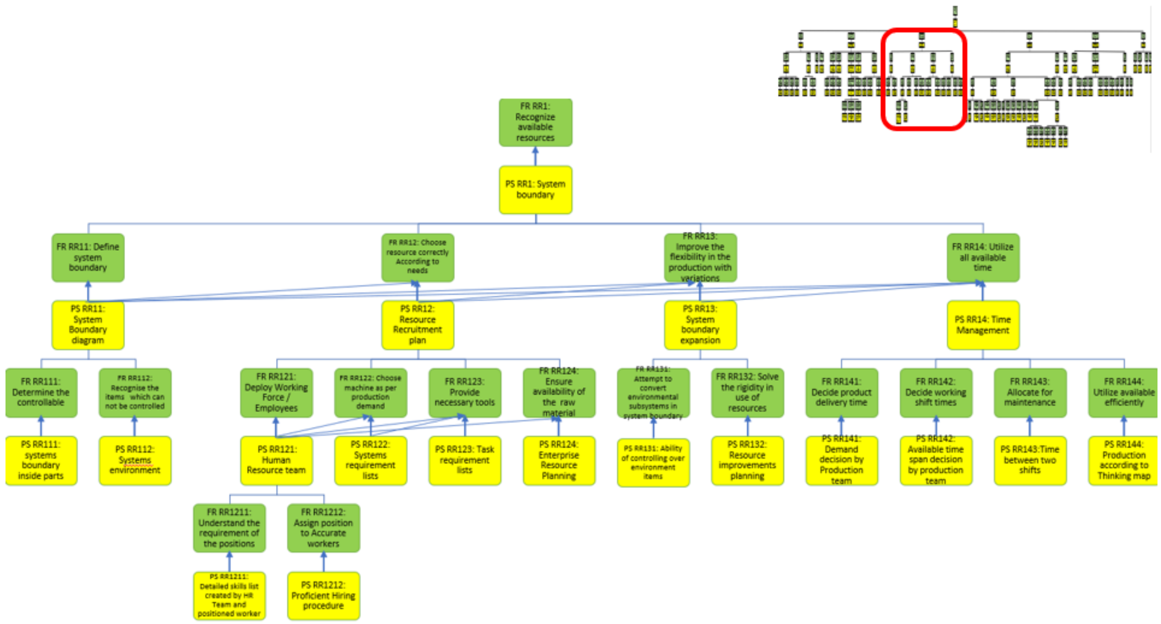

Fig. 4.5. Sustainable Manufacturing System Design Decomposition Recognize Resources

System boundary defined, then resources chose, then improved flexibility, and then utilized all time as shown in next the design matrix:

$$\begin{vmatrix} FRRR11 \\ FRRR12 \\ FRRR13 \\ FRRR14 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & X & X & 0 \\ X & X & X & X \end{vmatrix} \begin{vmatrix} PSRR11 \\ PSRR12 \\ PSRR13 \\ PSRR14 \end{vmatrix}$$

A system boundary diagram is crucial to understand the recognizing resources. System boundary starts by listing out the controllable sections of the facility, Which can be determined by inside parts of the system boundary diagram (FR PS pair RR111). The rest system environment is recognized as sections that can not be controlled (FR PS RR112) as shown above figure 4.5.

$$\begin{vmatrix} FRRR111 \\ FRRR122 \end{vmatrix} = \begin{vmatrix} X & 0 \\ 0 & X \end{vmatrix} \begin{vmatrix} PSRR121 \\ PSRR112 \end{vmatrix}$$

In any manufacturing plant, direct and indirect people are the key element. If the workers are skilled and have a good tone, it is considered a big plus point. Arrows from PS RR121 to all right-sided FR shows that 4.5. The selection of skilled and dedicated working people is a must (FR RR121) for that Human team (PS RR 121) is conditioned to resolve the requirements from job positions (FR RR 1211) and assign the position to an accurate candidate in the hiring process (FR RR 1212). Corresponding PSs are PS RR1211 "Detailed skills list created by HR Team and positioned worker" and PS RR1212 "Proficient Hiring procedure." After deploying the workforce, the Selection of machines, tools, and raw materials should be required by Systems requirement list, task list, and Enterprise Resource Planning (FR PS pairs RR122, RR 123, RR124). The Design matrix suggests to the first RR121, then RR122, RR123, and at the end RR 124, as shown below.

$$\begin{vmatrix} FRRR121 \\ FRRR122 \\ FRRR123 \\ FRRR124 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & X & X & 0 \\ X & X & 0 & X \end{vmatrix} \begin{vmatrix} PSRR121 \\ PSRR122 \\ PSRR123 \\ PSRR124 \end{vmatrix}$$

PS RR13 is one of the outputs of continuous improvement tone, To improve the flexibility of production system boundary can be expended by converting environment parts in the system boundary itself(FR RR131) and solving the rigidity in use of resources (FR RR132). The ability to control over environment parts is desired to convert in boundary (PS RR 131). Updating machines, tools, and other resources can achieve FR RR 132.

$$\begin{vmatrix} FRRR131 \\ FRRR132 \end{vmatrix} = \begin{vmatrix} X & 0 \\ 0 & X \end{vmatrix} \begin{vmatrix} PSRR131 \\ PSRR132 \end{vmatrix}$$

Sustainable Manufacturing System Design Decomposition endorses time as one the element of key resources, hence time management is recommended (PS RR14). Time Management includes deciding delivery timelines, shift time, and maintenance time with better efficiency (FR RR 141, RR142, FR RR143, and FR RR144). Respective solutions are demand decision by the Production team collectively after considering the workload and work pace (PS RR141), decision of selection available time span (PS RR142), Time between two shifts (PS RR143), and Production according to thinking mapping (PS RR1144) as shown in 4.5.

$$\begin{vmatrix} FRRR141 \\ FRRR142 \\ FRRR143 \\ FRRR144 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & X & X & 0 \\ X & X & 0 & X \end{vmatrix} \begin{vmatrix} PSRR141 \\ PSRR142 \\ PSRR143 \\ PSRR144 \end{vmatrix}$$

4.2.5 Thinking Mapping

The thinking Mapping branch acts as the bridge in SMSDD, connecting understanding of the system, positive tone, resources, to their next actual implementations. The decomposition of PS TM1 "CSD Thinking" has three main sections: Maximizing sales revenue, minimizing operation cost, and minimizing investment over the long-term. Their respective PSs are PS TM11 "Production to maximize customer satisfaction," PS TM12 "Elimination of non-value adding sources of cost" and PS TM13 "Investment based on long term strategy," Please refer figure 4.6 Path dependency suggests first maximize sales, then minimize cost and then minimize the investment, as shown in the design matrix.

$$\begin{vmatrix} FRTM11 \\ FRTM12 \\ FRTM13 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{vmatrix} \begin{vmatrix} PSTM11 \\ PSTM12 \\ PSTM13 \end{vmatrix}$$

CSD thinking triggers any organization's main need to make a profit by producing desirable customer products.

