A COMPARISION OF AXIOMATIC DESIGN THEORY AND SYSTEMATIC DESIGN PROCEDURE IN THE DESIGN OF A SOLID STATE FERMENTER

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ABSTRACT

Design theories and methodologies are guidelines to develop design solutions. Among many, the Axiomatic design theory (ADT) and Systematic design procedures (SDP) are two well-known approaches to design. For practical applications, the choice of the design methodology is difficult as there is no study to compare them. To close in such gap in literature, this thesis presents a study on comparison of these two design approaches. To facilitate the comparison, design of a solid state fermenter was taken as a vehicle.

The fermenter chosen for this study is was used for detoxification of phorbol esters from *Jatropha curcas*. *Jatopha curcas* is a woody plant and is one of the major sources for the production of bio-diesel as it is readily available and has unique composition. Processing *Jatopha curcas* for biodiesel also yields protein rich Jatopha curcas seed cake. This can be used as animal feedstock, cattle fodder or live feed stock. It is however known that phorbol esters present in the seed cake hinder the utilization of the seed cake as live feed stock. Solid state fermentation by fungi is an effective process to denature phorbol esters, which has been demonstrated at the laboratory scale. Development of an industrial scale solid state fermenter (SSF) is necessary.

This study applies SDP and ADT the same deign problem of SSF and compared based on the result of the design. It is noted that in ADT, the evaluation of design alternatives neither considers the cost of the system under design nor the delivery time of the system, but SDP does. To make the comparison on the same ground, an extension of ADT enabling it to consider the cost and delivery time (or time) was developed.

Several conclusions can be drawn from this study and they are: (1) ADT and SDP are complementary to each other and the one that integrates both is more effective to design; (2) The essence of Axiom 2 of ADT is to evaluate design alternatives with all factors that lead to difficulty to realize the design, but unfortunately the information content in the current ADT literature only considers the functional or quality aspect; (3) Previous reports suggest the presence of zigzag process only in ADT, However in this study it is evident that SDP exercises

the zigzag process as well; (4) the proposed formulation of information content by taking into consideration of the quality, cost, time aspects is more effective in design practice as quite often the cost and time are very important aspects to the customer.

The contribution of this thesis study is of two-fold. First, the SSF designed in this study is a pilot one in the field of the biochemical process and it has potential to be implemented. Second, this study concludes several unique findings of ADT and SDP with their relationship, which have further resulted in an integrated ADT and SDP design approach and a more complete formulation of information content capable of evaluating design alternatives from all aspects rather than the functional aspect only.

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DEDICATION

To:

Asher Sumay
Raj Bunnu
Esther Anuhya

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LIST OF ABBREVATIONS

DTM	Design theories and methodologies
ADT	Axiomatic design theory
SDP	Systematic design procedure
SSF	Solid state fermentation
FR	Functional requirement
DP	Design parameter
T	Temperature
R.H.	Relative humidity
S	System range
D	Design range
C	Common range

Chapter 1 INTRODUCTION

1.1 Research Background and Motivation

Design theories and methodologies (DTM) for general products are developed in the design research community and are taught in the school. However, their application to the real-life design problem is not convincing to industry (Zhang et al., 2012). It was thus an intention of this thesis to study the bottle-neck issue that may hinder the application of the design theories and methodologies. Two DTMs are chosen for a deep examination, which are Axiomatic Design Theory (ADT) (Suh, 1990) and Systematic Design Procedure (SDP) (Pahl and Beitz, 1984). To facilitate the comparison, design of a solid state fermenter for Jatropha was used as a vehicle.

Jatropha is a weed plant that can grow widely in arid conditions unsuitable for most food crops. Its seed oil can be used in the production of biodiesel fuel. In 2007 Goldman Sachs cited *Jatropha* as one of the best candidates for future biodiesel production. It is drought and pest resistant and produce seeds containing 27-40% oil, averaging 34.4% (Rakshit et al., 2008). Likewise, *Jatropha* oil is being promoted as an easily grown bio-fuel crop in hundreds of projects throughout Brazil and South East Asian countries.

"Jatropha seeds generate a large quantity of residual de-oiled seed cake with an average rate of 500 gm cake per kg of the seed used (while the oil is an excellent bio-diesel feedstock). The average chemical composition of de-oiled seed cake is: protein (60%), fat (0.6%), ash (9%), fibre (4%) and carbohydrates (26%)" (Belewu et al., 2010). However, the presence of several anti-nutrients in the de-oiled *Jatropha* curcas seed cake such as trypsin inhibitor, lectin, tannins, saponins, phytate and phorbol esters hinders its utilisation as animal feed stock. All these anti-nutrients except phorbol esters can be removed either by chemical or physical methods (Joshi et al., 2011). The phorbol esters possess a complex structure which cannot be digested by animals that restricts its use as live feed stock. However, if the seed cake is left to decay on its own, it will create environmental problems (Ahmed and Salimon, 2009).
Removal of phorbol esters is thus an important issue to be addressed. Various methods (physical, mechanical and chemical) of detoxification are documented in literature (Aderibigbe et al., 1997

Makkar and Becker, 1999). The biological method of detoxification is still at its beginning stage except for a few reports (Peace and Aladesanmi, 2008; Belewu et al., 2010), which used different fungi for the fermentation of *Jatropha* cake.

Fortunately, recent studies have found that the solid state fermentation of *Jatropha* seed cake can detoxify the anti-nutrients present in the seed cake. This biological method of detoxifying *Jatropha* seed cake has been used in a controlled condition with fungi. This method of detoxifying the seed cake has been highly successful at the laboratory scale. In this thesis, the laboratory level was scaled up to a higher level or scale. There were three questions proposed for this thesis:

Question 1: What is the best design for an industrial scale solid state fermenter?

Question 2: What is the relationship between the two DTMs?

Question 3: What are some specific obstacles in the application of the two DTMs?

1.2 Research Objectives

Based on the above discussion, specific research objectives were defined as follows:

Objective 1: Apply the SDP to the design of an industrial scale solid state fermenter for the detoxification of *Jatropha* seed cake. Specifically, the work should (1) find possible design solutions and (2) find the best one.

Objective 2: Apply the ADT to the design of an industrial scale solid state fermenter for the detoxification of *Jatropha* seed cake. Specifically, the work should (1) find possible valid design solutions.

Objective 3: Apply Axiom 2 of ADT to obtain the best design based on the design solutions generated from the first two objectives.

Objective 4: Compare ADT and SDP to lead to a more effective guideline for design.

The research was focused mainly on the application of the design theories and methodologies to the design of the industrial scale solid state fermenter. The research possibly generates the answers to the three questions as proposed in Section 1.1. It is further noted that the design solution makes sense at the so-called conceptual design phase.

1.3 Outline of the thesis

This thesis consists of six chapters. The remaining five chapters are outlined as follows:

In **Chapter 2** the literature review is carried out to further confirm the need and significance of the research objectives as described before. The literature review is focused on the two DTMs (ADT and SDP) and also on the background of the solid state fermenter as well as the composition of the seed cake and the morphology of the fungi.

In **Chapter 3** the design result and how the result is obtained by applying the SDP is discussed. The content of this chapter corresponds to the first research objective.

In **Chapter 4** the design result and how the result is obtained by applying Axiom 1 of ADT is discussed. The content of this chapter corresponds to the second research objective.

In **Chapter 5** the best design solution by applying Axiom 2 of ADT is derived and in this chapter, new information content called aggregate information content is proposed to modify the information content in the current literature. Axiom 2 is then applied to the aggregate information content to lead to the best design of SSF. The content of this chapter corresponds to the third research objective.

In **Chapter 6** the relationships of the ADT and SDP is discussed. The discussion eventually leads to a more effective guideline for design by combining ADT and SDP. The content of this chapter corresponds to the fourth research objective.

In **Chapter 7** the thesis is concluded with discussions. The best design solution for solid state fermenter, the research contribution out of this thesis, and future work is presented.

Chapter 2 LITERATURE REVIEW

2.1 Introduction

In this Chapter, literature review necessary to facilitate the understanding of this thesis, in particular the proposed research objectives and scope discussed in Chapter 1 is detailed. Section 2.2 introduces *Jatropha Curcas* and its applications including bioprocessing of it. Section 2.3 presents some basic concepts of design. Section 2.4 discusses Axiomatic design theory (ADT) (Suh, 1990). Section 2.5 discusses relevant research on Systematic design procedure (SDP) (Pahl and Beitz, 1984).

2.2 *Jatropha curcas* and the utilization of its seed cake as animal feedstock

Jatropha curcas L. Linnaeus 1753 is a small shrub plant which grows wildly in the tropics and sub-tropics. It is also known as physic nut or purging nut and is an important industrial crop that belongs to Euphorbiaceae family. For the biodiesel production, jatropha is used as a source in many of the Asian countries (Saetae and Suntornsuk, 2010). “The seed material comprises of 41% shell and 59% kernel. The kernel consists of 40–50% of oil” (Singh et al., 2008). According to Zanzi et al., (2008) Jatropha seeds can generate large quantity of de-oiled seed cake. The Jatropha oil can be utilized as biodiesel (Liang et al., 2010). The seed cake has a high potential to complement and substitute soybean meal as a protein source in livestock diets (Makkar et al., 1997).

The oil when extracted from Jatropha results in Jatropha oil and seed cake. The cake is found to contain a crude protein content between 57 and 64% with 90% true protein. With the exception of lysine, the amino acid is higher than FAO preference protein required for animal well-being and growth. However, *Jatropha curcas* contains some toxins and anti-nutrients (Cyanide, saponin, tannin, phytate, etc). *Jatropha curcas* which is found growing in semi-arid, arid and tropical environments contain various anti-nutrients which if properly processed could be used to replace most conventional feed stuffs (Belewu et al., 2009).

The percentage of essential amino acids and mineral contents can be comparable to those of other seed cakes used as a fodder (Trabi et al., 1997). According to Rakshit et al., (2008), *Jatropha curcas* contains various anti-nutrients like trypsin inhibitor, lectin, tannins, saponins, phytate and phorbolester. The average chemical composition of de-oiled seed cake is protein, 60%; fat, 0.6%; ash, 9%; fibre, 4% and carbohydrates, 26%. The presence of phorbol esters hinders the utilization of Jatropha seed cake as animal fodder. “Phorbol esters have been identified as main toxicants in cake which could not be destroyed even by heating at 160^{o}C for 30 min” (Makkar et al., 1997; Joshi et al., 2011). Phorbol ester compounds leads to toxicity in “Jatropha’ (Goel et al., 2007; Joshi et al., 2011). “Toxicity to snails” (Amin et al., 1972), “goats” (Adam and Magzoub, 1975; Joshi et al., 2011), “pigs” (Chivandi et al., 2006; Joshi et al., 2011), “rats” (Rakshit et al., 2008; Joshi et al., 2011), “humans” (Rai and Lakhanpal, 2008; Joshi et al., 2011), and “mice” (Li et al., 2010; Joshi et al., 2011) has been reported consequent to the consumption of Jatropha seeds or their seed cake. All these restrict the feed uses of the seed cake.

The toxins present in *Jatropha curcas* can be removed either by chemical or physical methods while phorbol ester is the most difficult toxin to be detoxified by these methods (Makkar et al., 1998; Makkar and Becker, 1999). However several biological methods of detoxifying the toxins are reported in the literature by (Peace and Aladesanmi, 2008; Belewu et al 2010) who used different fungi for the fermentation of Jatropha cake.

Various chemical methods to detoxify the toxins in Jatropha were tried, however the results doesn’t show up any detoxification of the toxins (Makkar et al., 1997; Areghore et al., 2003). Belewu (2008) carried out work on the detoxification of phorbol esters using dietary fungus (*Trichoderma harzanium*) but ended up with negative results. It should be noted that the fungus could produce some extracellular protein and enzymes which could degrade cellulose and chitin. These metabolites produced are not effective in detoxifying the most complex phorbol ester.

Fermentation has always been an important part of our lives and it has some benefits in addition to food. It can produce vital nutrients or eliminate anti-nutrients. Fermentation uses up food energy and can make conditions unsuitable for undesirable microbes. Belewu et al. (2010) reported on the effect of fungi treated *Jatropha curcas* kernel cake with encouraging results. Belewu and Sam (2010) noted that *Aspergillus niger* inoculated *Jatropha curcas* kernel cake can give a crude protein content of 65.75% which was similar to 63.06% found in Trichoderma longibrachiatum treated *Jatropha curcas* kernel cake. Belewu et al. (2010) opined that goat fed diet containing 50% Soybean meal plus 50% *Rhizopus oligosporus* treated *Jatropha curcas* kernel cake under confinement consumed adequate dry matter and other nutrients. Hence Belewu et al. (2010) evaluated the efficacy of cocktail of fungi (*Trichoderma harzanium, Penicillum sp, Trichoderma longibrachiatum, Aspergillus Niger*) on the biodegradation of *Jatropha curcas* kernel cake.

In the recent studies, detoxification of phorbol esters from *Jatropha curcas* seeds was carried out by using five different fungi belonging to the group of basidiomycetes. These fungi are generally regarded as 'mushrooms'. Most of these fungi produce a complex set of extra cellular enzymes such as laccase which are capable of degrading lignin, a complex bio-polymer present in wood. The enzymes are also referred to as ligninolytic enzymes which are highly non-specific (Muddada et al., 2012) and have the ability to degrade most of the hazardous chemicals including, complex hydro carbons, pesticides, dyes, poly-phenols, esters, etc. Hence, these fungi were selected for detoxification of phorbol esters by solid state fermentation (Muddada et al., 2012).

In the presence of de-oiled cake, all the fungi in solid plates have shown a very good growth. Growth of fungi was observed within two days of incubation at 30^{o}C. These observations have shown that the fungi have the ability to grow on de-oiled cake by using Jatropha seed cake as a substrate.

In the solid state substrate, no other media components are provided but still organism shows the growth. The growth of the organism starts within second day and continues till 14 days. Among the five fungi, the fungi *peniophora sp and p.noxius* showed the highest mycelial growth than others. It was found that the fungi used were able to detoxify the phorbol esters present in the Jatropha seed cake. It could be concluded that incubation of *Jatropha curcas* kernel cake with white rot fungi is promising as it can reduce the phorbol ester contents of the cake significantly so as to make a renewable feed for livestock animals (Muddada et al., 2012).

2.2.1 Production of laccase by *peniophora Sp* and *P.Noxius*

The food, agricultural and forestry industries produce large volumes of wastes annually which cause a serious disposal problem. In addition, the reutilization of biological wastes shows a great interest, since due to legislation and environmental reasons the industry is more and more forced to find an alternative use(s) for its residual matter. Most of such wastes are rich in soluble carbohydrates and also contain inducers of laccase synthesis, ensuring an efficient production of laccase. Furthermore, agro-wastes have shown to produce higher laccase activities than inert supports for the same fungal strain and culture conditions (Couto et al., 2007).

Solid state fermentation (SSF) holds a tremendous potential for the production of enzymes. It can be of special interest in those processes where the crude fermented product may be used directly as the enzyme source. In addition to the conventional applications in food and fermentation industries, microbial enzymes have attained a significant role in bio-transformations involving organic solvent media, mainly for bioactive compounds. SSF systems offer numerous advantages, including high volumetric productivity, relatively higher concentration of the products, less effluent generation as requirements for simple fermentation equipment (Couto et al., 2007).

Since the biotechnological applications require large amounts of low cost enzymes, one of the appropriate approaches for this purpose is to utilize the potential of lignocellulosic wastes, some of which may contain significant concentrations of soluble carbohydrates and inducers of enzyme synthesis ensuring the efficient production of ligninolytic enzymes (Elisashvili et al., 2001; Reddy et al., 2003; Moldes et al., 2004). The selection of appropriate plant residue adequate for fungus growth and target enzymes synthesis plays an important role in the development of an efficient biotechnology. The lignocellulolytic enzymes of basidiomycetes are of fundamental importance for the efficient bioconversion of plant residues and they are prospective for the various biotechnological applications in pulp and paper, food, textile and dye industries, bioremediation, cosmetics, analytic biochemistry, and many others.

The selection of a substrate for enzyme production in a SSF process depends upon several factors, mainly related with availability of the substrate, and thus may involve screening of several agro-industrial residues. In a SSF process, the solid substrate not only supplies the nutrients to the microbial culture growing in it but also serves as an anchorage for the cells. The substrate that provides all the needed nutrients to the microorganisms growing in it should be considered as the ideal substrate. However, some of the nutrients may be available in sub-optimal concentrations, or even absent in the substrates. In such cases, it would become necessary to supplement them externally with these. It has also been a practice to pre-treat (chemically or mechanically) some of the substrates before using in SSF processes, thereby making them more easily accessible for microbial growth.