The thinking branch of SMSDD mostly resembles Manufacturing System Design Decomposition; there are some FR PS pairs choose from MSDD.

Sustainable Manufacturing System Design Decomposition suggests maximizing sales by producing maximize with customer satisfaction (FR PS TM11). Maxi-

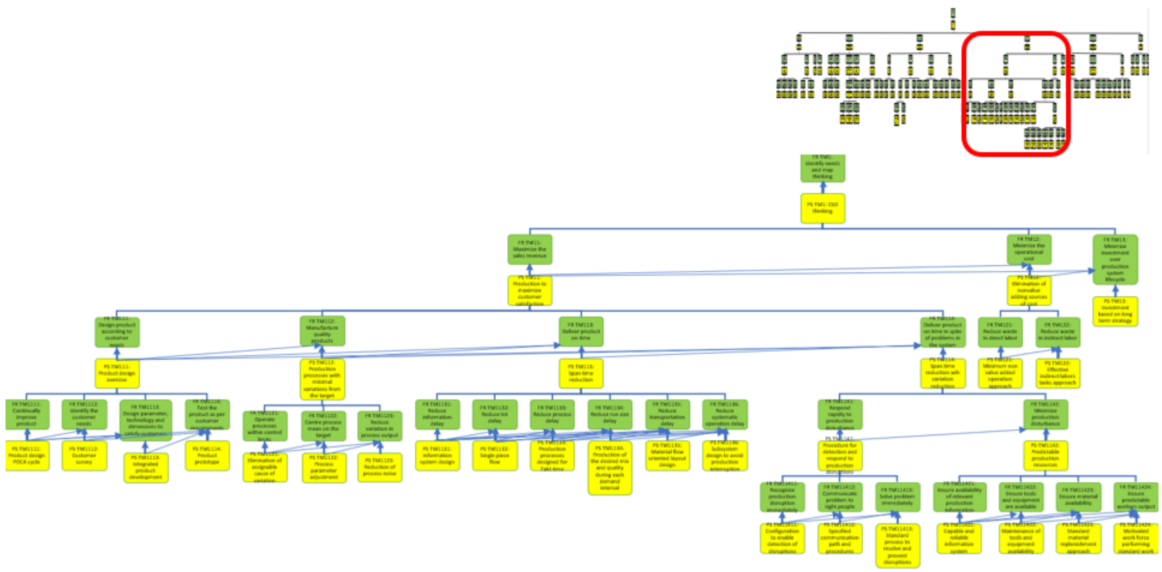

Fig. 4.6. Sustainable Manufacturing System Design Decomposition Thinking Mapping

mize customer satisfaction means manufacturing according to customer needs (FR TM111), quality products (FR TM112), On-time delivery (FR TM113), and keep manufacturing on time with quality products despite problems (FR TM114). Product design exercise is needed for designing customer desired products (FR PS pair TM111); production with fewer variations from the designed target is a must for excellent quality (FR PS pair TM112); Span time reduction required for on-time delivery (FR PS pair TM113), and span time with variation reduction has to do to the product with disruptions (FR PS pair TM114). This level of SMSDD is entirely path dependant, as can be seen in the design matrix.

$$\begin{vmatrix} FRTM111 \\ FRTM112 \\ FRTM113 \\ FRTM114 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & X & X & 0 \\ X & X & X & X \end{vmatrix} \begin{vmatrix} PSTM111 \\ PSTM112 \\ PSTM113 \\ PSTM114 \end{vmatrix}$$

Product Designing

Product Design Exercise (PS TM111) focuses on designing product design based on customer needs. As the effect of having a positive tone, the design process starts with Continuous improvement of the product (FR TM111) to achieve improvement of design. This can be achieved by Product Design PDCA Cycle (PS TM1111). A customer survey is necessary to identify the customer needs (FR PS pair TM1112). To satisfy customer needs product has to be equipped with the necessary technology, dimensions, and design parameters depending upon products. FR TM 1113 suggests to PS TM1113 shown in the figure in 4.6. After all the designing steps, the Product designing exercise has to test the products, hence Product prototyping is required. Below is the design matrix of the product design exercise PS TM111.

$$\begin{vmatrix} FRTM1111 \\ FRTM1112 \\ FRTM1113 \\ FRTM1114 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & X & X & 0 \\ X & X & X & X \end{vmatrix} \begin{vmatrix} PSTM1111 \\ PSTM1112 \\ PSTM1113 \\ PSTM1114 \end{vmatrix}$$

Quality

Production process with minimal variations from the target (PS TM112) is further decomposed into three elements: operate processes in limits (FR TM1121), Centre process mean on the target (FR TM1122), and Reduce variations in output (FR TM1123). Respective Physical Solutions are the Elimination of an assignable cause of the variations (PS TM1121), process parameter adjustment (PS TM1122), and Reduction of process noises (PS TM1124). These FR PS are referred from MSDD. Path dependency is covered next.

$$\begin{vmatrix} FRTM1121 \\ FRTM1122 \\ FRTM1123 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{vmatrix} \begin{vmatrix} PSTM1121 \\ PSTM1122 \\ PSTM1123 \end{vmatrix}$$

As it can be seen that bottom Physical Solutions can be further decomposed to a single level or more, and this the advantage of SMSDD provides industries the opportunity to design according to their most suitable Solutions. The ability to choose its own suitable PSs helps sustain the solutions long term and achieves the Functional Requirement of a long-term production lifestyle (FR13).

On-time delivery

The decomposition of PS TM113 "Span Time Reduction" encourages the elimination of all kinds of wastage of time by avoiding all delays in the system to deliver products on time. SMSDD addresses six delays: "Information delay" (FR TM1132) is usually caused by the transfer of information and the delay in the process of taking action after the information is received [33]. "Lot delays" (FR TM1132) occurs when parts are transported between operations in lots (also known as transfer batches) of greater than one. While one part in the lot is being processed, all other parts in the lot must wait in storage, either before or after the operation [34]. "Process delay" (FR TM1133) occurs when at the workstation, parts receiving rate is greater than the rate of processing parts, this leads to the accumulations of parts the downstream operations, the parts waiting in from of downstream process is process delays. "Run size delays" (FR TM1134) occurs when multiple part types are produced and the sequence of production does not match the sequence of products demanded by the customer [34]. "Transportation Delays" (FR TM1135) is delayed when parts have to be transported from one location to another.

To reduce information delays quick, efficient, and reliable information system design is a must (FR PS pair TM1131); with the help of "Single piece flow" (PS TM1132) lot delays can be reduced. according to takt time, production processes make the system balanced and reduce the process delays (FR PS pair TM1133). Production of the desirable mix and quality during each demand interval should have been done for reducing the run size delay (PS TM1134); And, material-oriented layout and subsystem design are must for reducing transportation delay and systematic operation delays (FR PS pairs TM1135 and 1136). The path dependency is as shown below:

$$\begin{vmatrix} FRTM1131 \\ FRTM1132 \\ FRTM1133 \\ FRTM1134 \\ FRTM1135 \\ FRTM1136 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 & 0 \\ X & X & X & 0 & 0 & 0 \\ X & X & X & X & 0 & 0 \\ X & X & X & X & X & 0 \\ X & X & X & X & X & X \end{vmatrix} \begin{vmatrix} PSTM1131 \\ PSTM1132 \\ PSTM1133 \\ PSTM1134 \\ PSTM1135 \\ PSTM1136 \end{vmatrix}$$

Production in spite of problem in the system

In industries, there are many variables and factors, this cause problems in systems. System engineers refer to these situations as 'abnormal conditions'. When things go according to plans and expected outcomes, it is known as a normal condition; and when things are different from expected, unusual is called 'abnormal condition'. Abnormal conditions are very often in industries. "Production despite a problem in the system" branch of decomposition addresses how can products can be produced in abnormal conditions (while having problems).

PS TM114 "Span time reduction with variation reduction" is decomposed further into FR TM 1141 "Respond rapidly to production disturbances," and FR TM1142 " Minimize production disturbance" as shown in figure 4.6. PS TM 114 "Procedure for detection and respond to production disruptions" and PS TM1142 " Predictable production resources" are the Physical Solutions to corresponding FRs. Path dependency suggests to first FR TM1141 after FR TM1142 as can be seen in the below design matrix.

$$\begin{vmatrix} FRTM1141 \\ FRTM1142 \end{vmatrix} = \begin{vmatrix} X & 0 \\ X & X \end{vmatrix} \begin{vmatrix} PSTM1141 \\ PSTM1142 \end{vmatrix}$$

The procedure for detecting disruptions and responding rapidly to it (PS TM1141) should have configurations to enable the detection of disruptions for finding disruptions immediately (FR PS pair TM1411); the standardized communication paths with procedures for communicating with the right people to respond to problems (PS TM1142); and Standard process to resolve to solve problems (FR PS pair TM1413). Design decomposition at this level of a branch is perfect path-dependent. PSs on the left side are supporting directly to Achieve right side FRs as can be seen in the design matrix.

$$\begin{vmatrix} FRTM11411 \\ FRTM11412 \\ FRTM11413 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{vmatrix} \begin{vmatrix} PSTM11411 \\ PSTM11412 \\ PSTM11413 \end{vmatrix}$$

Similarly, in order to minimize the production disturbance, predictable production resources should do make sure of the availability of the production information (FR TM11421), tools and equipment (FR TM11423), materials (FR TM11423), and predictable worker output (FR TM 11424). Corresponding PSs are a capable and reliable information system (PS TM11421), Maintenance of tools and equipment availability (PS TM11422), standard material replenishment approach (PS TM11423), and most importantly, motivated workforce performing standard work (PS TM11424).

$$\begin{vmatrix} FRTM11421 \\ FRTM11422 \\ FRTM11423 \\ FRTM11424 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & X & X & 0 \\ X & X & X & X \end{vmatrix} \begin{vmatrix} PSTM11421 \\ PSTM11422 \\ PSTM11423 \\ PSTM11424 \end{vmatrix}$$

4.2.6 Organization Structure

The organization structure focuses on defining the material and information flow structure based on the collective system design thinking map. Organization structure branch requires to update the value stream map and verify with Legos simulations. The complete decomposition is as shown in the following figure 4.7.

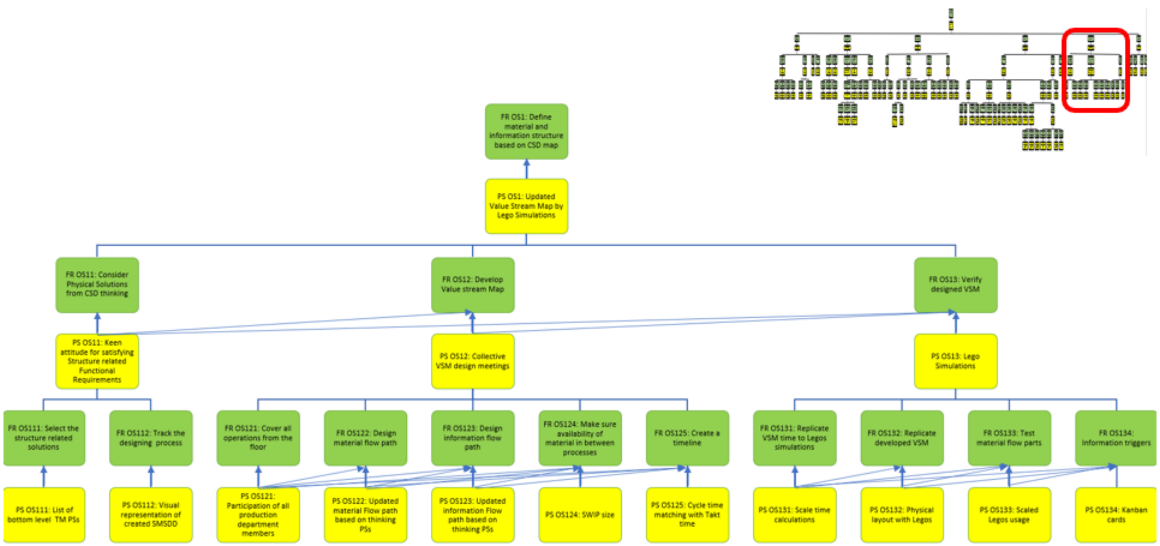

Fig. 4.7. Sustainable Manufacturing System Design Decomposition Organization Structure