Given the potential applications of laccases and the need for the development of economical methods for improving laccase production from fungi with an overall aim to reduce the cost of the industrial processes, the use of SSF, especially using plant byproducts as a support-substrate, is an appalling alternative.

2.2.2 Solid state fermenter

A solid state fermenter facilitates the space and environment for the process of solid state fermentation by providing the suitable conditions for the fungi to produce the enzymes. Depending on the type of substrate used and parameters considered in the solid state fermentation, the type of fermenter was classified in (Raghavarao et al., 2003).

For the design of a solid state fermenter, the key is to provide the space to perform the solid state fermentation process. The solid state fermentation process faces the major problem of contamination that has to be eliminated in order to perform the fermentation processes without affecting the fungi. The fermenter should also be effective in avoiding the entry of foreign ailments that can interfere with the process of fermentation in the reactor (Raghavarao et al., 2003).

The solid state fermentation process requires the minimal water content that has to be maintained in the substrate that is used in order to aid the fungi for SSF. Therefore a solid state fermenter has to be effective in providing the sources that can maintain the water content on the substrate (Raghavarao et al., 2003).

The distribution of fungi is another important perspective that should be considered while designing a solid state fermenter in order to provide the uniformity of the fungi throughout the substrate to detoxify or survive its particular purpose throughout the substrate (Raghavarao et al., 2003).

Fermenters can be classified into tray or drum type based on the orientations of the structures of the substrate holders in a fermenter. A tray type or drum type fermenter was used mostly in the case of a large scale SSF (Pandey, 1991). In a tray type fermenter, the platforms of holders are mostly of the wooden or metallic that does not interact with the substrate and fungi used in the process. These trays were generally arranged such that they are one above the other and maintain suitable gaps in between them (Pandey, 1992). In a drum type fermenter, a drum shaped reactor is designed in which the process of fermenter takes place in the drum space that is cylindrical area. The drum space consists of the inlet and outlets for air to pass through if needed. This type of reactors possesses the disadvantage of the particle aggregation at the bottom (Pandey, 1992).

For the fungi present in the solid state fermenter, the environment for their growth and synthesis of the enzymes are required. Maintenance of temperature, relative humidity, pH and water content within the reactor is crucial for fungal growth in the reaction. These parameters depend on the type and morphology of the fungi. Apart from maintaining these parameters, monitoring of these parameters should also be considered in design (Durand, 2003).

2.2.3 Maintenance and monitoring of parameters in solid state fermenter

Relative humidity and water content:

The presence of water content is an important factor in the process of SSF. The moisture required by the fungi is extracted from the water content present in the substrate (Lonsane et al., 1985). The water content is maintained in the process of solid state fermenter as high water content would lead to decreased porosity and low water content would leadsub-optimal growth of fungi. These drawbacks caused by increase or decrease in moisture content can beeliminated in the design of the SSF by including the monitoring devices or equipment in the design of the SSF (Lonsane et al., 1985).

Temperature:

The process of fermentation leads to the generation of metabolic heat in the reactor. The fungi used in the reactor works efficiently at a certain range of temperature. Therefore, in the reactor the temperature should be maintained and controlled. The temperature in the reactor is monitored in order to prevent the damage to the fungi in case of high temperatures developed in the reactor due to metabolism as well as low temperatures is prevented in order to control the mould growth in the reactor (Lonsane et al., 1985).

pH:

pH also plays a vital role in the process of SSF. The pH needs to be maintained in the reactor in order to provide the perfect environment for the fungal growth as well as its reaction to perform the specific task for which it was used in the reactor. Therefore the pH in the reactor is controlled and maintained for the optimal fungal growth and SSF (Lonsane et al., 1985). The pH in the reactor needs to be monitored in order to prevent acidification or basification of the substrate in the reactor (Lonsane et al., 1985).

Agitation:

In the process of SSF the distribution of the fungus needs to be carried for the uniformity of the process. Therefore in order to achieve this process, agitation of the fermenting substrate is done for the uniformity and optimal growth of the fungi (Lonsane et al., 1985).

2.3 Design and design process

Design is a process through which new products, processes, and organizations are created or synthesized in order to satisfy society's needs under certain conditions; the products, processes, and organizations can be generally called systems as they all have the structure. Design is thus to determine the structure of a product, process or organization (Pahl and Beitz, 1984). Generally, the design world is classified into four different domains which are the consumer, functional, physical and process domains. The whole process of design is to relate or map these four domains (Suh, 1995).

The functional domain includes what a product is ought to achieve as well as conditions where the product functions are described. The physical domain includes connected components of a product as well as the principle behind the connected components, which explains why the connected components can achieve the expected function of a product (Suh, 1995).

The process of design starts from deriving the functions of a product from the consumer needs for a product, and these functions have to be satisfied by the components in the physical domain. The consumer needs are confined to the consumer domain of the design in which the final product to be designed can satisfy the requirements stated in it. From the requirements in the consumer domain the design objectives of the functions of a product are defined which are called as the functional requirements (FRs). In order to satisfy the functional requirements in the functional domain physical solution were created in the form of design parameters (DPs) and the process of mapping these functional requirements to the DPs is nothing but the design process (Suh, 1995).

One of the main steps of the design process is to develop a function structure or problem structure based on the customer needs or requirements. A function structure is developed for product design by gathering or assembling the requirements initiated by the consumer needs. Similarly, the problem structure is developed in order to derive solutions for the design problems that involve more of problem solving rather than product manufacturing.

The last step in the process of design involves the development of the product structure for the function structure or development of the solution structure for the problem structure which would complete the conceptual design of systems or products.

2.4 Axiomatic design theory (ADT)

The ADT is based on the axioms that have a premise to lead to a good design. Based on (Suh, 1995) observation of good design practices, the ADT identifies Axiom 1 and Axiom 2 as a criterion to check out the best design (Suh, 1995). The following is an overview of ADT drawn from the literature (Suh, 1995; 1990).

In the axiomatic approach the design process is made out of four domains (i.e. consumer, functional, physical and process domain), as mentioned before. In this thesis, focusses only on the functional domain and physical domain, that is, the concern is mainly on the FR-DP relations. In ADT, the FR-DP relation is expressed by a matrix; see below.

$$\{FRs\} = [A]\{DPs\} \tag{2.1}$$

In the above equation, {FRs} is a matrix that consists of the set of FRs, and {DPs} is the matrix that consists of the set of DPS.

Axiom 1 in ADT is stated as (Suh, 1990): "*maintain the independence of the functional requirements.*"

Axiom 1 may also be called independence axiom. In order to satisfy Axiom 1 of ADT, the matrix A should be either a diagonal or triangular matrix. In the case of a diagonal matrix, each of the FRs is independently satisfied by one DP. Such designs are called uncoupled designs. When it comes to a triangular matrix, the independence of the functional requirements can be maintained only if the DPs are modified or changed in a particular order. Such types of designs are called decoupled designs (Suh, 1995).

The type of design such as coupled, uncoupled or decoupled was defined based on the relationship between the functional requirements and design parameters. Axiom 1 plays an important role in determining them. Whenever the independence of the functional requirements of a design is maintained, the design is called uncoupled designs. In uncoupled design the mapping of the functional requirements to the design parameters is path independent, which means that any of the functional requirements can be modified or removed without disturbing or effecting the other functional requirements (Suh, 1990). In the decoupled design the independence of FRs (Axiom 1) holds well until and unless the design parameters were fixed. In this case unlike the uncoupled design, the FRs cannot be changed or modified independently but they must follow a particular path. The coupled design is a type of design which does not satisfy Axiom 1. In a coupled design, the change in a particular design parameter would not only affect its respective functional requirement but also the other functional requirement, which leads to the dependency of the functional requirements (Suh, 1990).

According to ADT (Suh, 1990), in the first step of the design, the set of design solutions that satisfy Axiom 1 has been created. Next, the best in this set needs to be found, and this is achieved by another axiom (Axiom 2).

Axiom 2 of ADT is stated as (Suh, 1990): *"minimize the information content of the design.*"

Axiom 2 may also be called information axiom. According to Axiom 2, the design with the least information content is the best design (Suh, 1995). It is noted that the information content is defined as the probability of satisfying the chosen FRs. In general, the information content (I) is given by

$$I = \sum_{i=1}^{n} \log \left(\frac{1}{p_i}\right) \qquad (2.2)$$

In the above equation, p_i is the probability of the design parameter satisfying the respective FR_i. In case of n number of FRs, the total information content is the sum of individual information contents for each of the FRs under the assumption that all FRs are independent.

The probability of success assuming all probability density functions are a uniform distribution (Suh, 1995) can also be defined in terms of design range, system range and common range according to Suh (1995). The design range is defined as a range of values for the FRs, which is specifically defined by the designer. The system range is defined as a range of values that are provided by the proposed solution in order to satisfy the FRs. The common range is defined as a range of intersection between the design range and system range. The information content in this case can be expressed by

$$I=\log \text{(system range/common range)} \qquad (2.3)$$

For an ideal uncoupled design, the number of FRs is equal to number of DPs. Therefore, the information content is zero or the design matrix is diagonal.

2.5 Systematic design procedure

The systematic design procedure (SDP) approach consists two phases: product planning and product development. The following is an overview of these two phases drawn from the literature of Pahl and Beitz (1984).

2.5.1 Product planning

Product planning aims to know the context of a product development in design, which includes the information of the customers idea and is about a product to be designed and type of design. This context helps to decide where a product design is to start with.

The product planning phase also produces a design, problem statement and a technical specification (Pahl and Beitz, 1984). For instance, a product is totally a novel one, which means the function of the product is unique. In this case, the design needs to start with finding the principle of design solutions. A design may just be to optimize the size of a component or connection. In this case, product planning also determines the resources available to conduct product development, which include the human resource (i.e. design team) and method. Specifically, the resource and method ensures the success of finding design solutions and the success of finding the best design solutions. In SDP, the following methods are proposed for finding design solutions, namely conventional methods, intuitive methods and discursive methods (Pahl and Beitz, 1984). The conventional methods include gathering information by surveying, exploring patents, studying publications, literature review and so on. It also includes analysis of natural and technical systems. In the intuitive methods, the designer finds a solution based on its intuition. Brainstorming, Delphi method plays a major role in this case to find out solutions. Brainstorming mainly involves stimulation of ideas based on the problem. Whereas in the Delphi method, solutions depends on spontaneous suggestions given by a group of designers which are analyzed and evaluated accordingly. The discursive method follows a systematic search or study of physical processes (Pahl and Beitz, 1984). Further, in SDP, it is the scope of task in product planning to provide certain methods to identify the criteria to evaluate the design solution and weighing the criteria (Pahl and Beitz, 1984).

2.5.2 Product development process

The goal of product development is naturally to produce a product. If design is meant for development, the goal is to produce a document that specifies the design. According to SDP, there are the following activities at the product development phase such as task clarification, conceptual design, embodiment design and detail design. In this thesis, only the first two activities are of concern.

I. Task clarification

To refine the design specification created at the product planning phase and to eliminate any unnecessary and redundant requirements.

II. Conceptual design

According to SDP, the conceptual includes the following steps or activities such as defining a function structure, finding solutions, defining concepts and variants and evaluating variants. These activities are briefly discussed in the following.

(1) Defining a structure: It is noted that in SDP, the function is defined as an input-output relation that involves energy, material, and/or signal. It is usually the case that an overall function is to generalize such a physical entity or design. Design solution can be found to fulfill the overall function. Therefore, in most of the cases, an overall function needs to be decomposed into a set of sub-functions. From here, it makes sense to speak of the notion of function structure. According to SDP, a so-called abstraction of design problems may precede establishing a function structure, as the abstraction may lead to a level of simplicity (likely reducing the number of availabilities or constraints via abstraction).
(2) Searching for working principles: In SDP, the notion of working principles or solution principles was proposed. The working principles are the knowledge that governs the solution in particular the particular input-output relation (Zhang et al., 2005). For each of the sub-functions, the working principle or solution needs to be found in order to fulfill the design. The working principle or solution generally gives the physical effect for that a particular function or sub-function in order to fulfill it. The methods gathered in product planning phase will be employed for each of the sub-functions. It is to be noted that more than one solution may be found quite naturally, the solution principles need to be integrated to the one corresponding to the overall function. The integration includes the compatibility analysis among DPs.
(3) Developing concepts or conceptualization: In SDP, the concept is defined as an entity which is quantified to demonstrate how a solution principle works. Therefore, the conceptualization

of a solution principle will lead to a solution. Different ways of conceptualization lead to different solutions, and they are further called solution variants as they are from the same working principles. The process of conceptualization depends on specific working principles and thus domain specific knowledge. In SDP, the criteria to evaluate the solution variants are: simple construction, simple operation, easy maintenance, accessibility, safety, simple assembly, low complexity, bought out parts and few operational errors.

(4) Evaluation of solution variants: The weight on each of these criteria is determined subjectively by the designer.

Chapter 3 APPLICATION OF SYSTEMATIC DESIGN PROCEDURE TO THE SOLID STATE FERMENTER

3.1 Introduction

This chapter deals with the application of SDP for the design of the SSF, which detoxifies the *Jatropha* seed cake using the fungi *peniophora sp and p. noxius*. The design of this particular SSF is pilot design.

3.2 Problem statement

As discussed in Section 2.2, *Jatropha curcas* is a potential source of bio-diesel and the bi-product (which is the seed cake of *Jatropha curcas*) is rich in protein content. The Fungi *peniophora sp and p. noxius* has the potential to detoxify the toxic contents from the *Jatropha* seed cake through solid state fermentation (SSF). Therefore, the design problem statement would be "To design the solid state fermenter to detoxify the seed cake of *Jatropha curcas* by maintaining the optimum conditions for the fungi to degrade the phorbol esters present in the seed cake".

3.3 Assumptions of the design

The following are the assumptions of the design:

(1) The capacity of fermenting is 100kg of seed cake.
(2) The fermentation takes 7 days (Muddada et al., 2012).

3.3.1 Requirements of the SSF

The general requirements of this solid state fermenter are:

(1) Perform the solid state fermentation.
(2) Maintain the conditions of the process of the solid state fermentation.
(3) Able to detoxify the phorbol esters under the controlled conditions.

Table 3.1 gives a complete list of function requirements that are required of the solid state fermentation of Jatropha seed cake.

Table 3.1 Complete list of function requirements

REQUIREMENTS LIST
▪ Ferment the substrate
▪ Use a particular media
▪ The substrate is *Jatropha* Curcas
▪ Maintain moisture content
▪ Maintain temperature
▪ Maintain required pH
▪ Maintain Relative humidity
▪ Load the substrate
▪ Supports for holding the substrate
▪ Accessible locations
▪ Easy operations
▪ Environmental friendly
▪ Record the quantities
▪ Prevent contamination
▪ Hold the substrate
▪ Power consumption
▪ Maintain agitation
▪ Inoculation
▪ Nutrition for fungus
▪ Detoxify the phorbol esters

3.4 Conceptual design

The conceptual design is explained in detail in the following sections. The overall flow of conceptual design is shown in Figure 3.1.