The first requirement for defining material and information structure by updating VSM based on branch thinking mapping is to consider the PSs. Path depending arrow from CSD thinking to FR OS1 explains that the organization structure is based on a thinking map. Hence, prioritizing satisfy the structure-related FRs must consider Physical Solutions from CSD thinking (FR PS pair OS11). To have a keen attitude towards structure-based FRs, FR OS111 "Select the structure related solutions," and FR OS112 "Track the designing process" is required. A list of bottom-level TM PSs should have created to refer to the solutions to implement in defining organization structure (PS OS111); and Visual representation of SMSDD helps track the designing process and design more efficiently.

Collective Value Stream Map design meetings are necessary for developing (FR PS pair OS12), which include the involvement of all department representatives, the decision over the material as well as information flow path, creation of a timeline, and availability of the material throughout the process. Collective VSM meetings are further decomposed into 5 FRs: Cover all operations from the floor (FR OS121), Design material flow path (FR OS 122), Design information flow path (FR OS123), ensure the availability of material in-between processes (FR OS124) and Create a timeline (FR OS125). Corresponding PSs are Participation of all production department members (PS OS121), Updated material Flow path based on thinking PSs (PS OS122), Updated information Flow path based on thinking PSs (PS OS123), SWIP size (PS OS124), and Cycle time matching with Takt time (PS OS125). The design matrix shows the logic of achieving FR OS111 first and, FR OS112, FR OS113, FR OS114, and FR OS115 sequentially.

$$\begin{vmatrix} FROS121 \\ FROS122 \\ FROS123 \\ FROS124 \\ FROS125 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ X & X & X & 0 & 0 \\ X & X & X & X & 0 \\ 0 & 0 & 0 & 0 & X \end{vmatrix} \begin{vmatrix} PSOS121 \\ PSOS122 \\ PSOS123 \\ PSOS124 \\ PSOS125 \end{vmatrix}$$

Sustainable Manufacturing System Design Decomposition endorse testing of the created Value Stream Map. For verifying design Lego simulations are needed (FR PS pair OS13). Lego simulations are the task where the production operations are tested by replicating the production system on the table and considering Legos as the raw materials. Lego simulation has many advantages: easy to implement, less costly, helpful to analyze the material and information flow paths, and more importantly, Lego simulations support the collective learning approach.

Lego simulations(PS OS13) is further decomposed to four elements: replicate VSM time to legos simulations (FR OS131), replicate developed VSM (FR OS132), test material flow parts (FR OS133) and information triggers (FR OS134) and, respective physical solutions are Scale time calculation (PS OS131), Physical layout with legos (PS OS132), scaled legos usage (PS OS14) and Kanban cards (PS OS134). Following is the design matrix show the level is perfectly path dependant.

$$\begin{vmatrix} FROS131 \\ FROS132 \\ FROS133 \\ FROS134 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & X & X & 0 \\ X & X & X & X \end{vmatrix} \begin{vmatrix} PSOS131 \\ PSOS132 \\ PSOS133 \\ PSOS134 \end{vmatrix}$$

4.2.7 Implementing Solutions on the Floor

Sustainable Manufacturing System Design Decomposition strongly supports implementing the physical Solution by the standard worksheet. Standard Work is the organized Haman actions that are efficiently created in chronological sequence to achieve all Functional Requirements by Physical Solutions. The SMSDD functional requirement is stated as FR IP1 "Implement physical solutions in the plant" with associated PS IP1 "Work and Action by PDCA," as shown in figure 4.8.

PS IP "Work and Action by PDCA," is further decomposed into four central elements: the creation of the standard works for all actions derived from PSs of the first five branches (Understand System, Positive Tone, Recognize Resources, Thinking Map, and Organization Structure), Implement Standard work, examine the performance of after using Standard Work and update Standard worksheets as per needed. The second level of SMSDD is derived from PS IP1 "Work and Action by PDCA": FR IP11 "Generate Standard work for PSs," FR IP12 "Complete the standard Work," FR IP13 "Check against the measures," FR IP14 "Modify standard work as needed" with associated PS IP11 "Standard Work data base (Plan)," PS IP12 "Implementation of Standard work (Do)," PS IP13 "Performance check (Check)," and PS IP14 "Corrected Standard work (Act)." the design matrix is as follows:

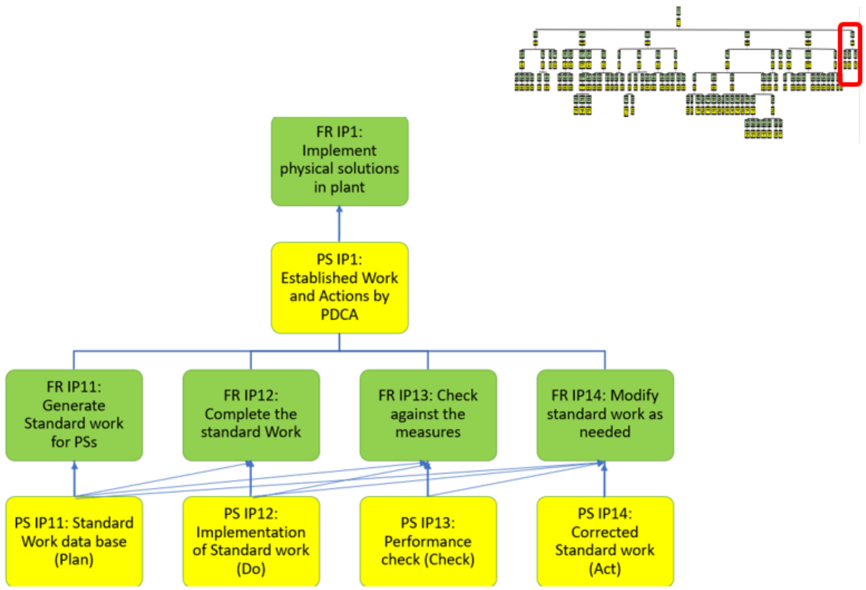

Fig. 4.8. Sustainable Manufacturing System Design Decomposition Implement Physical Solutions

$$\left|\begin{array}{c} FRIP11 \\ FRIP12 \\ FRIP13 \\ FRIP14 \end{array}\right| = \left|\begin{array}{cccc} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & X & X & 0 \\ X & X & X & X \end{array}\right| \left|\begin{array}{c} PSIP11 \\ PSIP12 \\ PSIP13 \\ PSIP14 \end{array}\right|$$