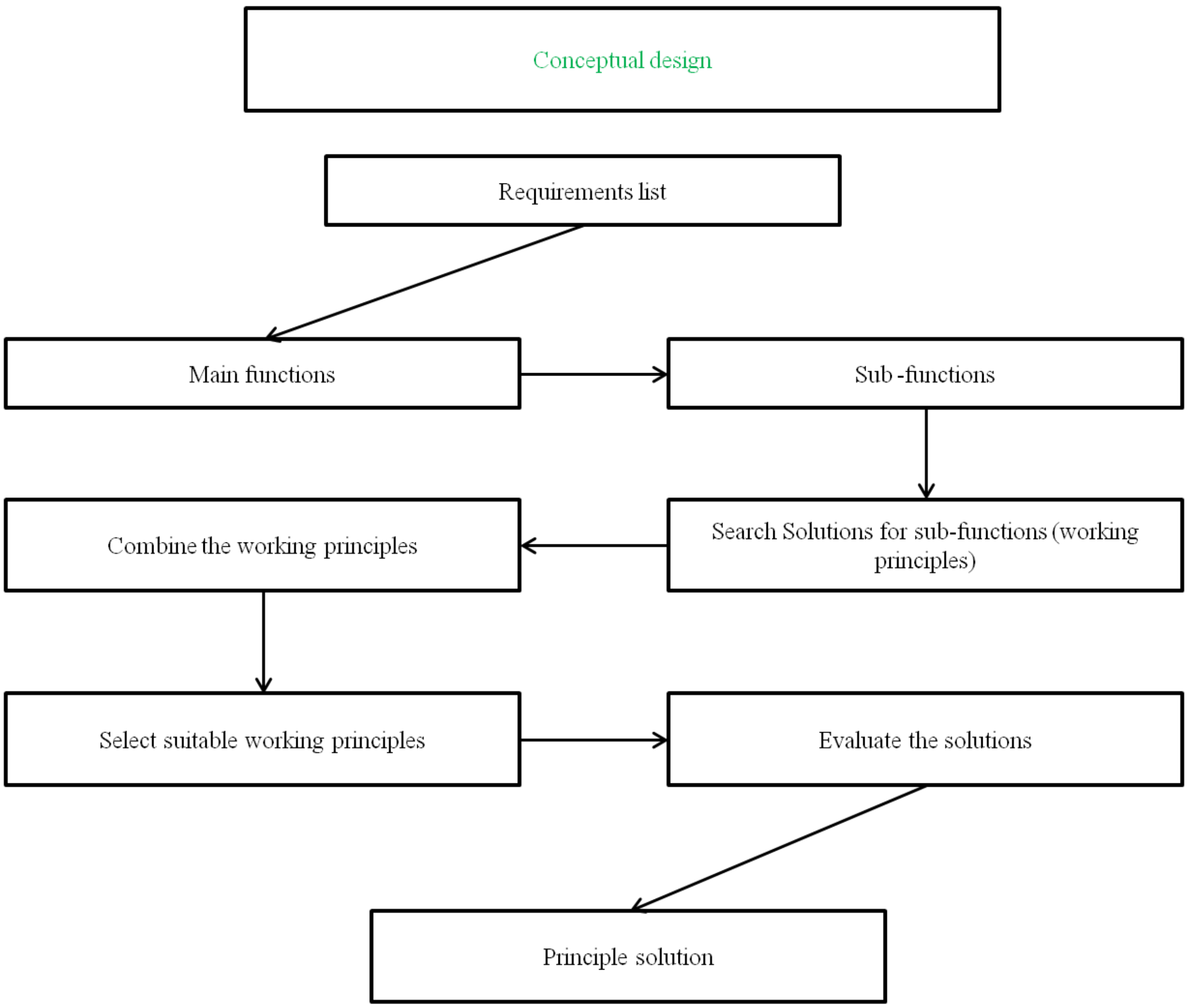

Figure 3.1 Steps for the Conceptual Design

3.4.1 Refine the requirements list

The complete list of function requirements stated in the above section is refined in this section by following the steps:

Step 1: eliminate personal preferences.

Step 2: omit requirements that have no direct bearing on the function and the essential constraints.

Step 3: transform quantitative data and reduce them to essential statements.

Step 4: generalize the results of the previous step as far as it is purposeful.

Step 5: formulate the problem in solution-neutral terms.

The five steps have been applied on the initial set of requirements and by eliminating the personal preferences and omitting the requirements that have no bearing on the function, and the results are listed in Table 3.2. For example, in this design, the requirement such as using a particular media has no direct effect on the function. This is because any type of media can be used for the solid state fermentation and similarly, we can design any fermenter that can have different locations but it does require that it has to have the perfect accessible location, only the perfect and best accessible location of accesses leads to the design to be ideal and convenient to handle. Similarly, for the other requirements such as easy operation, environmental friendliness, manufacturing cost, and power consumption have no effect with the solid state fermentation process and hence they are omitted and the refined list of requirements is generated.

Table 3.2 Refined Requirements List

REFINED REQUIREMENTS LIST
▪ Ferment the substrate
▪ Maintain moisture content
▪ Maintain temperature
▪ Maintain required pH
▪ Maintain relative humidity
▪ Load the substrate
▪ Supports for holding the substrate
▪ Prevent contamination
▪ Maintain agitation
▪ Inoculation
▪ Detoxify the phorbol esters

The third step, that is conversion of the quantitative data to a qualitative data, has been obtained in Table 3.3. Similarly, steps 4 and 5 are also applied to the previous step and it results in formulating the problem solution in a neutral way given in Table 3.4 and Table 3.5.

Table 3.3 Conversion of the quantitative data to a qualitative data

▪ Load the substrate such that the fermenter can hold the substrate and the media is inoculated and it is maintained in aseptic conditions. ▪ Maintain the temperature, pH, Relative Humidity and moisture content in the fermenter.

Table 3.4 Generalizing step-3 which is Step-4

▪ Carry out Solid State fermentation. ▪ Measure/maintain the parameters.

Table 3.5 Problem in solution neutral terms Step-5

▪ Apply Solid State Fermentation to detoxify the seed cake of *Jatropha* Curcas by monitoring and maintain the parameters.

3.4.2 Main function

The complexity of a problem depends on the complexity of the overall function. In this case, the overall function is, "applying the SSF to detoxify the *Jatropha* seed cake by monitoring the parameters", which was obtained from Table 3.5. The complexity involved in this function is that applying solid state fermentation, detoxifying and monitoring the temperatures possess three different characteristics, and therefore it is always complicated to deal with these three variables together. So the overall function is split to the main functions as shown in Figure 3.2.

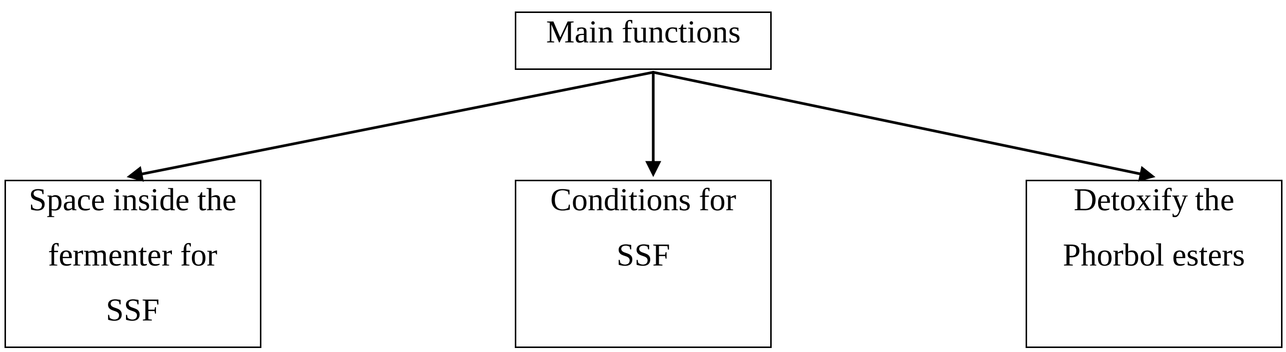

Figure 3.2 Main functions for the design of solid state fermenter

3.4.3 Sub-function

Any system can be divided into subsets and elements, so can any complex function or overall function is further broken-down to sub-functions of lower complexity. Basically, the combination of individual sub-functions would result in the function structure which apparently represents the overall function.

The purpose of breaking down the main functions is to determine the sub-functions of lower complexity to facilitate the subsequent search solution and to combine these sub-functions into a simple unambiguous function structure. The breakdown of the main function is shown in Table 3.6. These sub-functions are numbered accordingly and are presented in Table 3.7.

Table 3.6 Breakdown of the main functions

Main functions	Sub-Functions (SF)
Space inside the fermenter for SSF	○ Prevent contamination ○ Hold substrate ○ Support structures ○ Inoculation of fungi
Conditions for SSF	○ Monitor temperature (T) ○ Monitor pH ○ Monitor relative humidity (R.H)
Detoxify the phorbol esters	○ Maintain T and R.H ○ Maintain pH ○ Maintain moisture content ○ Distribution of fungi

3.4.4 Defining solution principles or working principles

For every sub-function (SF) stated in the above section, solution principles (SP) has to be derived. In this section, the possible SPs for all the SFs are found and given in Table 3.8. For every SP, there might be more than one SP.

Table 3.7 Sub-Functions derived from the main functions

	SUB-FUNCTIONS
SF 1	Prevent Contamination
SF 2	Hold Substrate
SF 3	Support Structures
SF 4	Inoculation of Fungi
SF 5	Monitor Temperature
SF 6	Monitor pH
SF 7	Monitor Relative Humidity (R.H)
SF 8	Maintain Temperature T and Relative Humidity (R.H)
SF 9	Maintain pH
SF 10	Maintain Moisture Content
SF 11	Distribution of Fungi

3.4.5 Combining working principles

Once the set of working principles is obtained, the next step is to generate an overall solution by combining the working principles. For each sub-function, there are several working principles i.e., each sub-function can be satisfied by different working principles as shown in Table 3.8. Therefore by combing each working principle for each sub-function an overall working structure or solution is generated, which has many. The combination is based on the establishment of physical and logical association of the sub-functions.

In this section, the sub-functions and respective solutions or working principles are listed in Table 3.8. The solutions or working principles are combined systematically by fulfilling specific sub-function with the neighboring sub-function in the table next to the working principle. This has to be done by combining only the possible and compatible working principles for each sub-function. Since there are several working functions for each of the sub-functions, the most compatible combinations are derived in this section. The compatible combinations are illustrated in Table 3.9, 3.10, 3.11, 3.12, and each of the tables has a different solution for each of the sub-functions.

Table 3.8 Solutions or working principles for each sub-function

Sub-Functions	Possible Solutions or working principles				
Hold Substrate	Trays	Drums	Conical Flasks	Packed bed	
Support Structures	Shelves Spaces	Drum holders	Flask holders	Cylindrical Support	
Prevent contamination	Closed containers	Covering drums	Tube boxes	Lid type for cylindrical Supports	
Inoculation	Serological pipette	Transfer pipette	Inoculating needle	Inoculating loop	
Measure T	Thermocouples	Thermistors	Pyrometer	Langmuir probes	Thermometers
Measure pH	Pen type	Conductivity meter	Membrane pH	pH electrodes	
Measure R.H	Hygrometers	Psychrometer	Capacitive humidity sensors	Thermal conductivity sensors	Hair tension hygrometer
Maintain T and R.H	Exhausts	Forced Air	Air conditioning		
Maintain pH	Add alkali	Add base			
Maintain water content	Evaporative cooling	Sprinkling water			
Distribution of fungi	Continuous agitation	Periodic agitation	Hand agitation		

Table 3.9 Combined solution principle-1

Sub-Functions	Solution Principles
SF 1	SP 1 (Drums)
SF 2	SP 2 (Drum holders)
SF 3	SP 3 (Closed containers)
SF 4	SP 4 (Serological pipette)
SF 5	SP 5 (Pyrometers)
SF 6	SP 6 (Conductivity meter)
SF 7	SP 7 (Psychrometers)
SF 8	SP 8 (Exhausts)
SF 9	SP 9 (Add alkali) (Muddada et al., 2012.)
SF 10	SP 10 (Evaporative cooling)
SF 11	SP 11 (Periodic agitation)

Table 3.10 Combined solution principle-2

Sub-Functions	Solution Principles
SF 1	SP 1 (Packed bed)
SF 2	SP 2 (Cylindrical support)
SF 3	SP 3 (Lid type for cylindrical Support)
SF 4	SP 4 (Transfer pipette)
SF 5	SP 5 (Pyrometers)
SF 6	SP 6 (Conductivity meter)
SF 7	SP 7 (Hair tension hygrometer)
SF 8	SP 8 (Exhausts)
SF 9	SP 9 (Add alkali) (Muddada et al., 2012)
SF 10	SP 10 (Evaporative cooling)
SF 11	SP 11 (Continuous agitation)

Table 3.11 Combined solution principle-3

Sub-Functions	Solution Principles
SF 1	SP 1 (Trays)
SF 2	SP 2 (Shelve spaces)
SF 3	SP 3 (Closed containers)
SF 4	SP 4 (Inoculating needle)
SF 5	SP 5 (Thermocouples)
SF 6	SP 6 (Pen type)
SF 7	SP 7 (Psychrometer)
SF 8	SP 8 (Air conditioning)
SF 9	SP 9 (Add alkali) (Muddada et al., 2012)
SF 10	SP 10 (Sprinkling water)
SF 11	SP 11 (Periodic agitation)

Table 3.12 Combined solution principle-4

Sub-Functions	Solution Principles
SF 1	SP 1 (Trays)
SF 2	SP 2 (Shelve spaces)
SF 3	SP 3 (Closed containers)
SF 4	SP 4 (Serological pipette)
SF 5	SP 5 (Thermistors)
SF 6	SP 6 (pH electrodes)
SF 7	SP 7 (Psychrometer)
SF 8	SP 8 (Exhausts)
SF 9	SP 9 (Add alkali) (Muddada et al., 2012)
SF 10	SP 10 (Sprinkling water)
SF 11	SP 11 (Periodic agitation)

3.5 Concept development

In order to develop the solution variants the working principles have to be conceptualized. The working principles are conceptualized by giving a qualitative and quantitative definition. The SPs are summed up to give solution variants to promising combinations of solution to the design problem. The basic idea of the developing the solution variants form the working principles is that, the solution variants makes the evaluation of the solutions easier as they reveal the technical as well as conceptual properties. The firming up of the principle solutions or working principles to solution variants are based on Table 3.13.

Table 3.13 Firming up into principle solution variants

Temperature	Range of temperature (20^o C to 30^o C) required by the fungi
pH	The system should maintain a pH of (6-7) required for the phorbol esters to detoxify
Moisture content	The ideal moisture content of 60- 80% should be maintained as an ideal condition for the fungal growth
Relative humidity	The system should maintain the required relative humidity conditions for the ideal fungal growth i.e., 80
Distribution of fungi	Speed of agitation should be according to the nature of the fungi
Measuring T	Capability of measuring the required range of temperature
Measuring pH	Capability of measuring the required range of pH
Measuring R.H	Capability of measuring the required range of R.H

Once the working principles are firmed to solution variants, the combined working principles are updated to the solution variants and are given in Tables 3.14, 3.15, 3.16 and 3.17 and in the present chapter we discuss only four variants as they are considered to be quiet practical for the given situation.

Table 3.14 Solution variant-1

Sub-Functions	Solution Principles
SF 1	SP 1 (Drums)
SF 2	SP 2 (Drum holders)
SF 3	SP 3 (Closed containers)
SF 4	SP 4 (Serological pipette)
SF 5	SP 5 (Pyrometers that measures a particular range of temperature)
SF 6	SP 6 (Conductivity meter for a particular range of pH)
SF 7	SP 7 (Psychrometers for required range of R.H)
SF 8	SP 8 (Exhausts that maintain Temperature T)
SF 9	SP 9 (Add Alkali to maintain required pH) (Muddada et al., 2012)
SF 10	SP 10 (Evaporative Cooling to maintain required water content)
SF 11	SP 11 (Periodic agitation to maintain appropriate distribution of fungi)

Table 3.15 Solution variant-2

Sub-Functions	Solution Principles
SF 1	SP 1 (Packed bed)
SF 2	SP 2 (Cylindrical support)
SF 3	SP 3 (Lid type for cylindrical support)
SF 4	SP 4 (Transfer pipette)
SF 5	SP 5 (Pyrometers that measures a particular range of temperature)
SF 6	SP 6 (Conductivity meter for a particular range of pH)
SF 7	SP 7 (Hair tension hygrometer for required range of R.H)
SF 8	SP 8 (Exhausts that maintain temperature T)
SF 9	SP 9 (Add alkali to maintain required pH) (Muddada et al., 2012)
SF 10	SP 10 (Evaporative cooling to maintain required water content)
SF 11	SP 11 (Continuous agitation to maintain appropriate distribution of fungi)

Table 3.16 Solution variant-3

Sub-Functions	Solution Principles
SF 1	SP 1 (Trays)
SF 2	SP 2 (Shelve spaces)
SF 3	SP 3 (Closed containers)
SF 4	SP 4 (Inoculating needle)
SF 5	SP 5 (Thermocouples that measures a particular range of temperature)
SF 6	SP 6 (Pen type for a particular range of pH)
SF 7	SP 7 (Psychrometer for required range of R.H)
SF 8	SP 8 (Air conditioning that maintain temperature T)
SF 9	SP 9 (Add alkali to maintain required pH) (Muddada et al., 2012)
SF 10	SP 10 (Sprinkling water to maintain required water content)
SF 11	SP 11 (Periodic agitation to maintain appropriate distribution of fungi)

Table 3.17 Solution variant-4

Sub-Functions	Solution Principles
SF 1	SP 1 (Trays)
SF 2	SP 2 (Shelve spaces)
SF 3	SP 3 (Closed containers)
SF 4	SP 4 (Serological pipette)
SF 5	SP 5 (Thermistors that measures a particular range of temperature)
SF 6	SP 6 (pH electrodes for a particular range of pH)
SF 7	SP 7 (Psychrometer for required range of R.H)
SF 8	SP 8 (Exhausts that maintain temperature T)
SF 9	SP 9 (Add Alkali to maintain required pH) (Muddada et al., 2012)
SF 10	SP 10 (Sprinkling water to maintain required water content)
SF 11	SP 11 (Periodic agitation to maintain appropriate distribution of fungi)

3.6 Evaluating the principle solution variants

The evaluation of the principle solution variants is basically to evaluate the best solution set for the different solutions. In order to evaluate a particular design solution, the following steps are followed, which are discussed as in different sections below.

3.6.1 Identify the criteria of evaluation

The basis for determining the evaluation criteria is from the requirement lists discussed in section 3.1. This is performed because the basic idea of a design methodology is to satisfy the set or requirements list by a solution. Therefore, the evaluation criteria has to satisfy the requirements of the designed system or process. It is always advisable to evaluate the proposed solutions in such a way that whether the derived solutions are compatible, practical and feasible (or not). For evaluating during this particular phase of the design, both technical as well as feasible characterizes should be considered.

Therefore it can be summarized that the evaluation criteria are derived by

1. How well the requirements list is satisfied.
2. How feasible the solutions are with respect to the requirements.
3. Whether it satisfies the technical characteristics of the requirements list.

The criteria for this particular problem are tabulated in Table 3.18.

3.6.2 Weighing the evaluation criteria

There are multi-criteria and therefore, the criteria need to be weighted. The weight is done based on the importance of those particular criteria on the design. Once the evaluation of the design criteria is decided each criteria is given a general weight based on the approximate balance of the criteria. The weight of the evaluation criteria is given in Table 3.19.

Table 3.18 Criteria for evaluation

Criteria for evaluation
▪ Simple construction
▪ Simple operation
▪ Easy maintenance
▪ Accessibility
▪ Safety
▪ Simple assembly
▪ Low complexity
▪ Bought out parts
▪ Few operational errors

3.6.3 Assessing the values

The next step in conceptual design is to assess the values for each of the evaluation criteria for each solution variant separately. The assessing of values mainly depends on the intuition of the designer with respect to the practical application and feasibility of the solution on the problem statement. For each of the solution variant on a particular scale of 0 to 5, the values are assessed. For this particular design problem, the assessed value for each of the solution variant is shown in Table 3.20.

3.6.4 Evaluation of criteria

For finding the overall score of each solution variant evaluation of each criterion is done. In order to evaluate the criteria, the assigned value is converted with respect to the weightage given for each criterion as shown in Equation (3.1). The overall weight of each variant is the sum of all individual weights of each criterion.

$$\text{Final Evaluation} = (\text{weigtage of each criteria}) \times \frac{\text{Value assigned for each criteria}}{5} \quad (3.1)$$

Table 3.19 Weight for each evaluation criterion

Criteria for evaluation	**Weight**
▪ Simple construction	0.14
▪ Simple operation	0.14
▪ Easy maintenance	0.14
▪ Cost	0.14
▪ Safety	0.14
▪ Simple assembly	0.14
▪ Low complexity	0.07
▪ Bought out parts	0.04
▪ Few operational errors	0.05

Table 3.20 Assigning the values for each variant according to the criterion

Criteria	**Variant 1**	**Variant 2**	**Variant 3**	**Variant 4**
Simple construction	2	3	4	4
Simple operation	2	2	3	3
Easy maintenance	2	3	3	4
Cost	3	4	4	3
Safety	4	3	4	3
Simple assembly	2	2	3	4
Low complexity	4	4	4	4
Bought out parts	2	2	3	4
Few operational errors	3	4	4	3

Table 3.21 Final evaluation of the Criteria for each solution variant.

Criteria	**Variant 1**	**Variant 2**	**Variant 3**	**Variant 4**
Simple construction	0.056	0.084	0.112	0.112
Simple operation	0.056	0.056	0.084	0.084
Easy maintenance	0.056	0.084	0.084	0.112
Cost	0.084	0.112	0.084	0.112
Safety	0.112	0.084	0.112	0.084
Simple assembly	0.056	0.056	0.084	0.112
Low complexity	0.056	0.056	0.056	0.056
Bought out parts	0.016	0.016	0.024	0.032
Few operational errors	0.03	0.04	0.04	0.03
Overall weightage	0.522	0.588	0.68	0.734

3.7 Best design solution

Once the evaluation of the solution variants is done, based on the score from the evaluation, the best solution is given for the problem. The best solution in the conceptual phase is Solution variant 4 and is given in Table 3.20.

3.8 Conclusion

The application of the systematic design procedure was described in this chapter. This theory was used to design the best solution for the SSF. The design started with the formulation of problem statement from which the requirements list was obtained. The conceptual design of SDP was applied to the requirements list.

In the conceptual design, the requirements list is refined. From this refined requirement list, main functions and sub-functions were derived. Based on the solution finding methods of SDP, the solutions or working principles for each sub-function were found. Four different solution variants were derived based on the combination of these solutions or working principles.

The evaluation technique of SDP was used to find out the best design solution and it was found that the solution variant four is the best possible design solution.

Chapter 4 APPLICATION OF AXIOMATIC DESIGN THEORY TO THE SOLID STATE FERMENTER

4.1 Introduction

This chapter deals with the valid design solutions of a solid state fermenter which detoxifies *Jatropha* seed cake with the application of Axiom 1 of ADT (axiomatic design theory). Besides designing the valid design solution, this chapter also explains the application of independence axiom (Axiom 1) of ADT. The details of independence axiom (Axiom 1) are referred to Chapter 2. This chapter is organized as follows. In Section 4.2, the problem statement of this design will be given. In Section 4.3, the overall function requirement will be discussed, followed by the discussion of the function decomposition in Section 4.4. In Section 4.5, the design parameters for the decomposed functions are derived followed by different design solutions in Section 4.6.

4.2 Problem statement

As discussed in the previous chapters, solid state fermentation by the fungi *peniophora sp and p.noxius* will result in the detoxification of phorbal esters from the *Jatropha* seed cake. In order to make it practical for an industrial scale, a solid state fermenter for this process has to be designed. The basis for this design (in fact for any design) is to state the problem first. In this particular design, the problem statement is "design of a solid state fermenter to detoxify *Jatropha* seed cake using the fungi *peniophora sp and p.noxius* under the controlled conditions".

4.3 Assumptions of the design

The following are the assumptions of the design:

(1) The capacity of fermenting is 100kg of seed cake.
(2) The fermentation takes 7 days (Muddada et al., 2012).

4.4 Defining the main functional requirement

In axiomatic design theory, the next step is to define the functional requirements based on the problem statement (Suh, 1998). The functional requirements should be defined in a solution neutral way. They are generally considered as a minimum set of requirements that must be satisfied. A set of functional requirements is defined based on the problem statement. In this particular problem, the solid state fermentation of the seed cake has to be carried out under the controlled conditions. Therefore, in order to carry out this fermentation process, the basic functional requirement would be a space to perform the solid state fermentation. Apart from the space, for a successful solid state fermentation, the controlled conditions have to be maintained. Maintenance of the controlled conditions for this process would be the next functional requirement. In addition to this, the detoxification of phorbol esters is the other functional requirement. The functional requirements for this design problem are given in Figure 4.1, where each of the main functions is considered as a FR and they are denoted as FR1, FR2 and FR3 (Table 4.1).

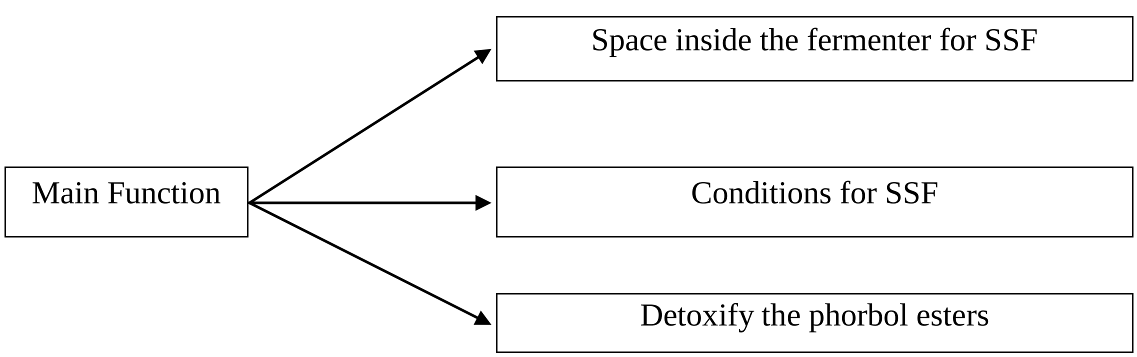

Figure 4.1 Functional requirements to design a solid state fermenter under controlled conditions

Table 4.1 Main Functions as FRs

FR 1	Space inside the fermenter for SSF
FR 2	Conditions for SSF
FR 3	Detoxify the phorbol esters

4.5 Decomposition of the functional requirement

The functional requirements stated in the above section are highly complex. The design parameters for these functional requirements are difficult to be found, and thus decomposition of these FRs is needed according to ADT. The decomposition of functional requirements would aid in finding out a feasible solution. Take the functional requirement ‘conditions for SSF’ as an example. The physical entity for this particular function is quite complex and there is no such single physical entity or DP for this FR. FR2 (i.e., control condition) is then decomposed into FR2.1, FR2.2, and FR2.3 (see Table 4.2). These FRs can be satisfied by the DPs to be discussed later, and as such, DP1 for FR1 can be found, that is, an aggregate of DPs for FR2.1, FR2.2, and FR2.3.

Similarly, the other two functional requirements (space to perform solid state fermentation and detoxification of phorbol esters) are decomposed into several sub-functional requirements such as ‘hold substrate’, ‘support structure’, ‘prevent contamination’, ‘inoculation’ and ‘maintain temperature’, ‘pH’, ‘water content’, ‘relative humidity’ and ‘distribution of fungi’, respectively. The complete decomposition of the main functions is shown in Figure 4.2. The description of the decomposed functions is given in Table 4.2.

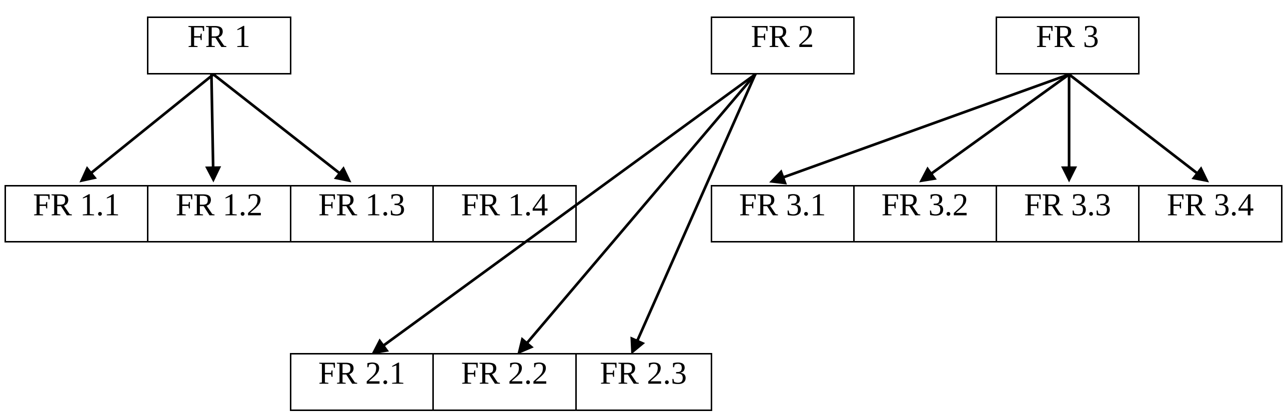

Figure 4.2 Decomposition of the main functions

4.6 Defining the design parameter

For each of the sub-functional requirements as described in Table 4.2, the design parameters need to be found. Let us take the functional requirement ‘measuring temperature’ for a close look. The possible physical entities or design parameters for it are thermometer, thermostats, thermocouple, Langmuir probes, RTD (resistance temperature detector) (Holman 1994). The design parameters for the remainder of the sub-functional requirements are derived and shown in Table 4.3 and they will be discussed later.

Table 4.2 Description of the sub-functions

	SUB-FUNCTIONS
FR 1.1	Hold substrate
FR 1.2	Support structures
FR 1.3	Prevent contamination
FR 1.4	Inoculation
FR 2.1	Measure T
FR 2.2	Measure pH
FR 2.3	Measure R.H.
FR 3.1	Maintain T and R.H
FR 3.2	Maintain pH
FR 3.3	Maintain water content
FR 3.4	Distribution of fungi

In finding DPs, there are two issues worthy of attention. First is that for a particular FR, there may be more than one DP, so a further evaluation is needed among all the DP options. Second is that one DP may not only affect one FR but FR' as well, so the effect of the DP to FR' cannot be ignored (otherwise, the system in design may suffer from the unforeseen problem). In the following, a detailed discussion of the process of finding DPs (or mapping of FR and DP) is presented. The discussion also includes the resolution of the second issue, namely, the application of Axiom 1 of ADT to the mapping of FR and DP. The resolution of the first issue is the business of applying Axiom 2, which will be discussed in Chapter 5. Different design solution (or design) options are called cases in the following.

Table 4.3 Possible design parameters for each of the functional requirements

Sub-Functions	Possible design parameters				
Hold Substrate	Trays	Drums	Conical Flasks	Packed bed	
Support Structures	Shelves Spaces	Drum holders	Flask holders	Cylindrical Support	
Prevent contamination	Closed containers	Covering drums	Tube boxes	Lid type for cylindrical Supports	
Inoculation	Serological pipette	Transfer pipette	Inoculating needle	Inoculating loop	
Measure T	Thermocouples	Thermistors	Pyrometer	Langmuir probes	Thermometers
Measure pH	Pen type	Conductivity meter	Membrane pH	pH electrodes	
Measure R.H	Hygrometers	Psychrometer	Capacitive humidity sensors	Thermal conductivity sensors	Hair tension hygrometer
Maintain T and R.H	Exhausts	Forced Air	Air conditioning		
Maintain pH	Add alkali	Add base			
Maintain water content	Evaporative cooling	Sprinkling water			
Distribution of fungi	Continuous agitation	Periodic agitation	Hand agitation		

4.6.1 Case 1

Mapping of FR1 to DP1:

The FR1.1 (hold substrate) is satisfied by the DP1.1 (drum type holder) and this drum type of holder would not satisfy the other functional requirements. The FR1.2 is mapped to the DP1.2 (drum holders), which does interact with the other functional requirements. Similarly the FR1.3 is mapped to DP1.3 and FR1.4 is mapped to DP1.4, neither of which interacts with the other FRs. Therefore Axiom 1 of ADT holds good for this design. The details of this are shown in Figure 4.3.

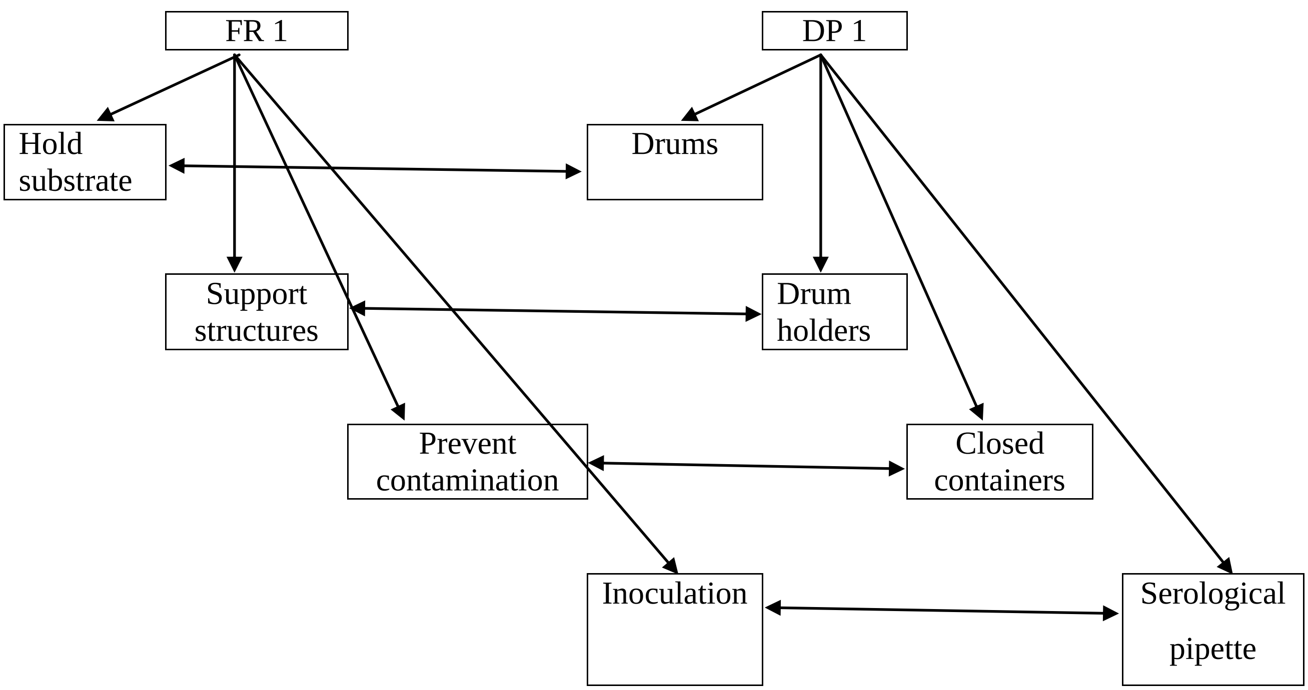

Figure 4.3 Mapping of FR1 to DP1 (Case 1)

Mapping of FR2 to DP2:

The FR 2.1, FR2.2 and FR2.3 are mapped to the DP2.1, DP2.2 and DP2.3, respectively and none of them interacts with other FRs. Therefore, this design satisfies the Axiom 1 of ADT. The details of this are shown in Figure 4.4.