4.3 Summary

Chapter 4 focuses on the creating the new system design decomposition that meets internal customer needs and external customers to achieve sustainability in the manufacturing system. This chapter describes the main six branches of the SMSDD in detail: Understand the System, Create the positive tone, Recognize the resources, Identify needs and mapping, Define material and information flow structure based on CSD map, and Implement Physical Solutions on the plant.

CHAPTER 5. CONSTRUCT VALIDITY APPROACH: SUSTAINABLE MANUFACTURING SYSTEM DESIGN DECOMPOSITION QUESTIONNAIRE

5.1 Introduction

The Sustainable Manufacturing System Design decomposition created in chapter 4 is meant for various designing manufacturing faculties. Chapter 5 develops a standard, repetitive, reliable, and well-structured set of questions called the Sustainable Manufacturing System Design Decomposition Questionnaire (SMSDDQ). In SMSDDQ, it is required to standardize observations, interviews, working floor visits. These evaluations are traced back to SMSDD and help to review from created decomposition's approach.

5.2 Development of Sustainable Manufacturing System Design Decomposition Questionnaire

SMSDDQ aims to observe the production plant concerning design decomposition. Dr. Cochran and Dr. Jochen Linck consider the Questionnaire a tool that supports gathering and interpreting the Manufacturing System Design Decomposition with associated questions for each leaf FR PS pair [30]. This tool aids to reflects the changes in the plant before SMSDD and plant after SMSDD adaptation. The Development of the Questionnaire with basic questions as following:

1. Should the questionnaire focus on FRs, or PSs or FR-PS Pairs?
2. In design decomposition, what is needed to evaluate? Top-level FR-PS pairs or bottom ones?
3. While evaluating Pairs, should do measured quantitatively or qualitatively?

The response to the first question is FR-PS pairs. The questionnaire can not be just Physical Solutions or Functional Requirements oriented, but it is FR-PS pairs. SMSDD provides all possible Functional Requirements for manufacturing, and Physical Solutions are to satisfy those FRs. Therefore, consideration of both FRs and PSs is a must.

To answer the second question, it is needed to understand "what is SMSDD questionnaire's output?" The questionnaire is for testing the system from the SMSDD point of view. As decomposition goes to the bottom level, Physical solutions become more and more specific. That causes a problem. By questioning the bottom level of Functional Requirement - Physical Solution pair limits the meaning of the Functional Requirement. For example, FR TM11422 "Ensure tools and equipment are available" and PS TM11422 "Maintenance of tools and equipment availability," here Physical Solutions are focusing only to ensure tools and equipment available, but the main reason for minimizing production disturbance is missing out. Therefore, the development of the questionnaire first questions the bottom levels to cover the full meaning of the branch, if that's not the case then more questions related to the higher-level FR-PS pair level questions must be asked.

The Sustainable Manufacturing System Design Decomposition has more than one-hundred of FR-PS pairs, some of them are difficult to measure quantitatively: for example, FR US111 "Explore work methods and procedures" and respective PS US111 "Current operation protocols." The FR-PS pair can not be evaluated quantitatively, the evaluation had to consider to what degree the plant facility considers current operation protocol and how much work methods and procedures are explored. Therefore, evaluation can be done either quantitatively or qualitatively.

5.3 Use of Sustainable Manufacturing System Design Decomposition Questionnaire

The questionnaire is completed before and after the implementation of the SMSDD in manufacturing facilities. The questionnaire is required to be completed by people from all levels of the organization departments. The tables below present the Sustainable Manufacturing System Design Decomposition Questionnaire (SMSDDQ). It contains 139 questions to corresponding FR PS pairs leaf are mentioned. A separate column also is given to fill Agreement scores and for comments.

Sustainable Manufacturing System Design Decomposition Questionnaire uses a Likert scale (E.g, Strongly disagree, disagree, neutral, agree, and strongly agree). Some of the questions from the SMSDD are reverse scale. For example, in the questionnaire, some questions are positively worded questions (E.g, We design our products considering our client's needs), but in the SMSDD it is negatively worded questions (E.g, Sometimes, we design products with-out considering the needs of our clients).

In the SMSDD questionnaire, strongly agree answers are scored of 5, agree = 4, neutral =3, disagree =2 and strongly disagree =1 for each question. Above is the case for positively worded questions. However, for the reverse scaled questions scoring scales run in the backward direction. For reverse questions, strongly agreed answers are scored of 1, disagree =2, neutral =3, disagree =4, and strongly disagree =5.

The average scale of the answered questions of the leaf FR-PS pairs will be calculated. The questionnaire's graphical representation gives evidence of how the system satisfies the objectives stated in the Sustainable Manufacturing System Design Decomposition. The diagram below is just an example of graphical representations of the filled SMSDD questionnaire.

The SMSDD evaluation process is been done before and after implementing the manufacturing system re-design. Based on the results from the questionnaire evaluation, the manufacturing system's physical solutions may be revised or changed.