Mapping of FR3 to DP3:

The FR 3.1 (maintain temperature and R.H) is satisfied by the DP3.1 (Exhausts), therefore it is mapped to the physical domain. It is noted that the exhaust however affects the FR3.3 (water content), therefore the DP3.1 is mapped to FR3.3 as well.

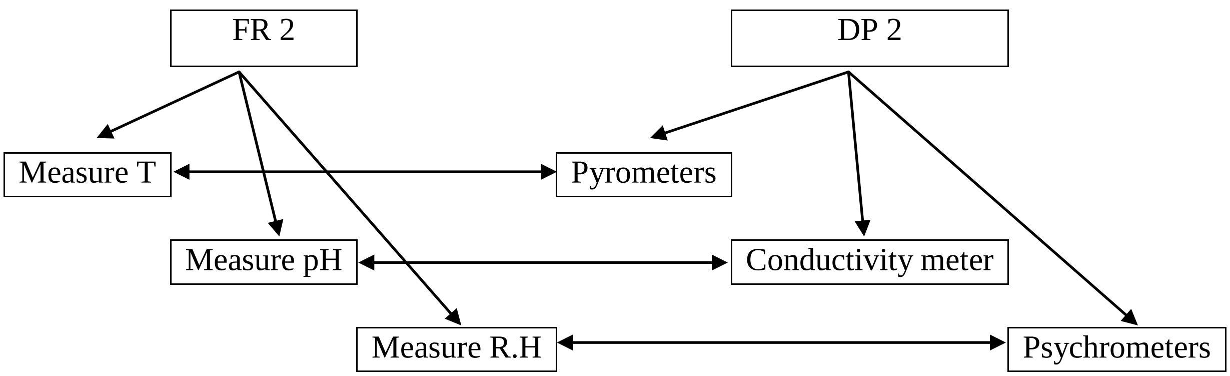

Figure 4.4 Mapping of FR 2 to DP2 (Case 1)

For the FR3.2, the DP3.2 (add alkali) has no effect on any of the other functional requirements. However, the DP3.3 (evaporative cooling) satisfies both the functional requirements FR 3.3 as well as FR3.1. Similarly the DP3.4 satisfies FR3.4 and FR3.1. It is because the evaporative cooling technique and agitation can aid in the regulation of temperature. The mapping process for this particular solution is shown in Figure 4.5. Therefore based on the mapping of the FRs to DPs for this case the design equation comes to be as follows:

$$\begin{Bmatrix} FR\ 3.1 \\ FR\ 3.2 \\ FR\ 3.3 \\ FR\ 3.4 \end{Bmatrix} = \begin{bmatrix} X & O & X & X \\ O & X & O & O \\ X & O & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} DP\ 3.1 \\ DP\ 3.2 \\ DP\ 3.3 \\ DP\ 3.4 \end{Bmatrix} \qquad (4.1)$$

The design matrix in this design equation shows that the FR3.1 is affected by the DP3.1, DP3.2, DP3.3 and the FR3.3 affected by the DP3.1 and DP3.3. Therefore, based on the design matrix, the design solution is a coupled design. A coupled design cannot hold Axiom 1. The chosen design parameters for the FRs are shown in Table 4.4

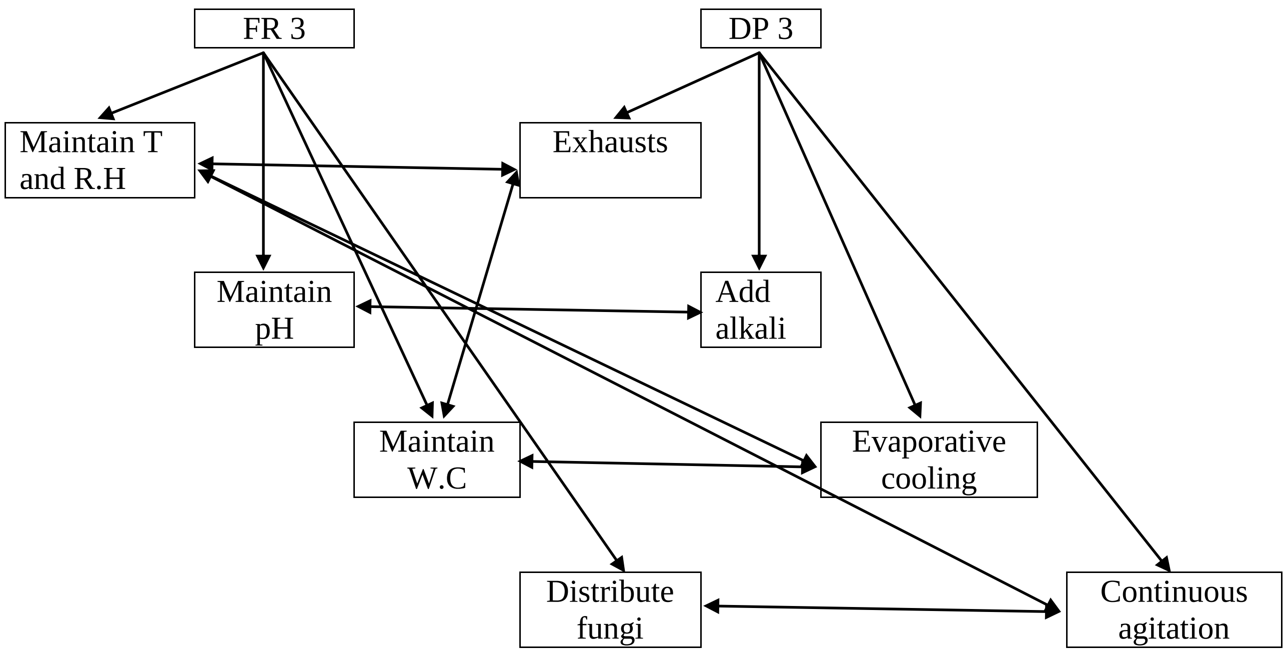

Figure 4.5 Mapping of FR3 to DP3 (Case 1)

For this case, the chosen design parameters for the functional requirements are given in Table 4.4.

Table 4.4 Functional requirements chosen for respective design parameters (Case 1)

Functional Requirements	**Design Parameters**
FR1.1	DP1.1 (Drums)
FR1.2	DP1.2 (Drum Holders)
FR1.3	DP1.3(Closed containers)
FR1.4	DP1.4 (Serological pipette)
FR2.1	DP2.1 (Pyrometers)
FR2.2	DP2.2 (Conductivity Meter)
FR2.3	DP2.3 (Psychrometers)
FR3.1	DP3.1 (Exhausts)
FR3.2	DP3.2 (Add Alkali) (Muddada et al., 2012)
FR3.3	DP3.3(Evaporative cooling)
FR3.4	DP3.4 (continuous agitation)

4.6.2 Case 2

Mapping of FR1 to DP1:

The FRs are mapped to the DPs and all the DPs when mapped back to the functional domain and do not interact with the other FRs except for their respective FR. This is illustrated in Figure 4.6.

Mapping of FR2 to DP2:

Similarly, the chosen design parameters (DP1.1, DP1.2, and DP1.3) satisfy their respective functional requirement (FR1.1, FR1.2 and FR1.3) which does not show any relation to the other FRs. The details of this are shown in Figure 4.7.

Mapping of FR3 to DP3:

In this case, almost the same set of DPs was chosen except for the DP3.4. This DP is changed to the periodic agitation instead of continuous agitation. The difference in them is that continuous agitation would lead to a temperature gradient but the periodic agitation would prevent the control of temperature through agitation. In this case the DP3.4 does not interact or affect the FR3.1. Therefore, the mapping of the solution is given in Figure 4.8.

Even though the DP3.4 was changed the remainder of the DPs remains the same. This still results in a coupled design, which violates the Axiom 1 of the ADT. The solution for this is as follows:

$$\begin{Bmatrix} FR\ 3.1 \\ FR\ 3.2 \\ FR\ 3.3 \\ FR\ 3.4 \end{Bmatrix} = \begin{bmatrix} X & O & X & O \\ O & X & O & O \\ X & O & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} DP\ 3.1 \\ DP\ 3.2 \\ DP\ 3.3 \\ DP\ 3.4 \end{Bmatrix} \quad (4.2)$$

Table 4.5 Functional requirements chosen for respective design parameters (Case 2)

Functional Requirements	Design Parameters
FR1.1	DP1.1 (Packed bed)
FR1.2	DP1.2 (Cylindrical Support)
FR1.3	DP1.3 Lid type for cylindrical Supports)
FR1.4	DP1.4 (Transfer pipette)
FR2.1	DP2.1 (Pyrometer)
FR2.2	DP2.2 (Conductivity meter)
FR2.3	DP2.3 (pH electrode)
FR3.1	DP3.1 (Exhausts)
FR3.2	DP3.2 (Add alkali) (Muddada et al., 2012)
FR3.3	DP3.3(Evaporative cooling)
FR3.4	DP3.4 (Periodic agitation)

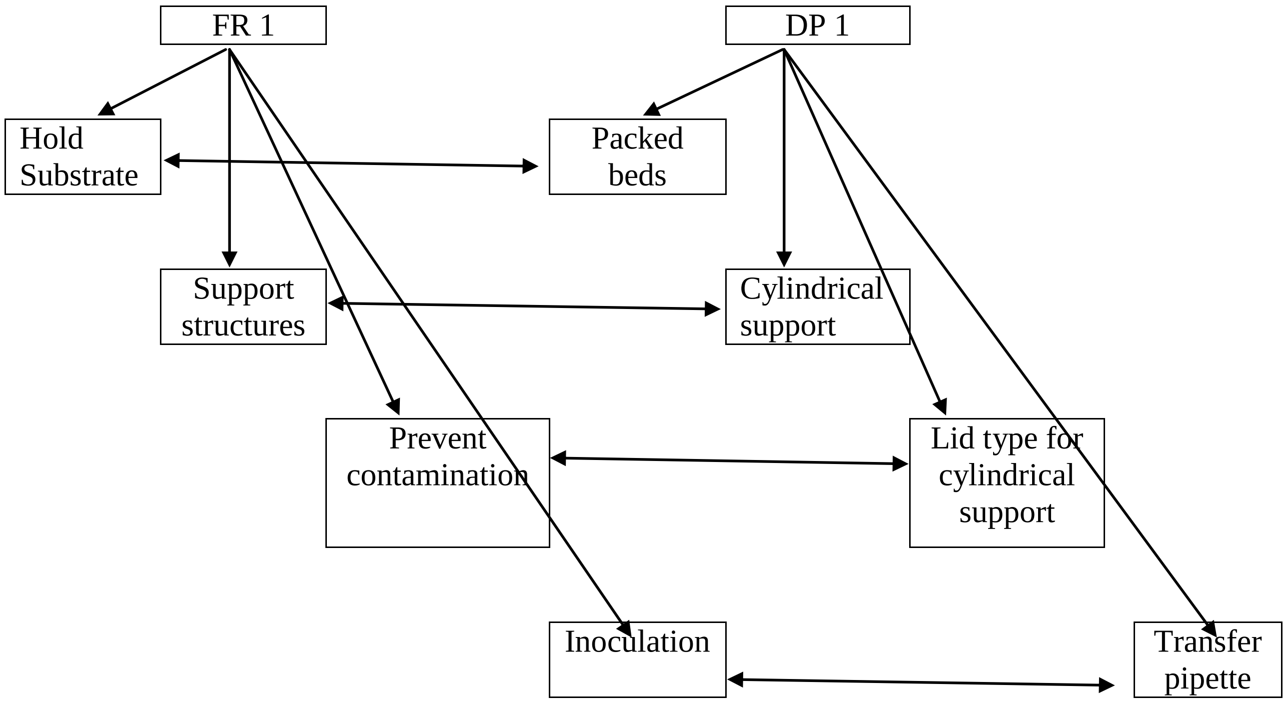

Figure 4.6 Mapping of FR1 to DP 1 (Case 2)

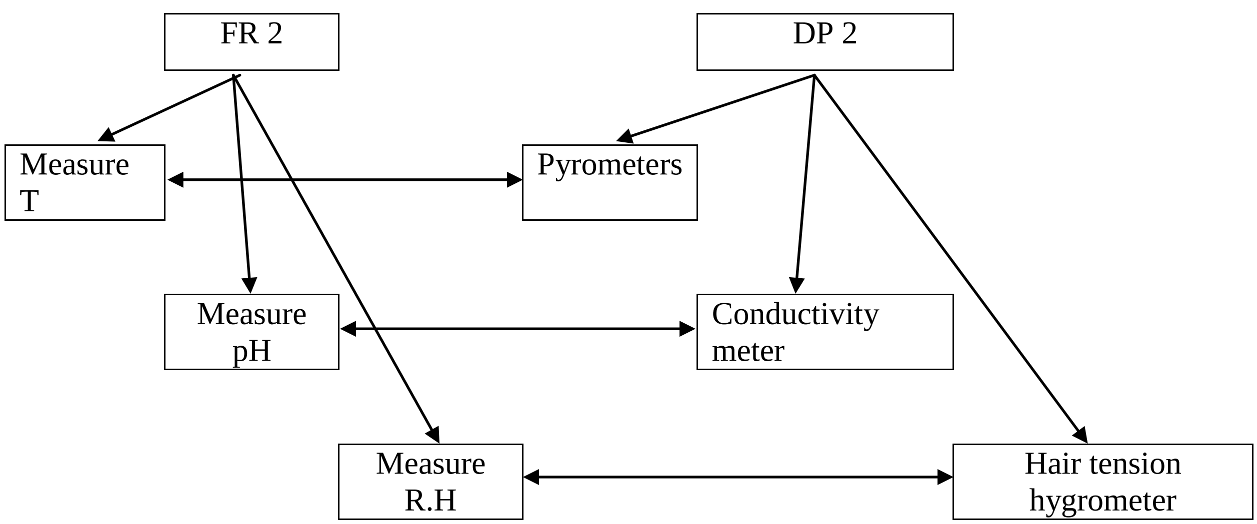

Figure 4.7 Mapping of FR2 to DP2 (Case 2)

The functional requirements and deign parameters chosen for this particular case are given in Table 4.5.

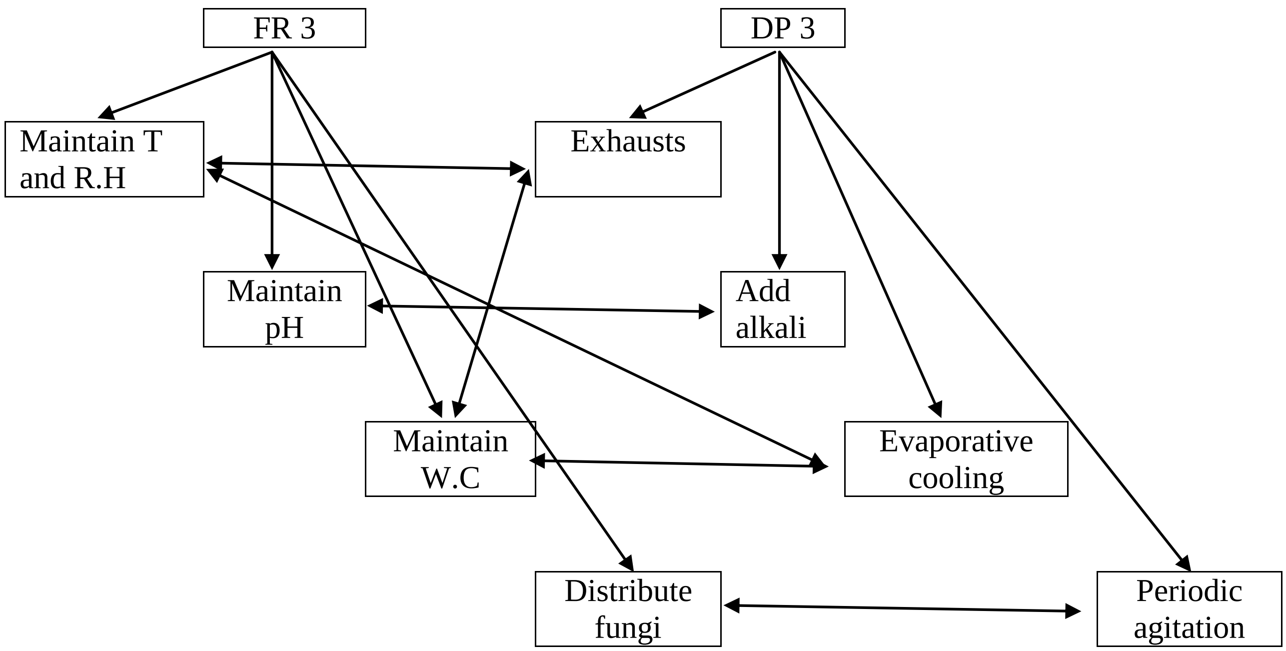

Figure 4.8 Mapping of FR3 to DP3 (Case 2)

4.6.3 Case 3

Mapping of FR1 to DP1:

All the DPs chosen in this case are uncoupled. The details of this mapping are shown in Figure 4.9.