5.4 Sustainable Manufacturing System Design Decomposition Questionnaire

FR/PS	Questionnaire (5 is Strongly Agree)	Agreement Score (1-5)	Answers / Comments
FR US11	Understand work/ action through out facility		
PS US11	Gemba Walks		
US11-Q1	We often do gemba walks to understand work/ actions.		
US11-Q2	What is the usual frequency of gemba walks in plant?(In months)		
US11-Q3	We have a special data system for documenting gemba walk reports.		
US11-Q4	We have decided sets of instruction on gemba walks.		
FR US111	Explore work methods and procedures		
PS US111	Current Operation protocols		
US111-Q1	We compulsorily explore our work methods and procedure at workstations		
US111-Q2	On gemba walks we have easy access to current operations protocols		
US111-Q3	How much time it takes to explore work actions in all workstations?		
FR US112	Observe machines design, equipment and tooling		

PS US112	List of machine designs, equipment and tooling		
US112-Q1	We go through lists of machine designs, equipment and tooling to observe machines on gemba walks		
US112-Q2	List of machines and equipment have their respective reasons and task order to understand tools in depth		
FR US113	Observe work station arrangement		
PS US113	Cell and work station layout		
US113-Q1	In gemba walks, we see the cell and work station layout for effective observation of work station.		
US113-Q2	We have update cell and workstation layout after every major and minor changes.		
FR US12	Get to know the material and information flow path structure		
PS US12	Value Stream Map		
US12-Q1	The value stream maps we use are extremely accurate and reliable.		
US12-Q2	Value Stream Maps are informative to get to know the material and information flow path		
US12Q-3	Do our employees know to read Value Stream Map (VSM)?		
FR US121	Understand the material flow path		
PS US121	Material Flow Diagram		
US121-Q1	Referring material Flow Diagrams at floor helps to understand material flow path		

US121-Q2	Does inventory and Standard work in Progress (SWIPs) are included and well labeled in material flow diagrams?		
US121-Q3	Our material flow diagram explore all material motions, starting from raw supplier in-loading to shipping uploading.		
FR US122	Identify information triggers		
PS US122	Information Flow circuit diagram		
US122-Q1	Information flow circuit diagram are often used to know information triggers		
US122-Q2	With the help of information circuit diagrams we find information trigger easily and avoid the miscommunication.		
US122-Q3	When there is confusions, we use diagrams to avoid the miscommunication.		
FR US13	Comprehend thinking		
PS US13	SMSDD questionnaire		
US13-Q1	We fill and analyze questionnaire for comprehend the thinking of the system.		
US13-Q2	we have effective way to comprehend thinking by filling SMSDD questionnaire.		
US13-Q3	We all members of the facility from all departments fill questionnaires.		
FR US14	Evaluate Tone		
PS US14	Conversation with work force		

US14-Q1	Conversation while working on actual floor and office meetings reflect accurate natural tone.		
US14-Q2	We plan conversation with team, but it doesn't help us to evaluate team's tone (Reverse).		
FR PT111	Acknowledge external customer needs		
PS PT111	Customer devoted frame of mind		
PT111-Q1	We have understood the important of understanding needs of the external customers		
PT111-Q2	We have customer devoted frame of mind for understanding the external customer needs.		
PT111-Q3	We have understood most of the External Customer needs.		
FR PT112	Understand the internal customers and their needs		
PS PT112	Employee participation in throughout system designing process		
PT112-Q1	We value our internal customer's needs.		
PT112-Q2	Our employees have authority to participate in designing processes.		
PT112-Q3	We have a collective agreement on the designed system.		
FR PT113	Attain consensual agreement with solutions		
PS PT113	Group learning approach		
PT113-Q1	In meetings, we have group learning approach to collective agreement with solution brought up on the table.		

PT113-Q2	Group learning approach aids to bring all members on same page.		
PT113-Q3	Because of group learning approach, more brain involve in finding solutions, and results into better efficient solutions.		
FR PT12	Understand the need of change		
PS PT12	Continuous Improvement Culture		
PT12-Q1	We have Continuous Improvement environment in all departments.		
PT12-Q2	Employee have mindset for looking improvements in system and bring new techniques for improvements.		
PT12-Q3	On regularly bases we implement new ideas collected from employees.		
FR PT1311	Find the possible injury scopes		
PS PT1311	Safety Failure Mode Effect Analysis		
PT1311-Q1	We keep records of all injuries on all facility.		
PT1311-Q2	We do Failure Mode Effect Analysis of the safety to determine the future possible injuries.		
PT1311-Q3	We have eliminated safety incidents.		
FR PT1312	Safety to avoid the injuries while working		
PS PT1312	PPE and safety instructed Standard Work		
PT1312-Q1	We strictly follow the safety PPEs and included safety related instructions in Standard Work Sheets.		

PT1312-Q2	We have zero safety incidents because if safety instructions.		
PT1313-Q2	We design for efficiency and comfort of employee's at working stations.		
PT1313-Q3	We reduced the risk of illness with ergonomics changes.		
FR PT14	Sustain positive Tone		
PS PT14	satisfaction of achieving goals (FRs)		
PT14-Q1	Team's tone is always high when we achieve Functional Requirements.		
PT14-Q2	Satisfactions of meeting FRs helps team motivated and inspired.		
PT14-Q3	We often see our workers working dedicatedly and fully devoted to given tasks.		
FR RR111	Determine the controllable		
PS RR111	List of the inner systems boundary parts		
RR111-Q1	We refer System Boundary diagram to categorize resources.		
RR111-Q2	It is easy to identify the controllable sections in industry.		
RR111-Q3	System boundary diagrams are best for the visual representation of available resources		
FR RR112	Recognize the items which can not be controlled		
PS RR112	List of the system environments		
RR112-Q1	We have standardized way to list system boundary respective to projects.		
FR RR121	Deploy Working force / Employees		
PS RR121	Human Resources Team		

RR121-Q1	We have skilled labor force as a result of standardized hiring method.		
RR121-Q2	We understand requirement first by of the position.		
RR121-Q3	We assign position to worker matching profile with positions requirement skills list.		
FR RR122	Choose machine as per production demand		
PS RR122	Systems requirement lists		
RR122-Q1	All machines are capable for all doing necessary operations on floor.		
RR122-Q2	We do selection of machines are done per systems requirement.		
FR RR123	Provide necessary tools		
FR RR123	Task requirement list		
RR123-Q1	We lists of tasks and respective required tools.		
RR123-Q2	We do the selection of equipment and tools based on tasks requirement.		
FR RR124	Ensure availability of the raw material		
PS RR124	Enterprise Resource Planning		
RR124-Q1	To track materials in the facility, we have an Enterprise Resource Planning database.		
RR124-Q2	We always have updated information about raw material quantity.		
RR124-Q3	We follow standard procedure for updating database on regular base.		

FR RR141	Decide product delivery time		
PS RR141	Demand decision by production		
RR141-Q1	We decide product delivery time based on demanded quantity.		
RR141-Q2	For deciding delivery time, we analyse the pace of the system.		
FR RR142	Decide working Shift time		
PS RR142	Available time decision by production team		
RR142-Q1	If we have more orders then we increase our available time which increases our numbers of shifts.		
RR142-Q1	Number of working are dependent on available time calculations		
RR142-Q2	We decide working shift time based on available time decision		
FR RR143	Utilize available efficiently		
PS RR143	Production according to thinking mapping		
RR143-Q1	We do production as per solutions derived in CSD thinking mapping branch.		
FR RR144	Allocate time for maintenance		
PS RR144	Time between two shifts		
RR144-Q1	Usually when we are behind schedule then have no time for maintenance.		
RR144-Q2	We dedicate a portion of every day solely for maintenance		

RR144-Q3	We emphasize proper maintenance as a strategy for achieving schedule.		
FR TM1111	Continually improve product		
PS TM11111	Product design PDCA cycle		
TM1111-Q1	Our products are designed as per our customer needs.		
TM1111-Q2	We manufacture our product based on same old designs without any changes (Reverse).		
TM1111-Q3	We continuously improve design of products by product design PDCA cycle.		
FR TM1112	Identify the customer needs		
PS TM1112	Customer survey		
TM1112-Q1	Having customer surveys is advantage to understand the customer needs.		
TM1112-Q2	We have standardized system to track of surveys of all of our clients		
TM1112-Q3	Sometimes we design product without considering the needs of our clients.(Reverse)		
FR TM1113	Design parameter, technology, and dimensions to satisfy customers		
PS TM1113	Integrated product development		
TM1113-Q1	Do we design products in our facility or we receive designs form customer itself.		
TM1113-Q2	Our design engineers design product using new technology and updates in physical dimensions.		
FR TM1114	Test the product as per customer requirements		

PS TM1114	Product prototype		
TM1114-Q1	We are confident about out designs, so we don't test the of our products. (Reverse)		
TM1114-Q2	Before sending drawings and designs for production, we strictly test the performance of the designed product and once tests are positive then only we start manufacturing.		
TM1114-Q3	How do you test your product designs?		
FR TM1121	Operate processes within control limits		
PS TM1121	Elimination of assignable cause of variation		
TM1121-Q1	We have eliminated assignable causes of variations and working in limits, resulting zero defects.		
TM1121-Q2	We have understood all possible causes to operating process within control limits.		
FR TM1122 PS TM1122	Centre process mean on the target Process parameter adjustment		
TM1122-Q1	process parameter is only set within tolerance, but not necessarily on target. (reverse)		
TM1122-Q2	we operate on target.		
TM1122-Q3	We continuously monitor processes to check whether they are staying within tolerance specifications.		

FR TM1123	Reduce variation in process output		
PS TM1123	Reduction of process noise		
TM1123-Q1	We have procedure to distinguish between common and assignable causes of variations in process of quality.		
TM1123-Q2	We have standard procedure to eliminate root cause of quality variation.		
TM1123-Q3	We have procedure that enable operators to detect a change in the process inputs rapidly.		
TM1123-Q4	Disturbance from outside the process are detected before they can affect the process output.		
FR TM1131	Reduce information delay		
PS TM1131	Information system design		
TM1131-Q1	It is normal on our employees to wait for signals at workstation. (Reverse)		
TM1131-Q2	We have fast information flow hence we have minimum information delays.		
TM1131-Q3	We have standardized work actions, in case of lack of information.		
FR TM1132	Reduce lot delay		
PS TM1132	Single piece flow		
TM1132-Q1	The internal transfer batch size is usually larger than 2 hours of production. (Reverse)		
TM1132-Q2	We usually transport small parts in large containers or large bins. (reverse)		
TM1132-Q3	We are transporting standard quantities between operations-i.e. each trip transports the same number or parts		

FR TM1133	Reduce process delay		
PS TM1133	Production processes designed for Takt time		
TM1133-Q1	We determine takt time at an early stage of a manufacturing system design project.		
TM1133-Q2	We have clear customer-supplier relations throughout the value stream and production pace is based on takt time.		
TM1133-Q3	We design each operator's work loop to run as close to takt time as possible.		
TM1133-Q4	When manual cycle times are longer than takt time, we try to divide the operation into two or more operations to achieve takt time with each operation (rather than having two operators performing the same operation in parallel)		
FR TM1134	Reduce run size delay		
PS TM1134	Production of the desired mix and quality during each demand interval		
TM1134-Q1	We usually meet the production schedule every day.		
TM1134-Q2	We frequently produce more (or less) than scheduled. (reverse)		
TM1134-Q3	We frequently produce more (or less) of a particular part type per day than the downstream customer consumes per day (reverse).		
TM1134-Q4	What is your policy in determining run sizes for the different operations?		
FR TM1135	Reduce transportation delay		
PS TM1135	Material flow oriented layout design		

TM1135-Q1	We have laid out the shop floor so that our machines and processes are in close proximity to each other.		
TM1135-Q2	The shop floor layout has functional departments.		
FR TM1136	Reduce systematic operation delay		
PS TM1136	Subsystem design to avoid production interruption		
TM1136-Q1	Material handling and transportation equipment does not limit the pace of the production.		
TM1136-Q2	Operators frequently perform activities, which disrupt the standardized work (reverse).		
FR TM11411	Recognize production disruption immediately		
PS TM11411	Configuration to enable detection of disruptions		
TM11411-Q1	Machine down times are immediately noticed.		
TM11411-Q2	We use devices such as Andon boards or radio communications to signal the occurrence of disruptions.		
TM11411-Q3	We can always determine which upstream machine is responsible for a defect.		
FR TM11412	Communicate problem to right people		
PS TM11412	Specified communication path and procedures		
TM11412-Q1	We have standard communication paths to contact support staff.		