Mapping of FR2 to DP2:

Even though the DPs were changed, there was no coupling among the DPs. The details of this mapping are shown in Figure 4.10.

Mapping of FR3 to DP3:

In this case, the DP 3.1 is chosen as air conditioning. This DP does not interact with the other DPs. The DP 3.3 (Evaporative cooling) would interact with the FR 3.1. The details of this mapping are shown in Figure 4.11.

The design equation for this mapping is given by

$$\begin{Bmatrix} FR\ 3.1 \\ FR\ 3.2 \\ FR\ 3.3 \\ FR\ 3.4 \end{Bmatrix} = \begin{bmatrix} X & O & X & O \\ O & X & O & O \\ O & O & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} DP\ 3.1 \\ DP\ 3.2 \\ DP\ 3.3 \\ DP\ 3.4 \end{Bmatrix} \quad (4.3)$$

In this particular case it is quite evident that the design is a coupled design. Therefore this design violates the Axiom 1 and hence this design cannot be the best design.

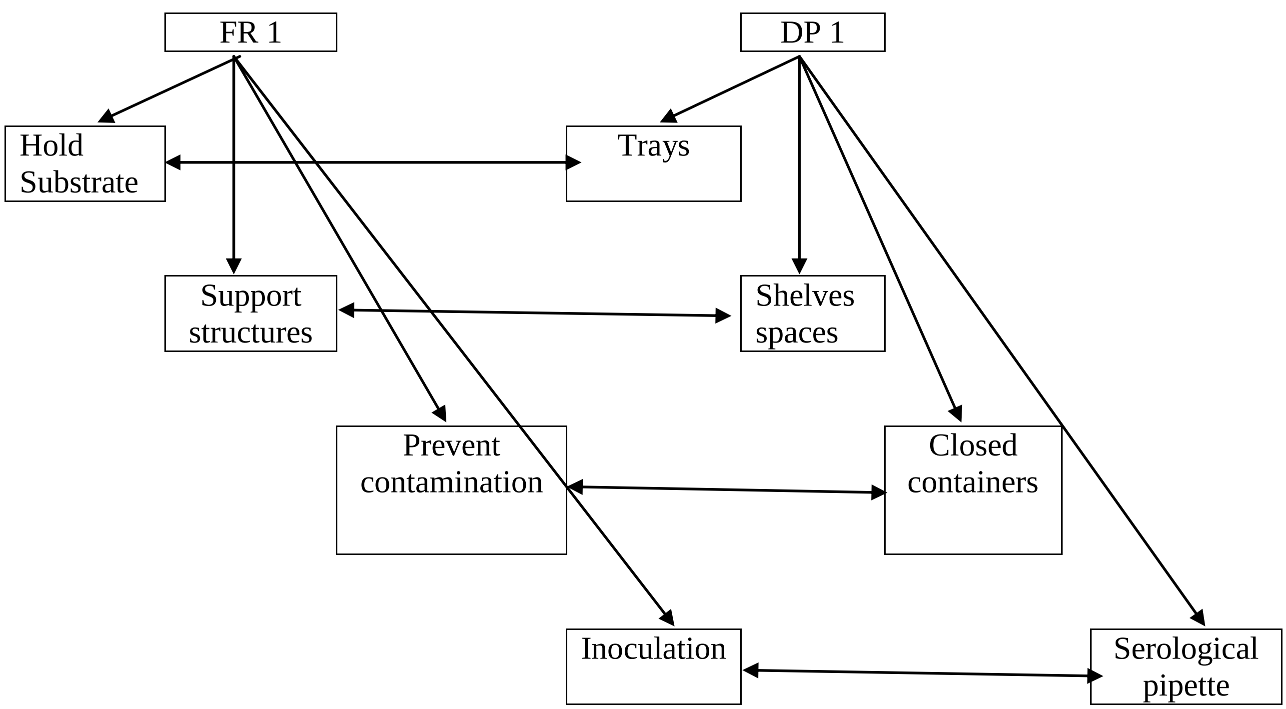

Figure 4.9 Mapping of FR1 to DP1 (Case 3)

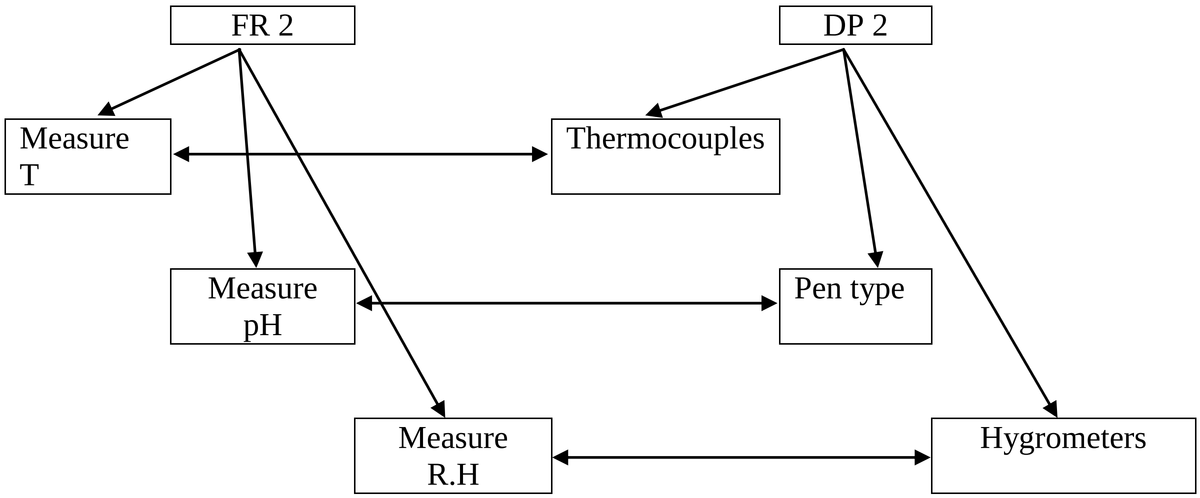

Figure 4.10 Mapping of FR2 to DP2 (Case 3)

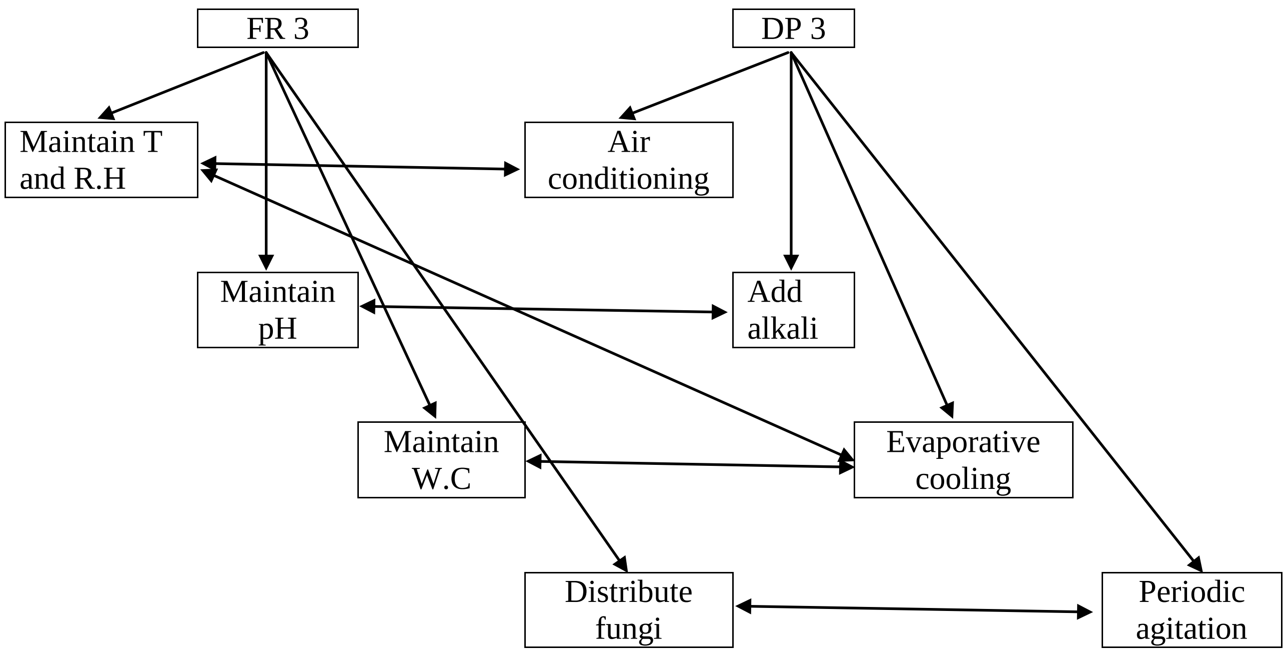

Figure 4. 11 Mapping of FR3 to DP3 (Case 3)

The design parameters and functional requirements for this case are chosen as shown in Table 4.6.

Table 4.6 Functional requirements chosen for the respective design parameters (Case 3)

Functional Requirements	**Design Parameters**
FR1.1	DP1.1 (Trays)
FR1.2	DP1.2 (Shelves spaces)
FR1.3	DP1.3(Closed containers)
FR1.4	DP1.4 (Serological pipette)
FR2.1	DP2.1 (Thermocouple)
FR2.2	DP2.2 (Pen type)
FR2.3	DP2.3 (Psychrometer)
FR3.1	DP3.1 (Air conditioning)
FR3.2	DP3.2 (Add alkali) (Muddada et al., 2012)
FR3.3	DP3.3 (Evaporative cooling)
FR3.4	DP3.4 (Periodic agitation)

4.6.4 Case 4

The mapping of the FR1 to DP1 and FR2 to DP3 is shown in Figure 4.12, Figure 4.13 respectively, and it is evident from them that they are uncoupled designs.

Mapping of FR3 to DP3:

In this case, the DP 3.1 chosen is the Air conditioning. This DP3.1 will not interact with any of the other FRs except for FR 3.1. On the other hand, the DP 3.3 is changed to Sprinkling water. The DP 3.3 would just interact with FR 3.3 but not with any other FRs. Therefore, the mapping of the case is shown in Figure 4.14 and the design equation is as follows:

$$\begin{Bmatrix} FR\ 3.1 \\ FR\ 3.2 \\ FR\ 3.3 \\ FR\ 3.4 \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ O & X & O & O \\ O & O & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} DP\ 3.1 \\ DP\ 3.2 \\ DP\ 3.3 \\ DP\ 3.4 \end{Bmatrix} \qquad (4.4)$$

Based on the design matrix, it is quite evident that the design is an uncoupled design and an uncoupled design maintains the independency of the FRs and hence it follows Axiom 1. The FRs and DPs chosen for this are shown in Table 4.7.

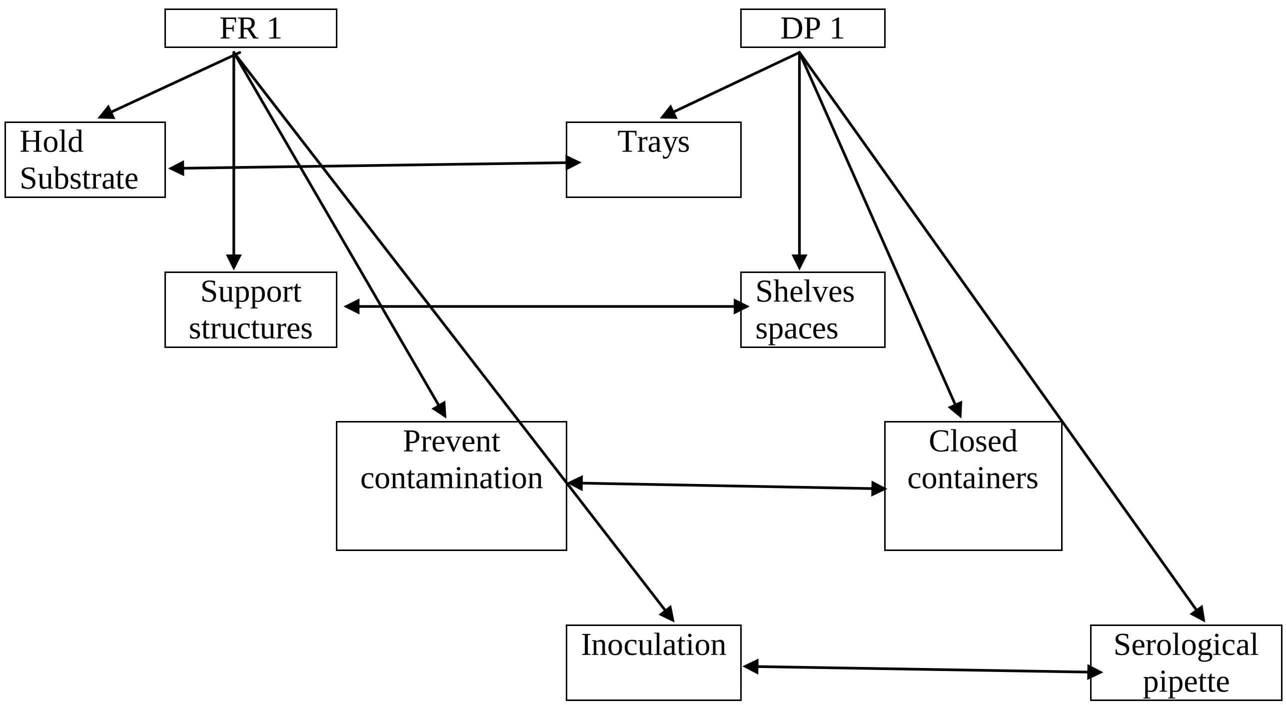

Figure 4.12 Mapping of FR1 to DP1 (Case 4)

Table 4.7 Functional requirements chosen for respective design parameters (Case 4)

Functional Requirements	**Design Parameters**
FR1.1	DP1.1 (Trays)
FR1.2	DP1.2 (Shelves Spaces)
FR1.3	DP1.3 (Closed Containers)
FR1.4	DP1.4 (Serological Pipette)
FR2.1	DP2.1 (Thermocouple)
FR2.2	DP2.2 (Pen type)
FR2.3	DP2.3 (Psychrometers)
FR3.1	DP3.1 (Air Conditioning)
FR3.2	DP3.2 (Add Alkali)
FR3.3	DP3.3 (Sprinkling water) (Muddada et al., 2012)
FR3.4	DP3.4 (Periodic agitation)

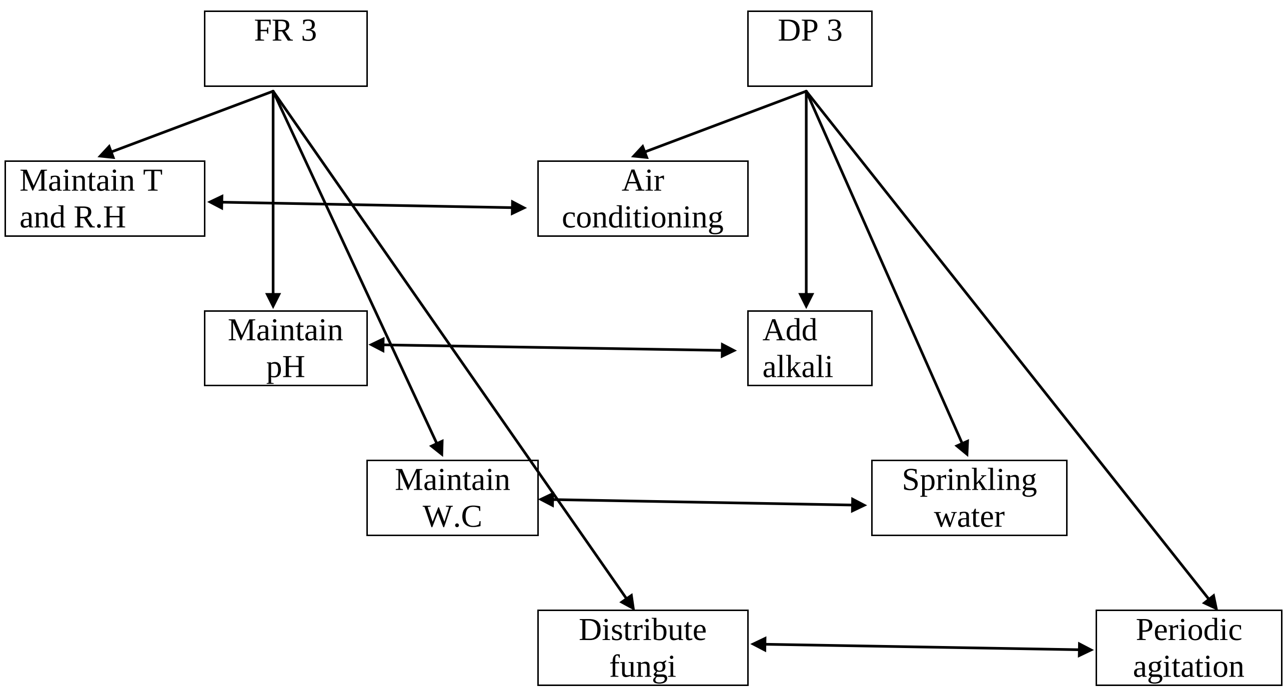

Figure 4.13 Mapping of FR3 to DP3 (Case 4)

4.6.5 Case 5

In this case, the DP 1.4 is changed to Transfer pipette and the other DPs remain the same as case 4. The mapping of the FR1 to DP1, FR2 to DP2 and FR3 to DP3 is shown in Figure 4.15, Figure 4.16 and Figure 4.17, and it is evident from them that they are uncoupled designs. The design matrix for FR3 to DP3 is shown by

$$\begin{Bmatrix} FR\ 3.1 \\ FR\ 3.2 \\ FR\ 3.3 \\ FR\ 3.4 \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ O & X & O & O \\ O & O & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} DP\ 3.1 \\ DP\ 3.2 \\ DP\ 3.3 \\ DP\ 3.4 \end{Bmatrix} \quad (4.5)$$

Based on the design matrix, it is quite evident that the design is an uncoupled design and an uncoupled design maintains the independency of the FRs and hence it follows Axiom 1. The FRs and DPs chosen for this are shown in Table 4.8.

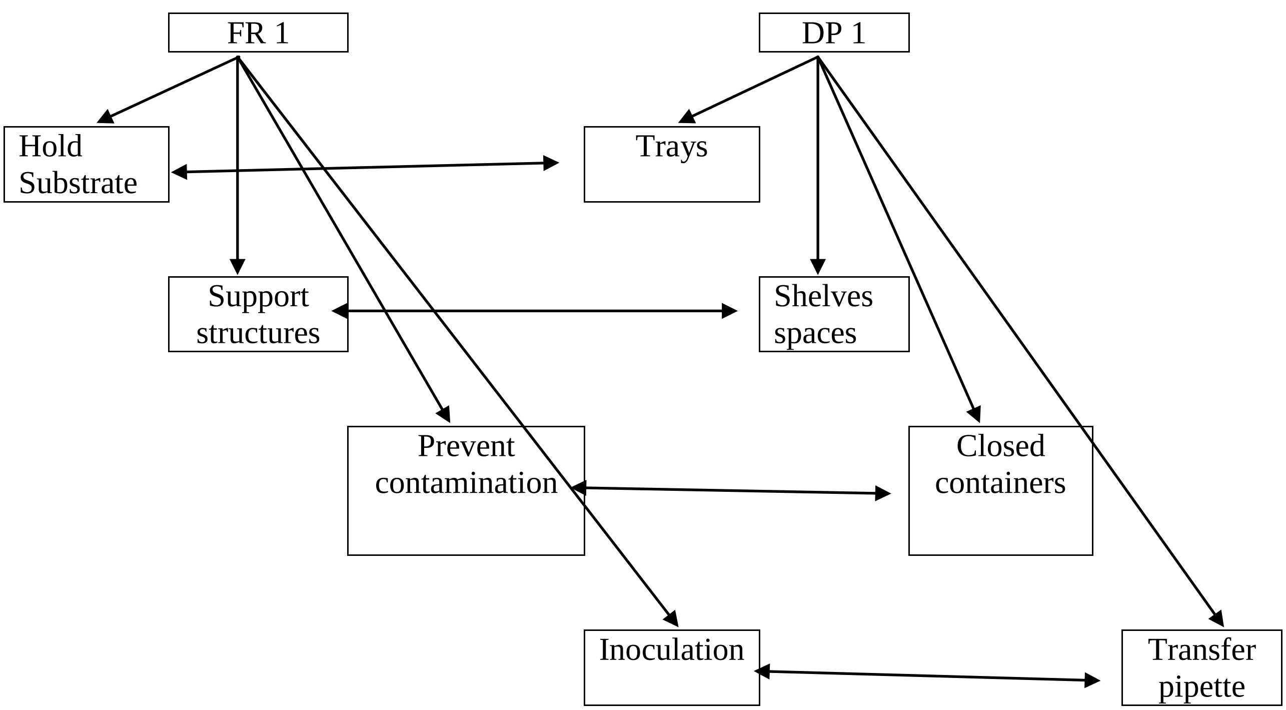

Figure 4.14 Mapping of FR1 to DP1 (Case 5)

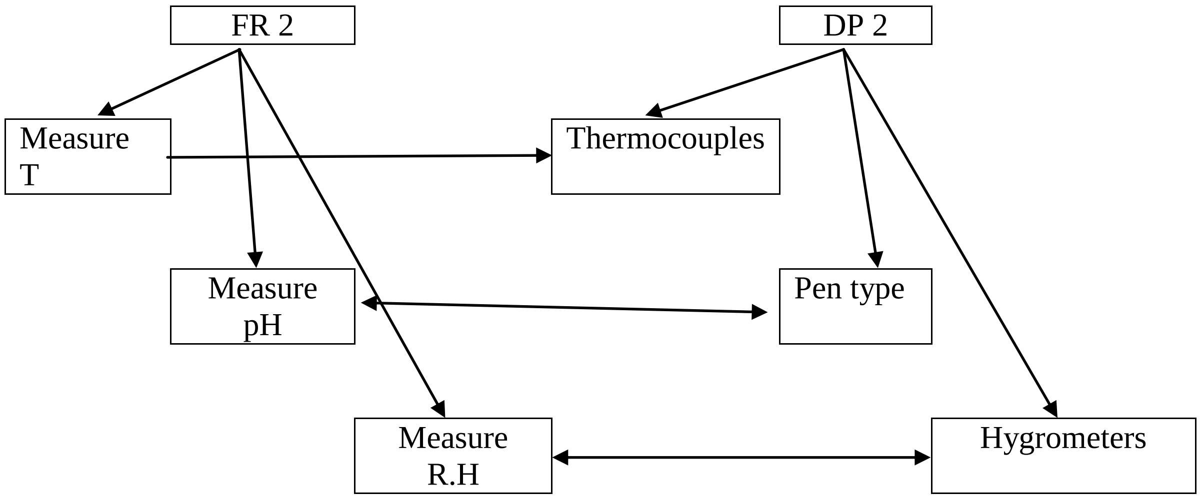

Figure 4.15 Mapping of FR2 to DP2 (Case 5)

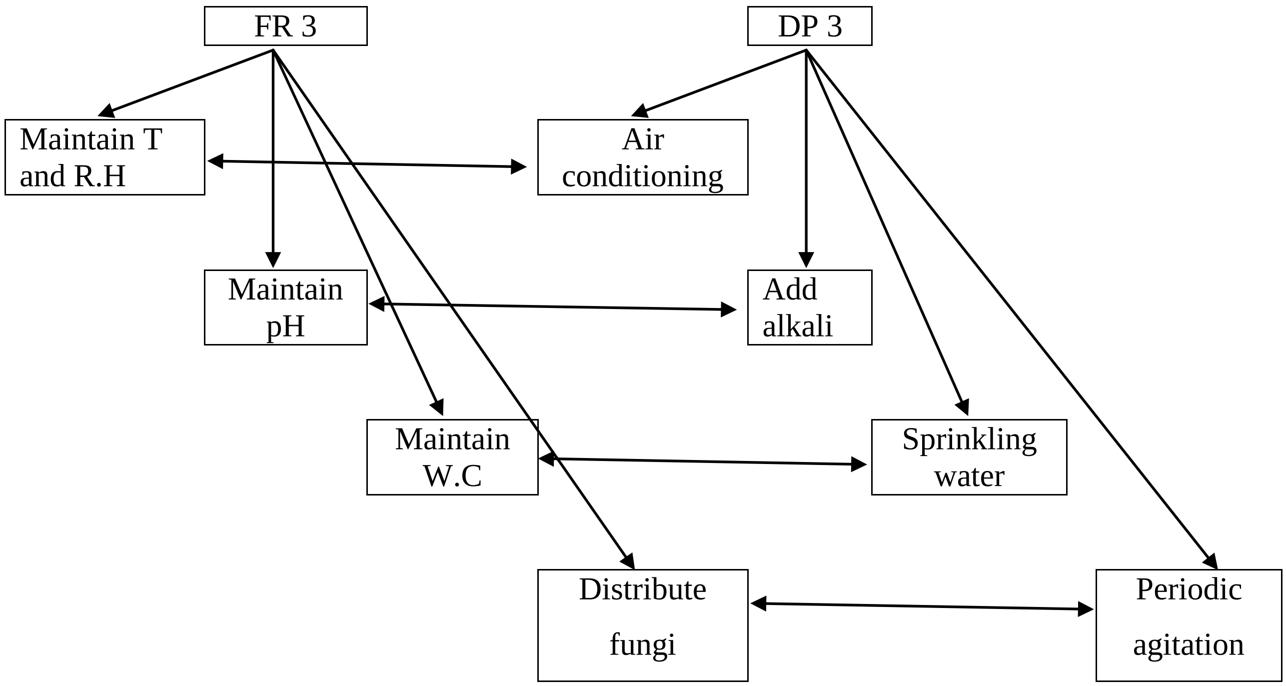

Figure 4.16 Mapping of FR3 to DP3 (Case 5)

Table 4.8 Functional requirements chosen for respective design parameters (Case 5)

Functional Requirements	**Design Parameters**
FR1.1	DP1.1 (Trays)
FR1.2	DP1.2 (Shelves Spaces)
FR1.3	DP1.3 (Closed Containers)
FR1.4	DP1.4 (Transfer Pipette)
FR2.1	DP2.1 (Thermocouple)
FR2.2	DP2.2 (Pen type)
FR2.3	DP2.3 (Psychrometers)
FR3.1	DP3.1 (Air Conditioning)
FR3.2	DP3.2 (Add Alkali) (Muddada et al., 2012)
FR3.3	DP3.3 (Sprinkling water)
FR3.4	DP3.4 (Periodic agitation)

4.6.6 Case 6

In this case, the DP 2.1 is changed to Thermometers and the other DPs remain the same as case 4. The mapping of the FR1 to DP1, FR2 to DP2 and FR3 to DP3 is shown in Figure 4.18, Figure 4.19 and Figure 4.20 (respectively), and it is evident from them that they are uncoupled designs. The design matrix for FR 3 to DP 3 is shown by

$$\begin{Bmatrix} FR\ 3.1 \\ FR\ 3.2 \\ FR\ 3.3 \\ FR\ 3.4 \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ O & X & O & O \\ O & O & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} DP\ 3.1 \\ DP\ 3.2 \\ DP\ 3.3 \\ DP\ 3.4 \end{Bmatrix} \quad (4.6)$$

Based on the design matrix, it is quite evident that the design is an uncoupled design and an uncoupled design maintains the independency of the FRs and hence it follows Axiom 1. The FRs and DPs chosen for this are shown in Table 4.9.

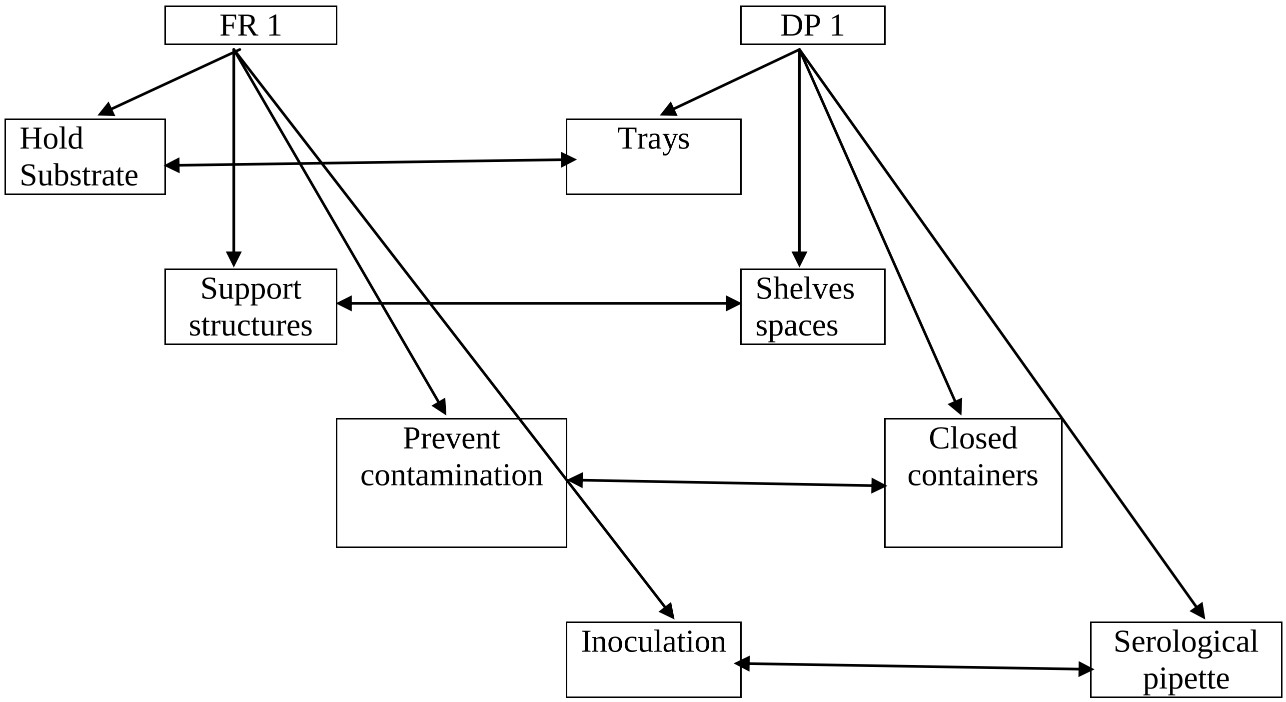

Figure 4.17 Mapping of FR1 to DP1 (Case 6)

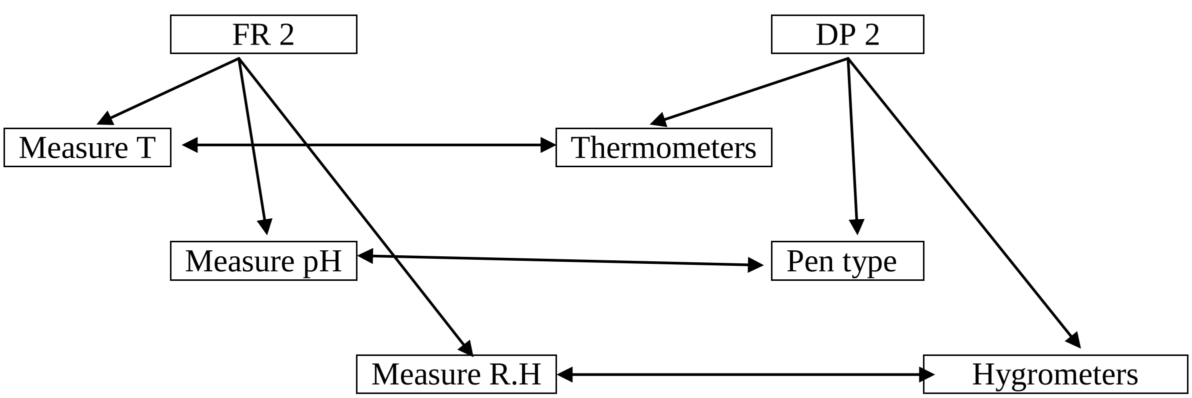

Figure 4.18 Mapping of FR2 to DP2 (Case 6)

Table 4.9 Functional requirements chosen for respective design parameters (Case 6)