TM11412-Q2	Our communication devices allow rapid correspondence (e.g. walkie talkies, andon boards)		
FR TM11413	Solve problem immediately		
PS TM11413	Standard process to resolve and prevent disruptions		
TM11413-Q1	We follow standard procedures for resolving problems.		
TM11413-Q2	We have frequent group sessions where we discuss problems and develop solutions to prevent re occurrence		
TM11413-Q3	To keep production moving, we usually solve problems only temporarily. Re occurrence of the disruption is likely, since the root cause is not eliminated		
TM11413-Q4	How would you characterize your problem solving process?		
FR TM11421	Ensure availability of relevant production information		
PS TM11421	Capable and reliable information system		
TM11421-Q1	Our operators have access to all information regarding their tasks.		
TM11421-Q2	The operators always understand what to produce, when to produce, and how to produce		
TM11421-Q3	Operators have easy access to process information		
FR TM11422	Ensure tools and equipment are available		
PS TM11422	Maintenance of tools and equipment availability		

TM11422-Q1	We have standardize inventory for all required tools and equipment.		
FR TM11423	Ensure material availability		
PS TM11423	Standard material replenishment approach		
TM11423-Q1	We have standard levels of inventory between sub-systems for each part.		
TM11423-Q2	Our part suppliers deliver on a just in time basis.		
FR TM11424	Ensure predictable workers output		
PS TM11424	Motivated work force performing standard work		
TM11424-Q1	We time each operating step in detail and include the information in the work instructions.		
TM11424-Q2	Variation in work completion time is being solved either by adjusting the work method or through operator training		
FR OS11	Consider Physical Solutions from CSD thinking		
PS OS11	Keen attitude for satisfying Structure related Functional Requirements		
OS11-Q1	While designing Value stream Map we have tradition approach. (Reverse)		
OS11-Q2	We create the lists of Physical Solutions to implement on VSM creation process.		
FR OS112	Track the designing process		
PS OS112	Visual representation of created SMSDD		
OS112-Q1	Having visual representation of SMSDD helps us to track current designing stage.		

FR OS121	Cover all operations from the floor		
PS OS121	Participation of all production department members		
OS121-Q1	Participation of all member is necessary in creating Value Stream Map. (reverse)		
OS121-Q2	We include members from all department from the floor to cover all operations.		
FR OS122	Design material flow path		
PS OS122	Updated material Flow path based on thinking PSs		
OS122-Q1	While designing material path flow, we consider all PSs from Thinking Map branch.		
OS122-Q2	It is the best practice to consider structure related FR PS Pairs in Material flow path designing.		
FR OS123	Design information flow path		
PS OS123	Updated information Flow path based on thinking PSs		
OS123-Q1	Consideration of thinking Map branch PS is must in the process of designing information flow path.		
FR OS124	Make sure availability of material in between processes		
PS OS124	SWIP size		
OS124-Q1	We always determine the size of SWIP for assurance of availability of material while processes.		
OS124-Q2	We have determined sizes for all SWIPs in system.		

FR OS13	Verify designed VSM		
PS OS13	Lego Simulations		
OS13-Q1	We do scale calculations to replicate floor time with legos simulations.		
OS13-Q2	We exactly replicate Value stream Map design into legos simulations.		
OS13-Q3	Kanban cards are efficient to replicate the information triggers in the system.		

5.5 Summary

This chapter described the development and use of Sustainable Manufacturing System Design Decomposition Questionnaire. The questionnaire has 139 Likert-scaled questions associated with the leaf FR PS pairs. The developed questionnaire helps to gather information for future use cases.

CHAPTER 6. CONCLUSIONS AND FUTURE RESEARCH

6.1 Hypothesis Results

The alternate hypothesis of this thesis is that using the Sustainable Manufacturing System Design Decomposition (SMSDD) to design a manufacturing system does lead to design and implementation of an efficient and sustainable manufacturing system. The null hypothesis is that using the Sustainable Manufacturing System Design Decomposition (SMSDD) to design a manufacturing system does not lead to design and implementation of an efficient and sustainable organization. The thesis provides a logical argument regarding sustainability requirements in the form of the SMSDD and plan to test the research hypothesis.

Due to the breadth of the topic and time constraints, no experimental data are taken. Instead, a road-map for data collection and experimental validation is developed. The validation approach is two-fold. The creation of the SMSDD is considered a type of system design validation because it is constructed to follow the rules of Axiomatic Design. The SMSDD serves as a framework for defining and addressing ever-changing customer needs and system design requirements.

Secondly, the questionnaire provides additional validation as it provides the ability to assess how well the currently stated leaf Functional Requirements in the SMSDD are being achieved. The research hypotheses are formally stated as:

Ho: Using the Sustainable Manufacturing System Design Decomposition (SMSDD) to design a manufacturing system does not lead to an efficient and sustainable manufacturing system.

Ha: Using the Sustainable Manufacturing system Design Decomposition (SMSDD) to design a manufacturing system does lead to an efficient and sustainable manufacturing system.

6.2 Contribution to the Existing Body of Knowledge

This thesis brings together the bodies of knowledge considered by the Collective System Design Methodology and Manufacturing System Design Decomposition. This thesis identifies the internal and external customer needs for designing manufacturing systems and argues that a system can be sustainable only when the needs of the internal and external customers are recognized and met. In addition to identifying customer needs, this thesis provides the SMSDD as a system design framework to satisfy customer needs. This thesis argues that using the newly designed framework will design an effective and sustainable manufacturing system.

6.3 Future Research

The future research related to this thesis involves the validation of the created Manufacturing System Design Decomposition Questionnaire and implementation of Sustainable Manufacturing System Design Decomposition in the manufacturing enterprise. The future step is to implement the SMSDD as a framework and to observe the results in achieving the Functional Requirements state in the SMSDD. The research should be directed at feedback between procedures and corresponding Physical Solutions to achieve the Functional Requirements. Based on the results of future use cases, the SMSDD can be used as a framework to develop and to explore additional Functional Requirements and their respective Physical Solutions for achieving sustainability.

6.4 Vision for this Research

The long-term hope and vision for this thesis is that the changes and solutions that are implemented in manufacturing plants are made to sustain the manufacturing system for the long term. The main idea is that industrial engineers and workers from industries in the future are able to identify their Physical Solutions and have a complete idea of the Functional Requirements behind their work to develop effective Physical Solutions.

As a result, the common tendency of copying the solutions approach will be changed. With this new method of considering the internal customer needs, labor work tone will be positive and result in better efficiency and long-term sustainability since the people within a system are motivated to improve their own system and feel ownership in the design decisions.

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