Functional Requirements	**Design Parameters**
FR1.1	DP1.1 (Trays)
FR1.2	DP1.2 (Shelves Spaces)
FR1.3	DP1.3 (Closed Containers)
FR1.4	DP1.4 (Serological Pipette)
FR2.1	DP2.1 (Thermometer)
FR2.2	DP2.2 (Pen type)
FR2.3	DP2.3 (Psychrometers)
FR3.1	DP3.1 (Air Conditioning)
FR3.2	DP3.2 (Add Alkali) (Muddada et al., 2012)
FR3.3	DP3.3 (Sprinkling water)
FR3.4	DP3.4 (Periodic agitation)

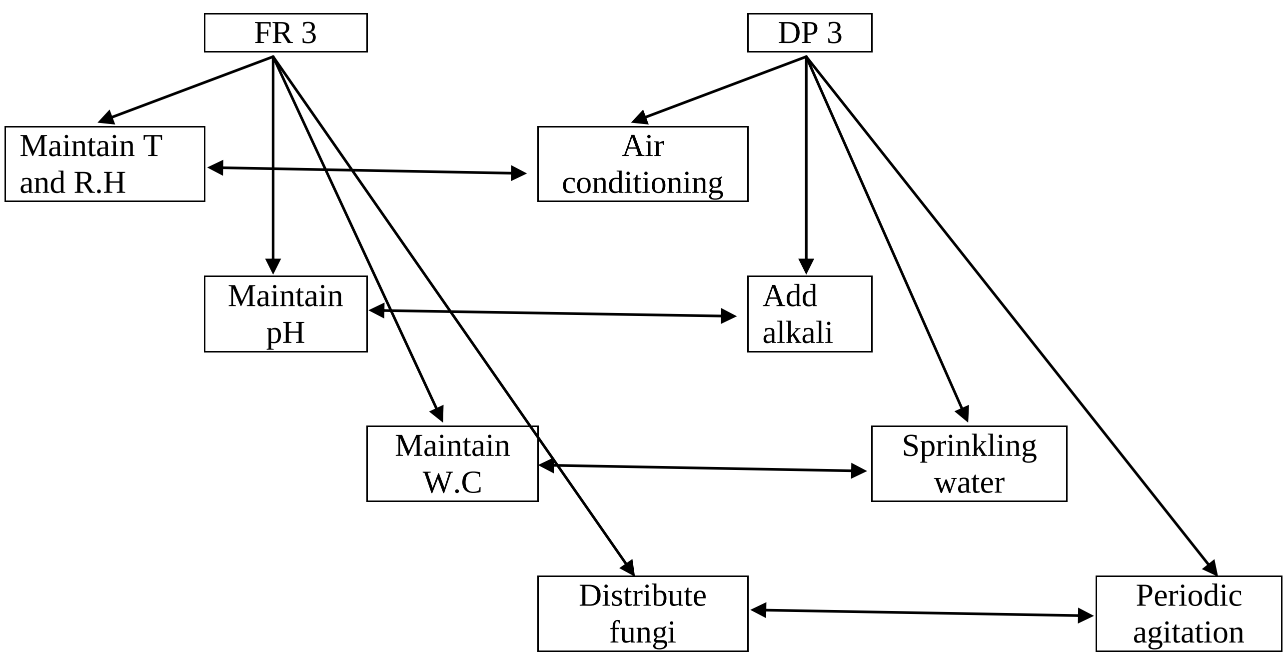

Figure 4.19 Mapping of FR3 to DP3 (Case 6)

4.6.7 Case 7

In this case, the DP 1.4 is changed to Transfer pipette and DP 2.1 is changed to thermometer and remaining DPs are the same as that of case 4. The mapping of the FR1 to DP1, FR2 to DP2 and FR3 to DP3 is shown in Figure 4.21, Figure 4.22 and Figure 4.23 (respectively), and it is evident from them that they are uncoupled designs. The design matrix for FR 3 to DP 3 is shown by

$$\begin{Bmatrix} FR\ 3.1 \\ FR\ 3.2 \\ FR\ 3.3 \\ FR\ 3.4 \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ O & X & O & O \\ O & O & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} DP\ 3.1 \\ DP\ 3.2 \\ DP\ 3.3 \\ DP\ 3.4 \end{Bmatrix} \qquad (4.7)$$

Based on the design matrix, it is quite evident that the design is an uncoupled design and an uncoupled design maintains the independency of the FRs and hence it follows Axiom 1. The FRs and DPs chosen for this are shown in Table 4.10.

Table 4.10 Functional requirements chosen for respective design parameters (Case 7)

Functional Requirements	**Design Parameters**
FR1.1	DP1.1 (Trays)
FR1.2	DP1.2 (Shelves Spaces)
FR1.3	DP1.3 (Closed Containers)
FR1.4	DP1.4 (Transfer Pipette)
FR2.1	DP2.1 (Thermometers)
FR2.2	DP2.2 (Pen type)
FR2.3	DP2.3 (Psychrometers)
FR3.1	DP3.1 (Air Conditioning)
FR3.2	DP3.2 (Add Alkali) (Muddada et al., 2012)
FR3.3	DP3.3 (Sprinkling water)
FR3.4	DP3.4 (Periodic agitation)

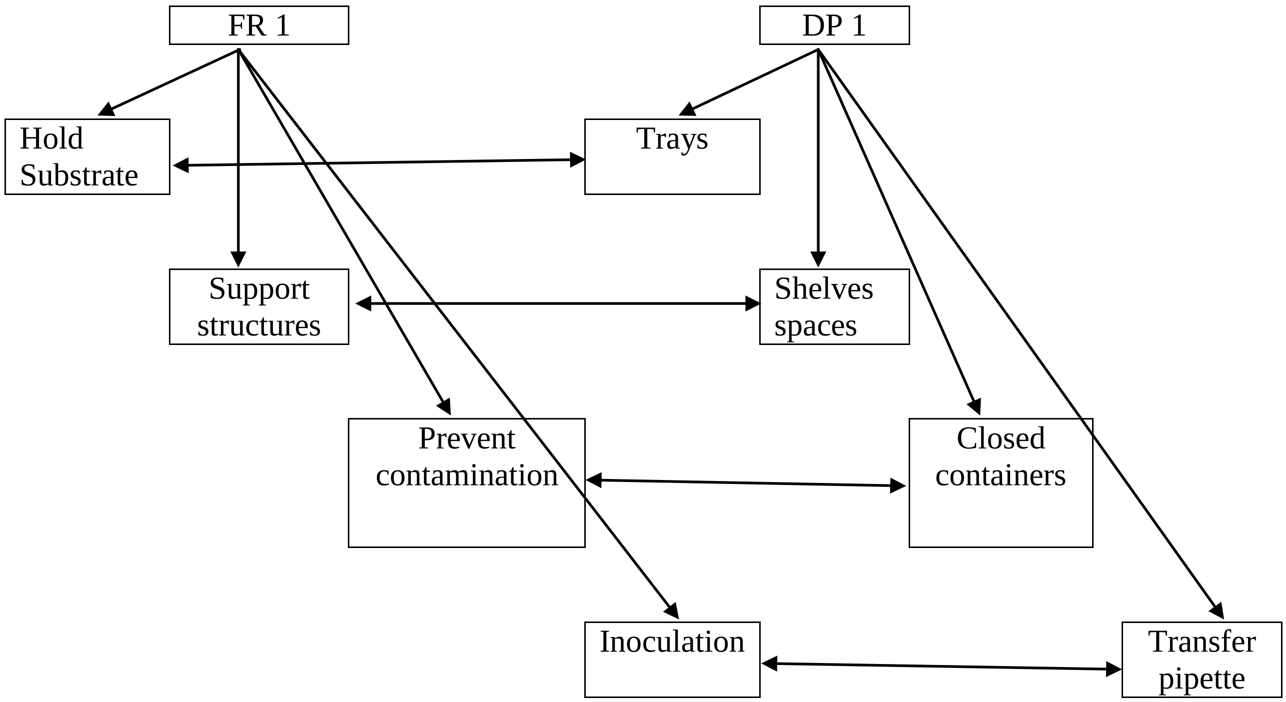

Figure 4.20 Mapping of FR1 to DP1 (Case 7)

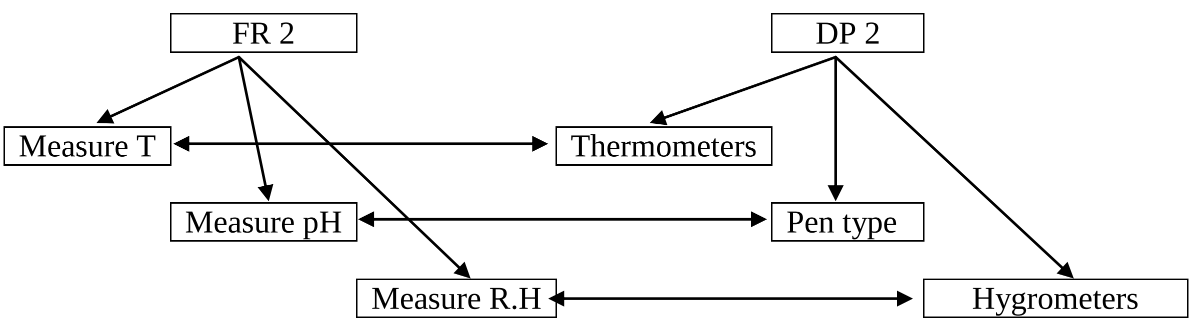

Figure 4.21 Mapping of FR2 to DP2 (Case 7)

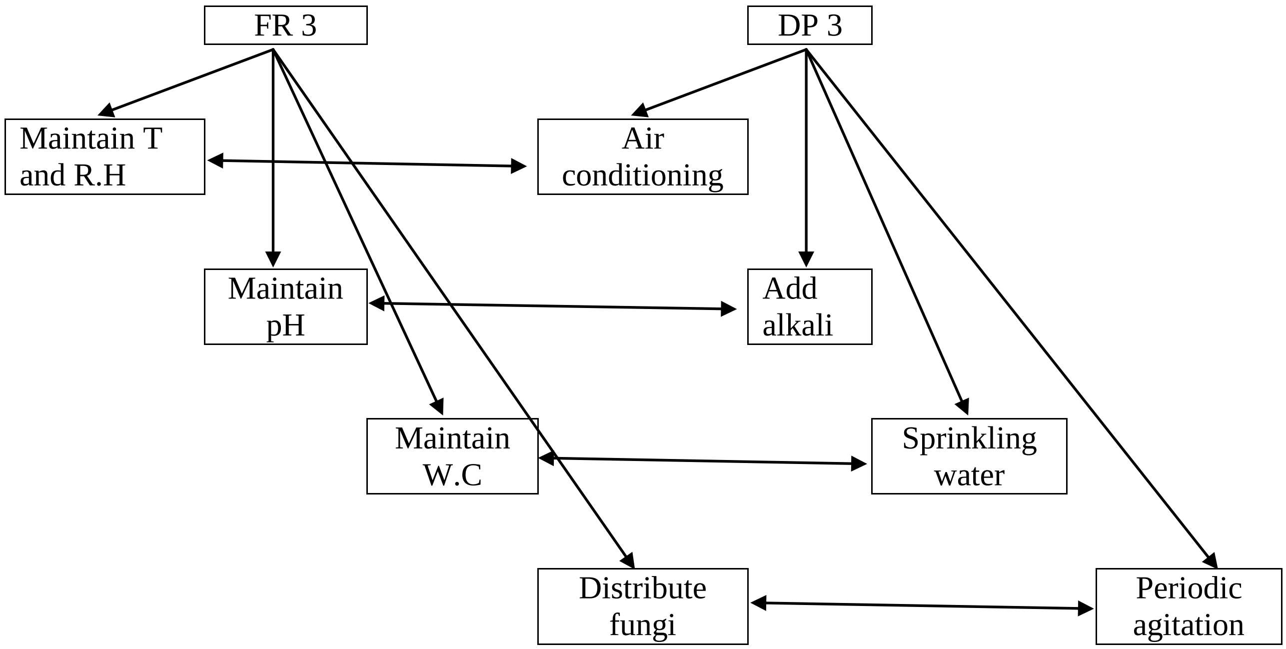

Figure 4.22 Mapping of FR3 to DP3 (Case 7)

4.7 Valid design solutions

The preceding discussion has shown that four different solutions hold Axiom 1 of ADT. Therefore, these four design solutions are considered to be a valid design solution, and they are listed in Table 4.11.

4.8 Conclusion

The application of axiomatic design theory was described in this chapter. This theory was used to design the best possible solution for the solid state fermenter with the help of based on the Axiom 1 in particular. In this chapter, the mapping of the FRs to the DPs was found and based on the design matrix and design equation, the type of design was derived. In addition to that, the independency of the FRs was with Axiom 1 of ADT.

Table 4. 11 Valid design solutions

	Design 1	**Design 2**	**Design 3**	**Design 4**
DP 1.1	Trays	Trays	Trays	Trays
DP 1.2	Shelves	Shelves	Shelves	Shelves
DP 1.3	Closed containers	Closed containers	Closed containers	Closed containers
DP 1.4	Serological Pipettes	Transfer Pipettes	Serological Pipettes	Transfer Pipettes
DP 2.1	Thermocouple	Thermocouple	Thermometer	Thermometer
DP 2.2	Pen type	Pen type	Pen type	Pen type
DP 2.3	Psychrometer	Psychrometers	Psychrometer	Psychrometers
DP 3.1	Air-Conditioning	Air-Conditioning	Air-Conditioning	Air-Conditioning
DP 3.2	Add alkali	Add alkali	Add alkali	Add alkali
DP 3.3	Sprinkling water	Sprinkling water	Sprinkling water	Sprinkling water
DP 3.4	Periodic agitation	Periodic agitation	Periodic agitation	Periodic agitation

During the process of designing the best possible solution, the overall FRs were decomposed into lower levels in order to make sure that the design solution can be found. While choosing the design parameters, almost all the possible design parameters were gathered and different combinations of the design parameters were chosen to give the best solution. Seven different cases were discussed, where three of the cases failed to satisfy the Axiom 1 and four cases succeeded in satisfying Axiom 1. Based on this, the best possible solution for this type of design was derived. Therefore, it can be concluded that the application of Axiom 1 of ADT can aid in finding out the best possible design solution.

Chapter 5 AGGREGATED INFORMATION CONTENT: CONCEPT AND APPLICATION

5.1 Introduction

This chapter presents the study on application of Axiom-2 of ADT. Particularly, Axiom-2 was applied to the design solutions of the SSF, derived from the application of Axiom 1 of ADT. In this chapter instead of using the information content as originally proposed by Suh (1990), in which only the function or quality of a system under design is considered, the so-called aggregated information content was formulated in order to best represent the original meaning or purpose of information content, that is, a measure of the difficulty to realize a design. Further, the difficulty should not only be the business of how to realize the feature of design but also that of the effort (i.e., the cost) and time needed for the realization of the design. It is then argued in this chapter, Axiom 2 must be based on the aggregated information content rather the information content. Based on the aggregated information content and Axiom 2, the best design solution was found among the valid design solutions (as a result of applying Axiom 1 of ADT). That is, the design solution (Solution 4) stood as the best design solution.. This chapter is organized as follows. In Section 5.2, the aggregated information content is described in details. In Section 5.3, the system range in lieu of the aggregated information content is presented for the SSF, followed by Section 5.4 for the design range and by Section 5.5 for the common range. In Section 5.6 and Section 5.7, the evaluation of the design solutions of the SSF is conducted. A conclusion is presented in Section 5.8.

5.2 Aggregated information content

In the previous chapter, Axiom 1 of ADT was applied to derive the valid design solutions. Therefore, in order to find out the best design solution among them, Axiom 2 of ADT has to be applied. In order to apply Axiom 2 the information content for all the valid design solutions has to be derived. In the literature of ADT, the information content is calculated based on the quality of the functional requirement. Therefore, in that case, the design evaluation would be best in terms of quality only and it might lack efficiency in terms of cost and time of the product. Hence, while manufacturing a system the cost, quality and time play vital roles. Therefore, these three aspects should be considered when deriving the information content. In order to derive the information content that include all these aspects, the system range, design range and common range for these aspects (quality/function, cost, time) need to be defined. Once the system, design and common range for these are defined, the information content for each aspect is found out and weightage is assigned to each of the information content and aggregated Information content is thus formed. From the aggregated information content the overall information content is found and used for evaluating the valid design solutions derived out of Axiom 1 of ADT. The process of deriving the aggregated information content is shown in Figure 5.1.

5.3 System range

In the previous chapter, it was shown that four design solutions are valid for manufacturing a system. The valid design solutions are mentioned in Table 5.1. Now, for each of the design parameter of a design solution, a system range has to be defined. Since the system range has to be defined for cost, quality and time, it is defined as follows:

System range (S) of cost for the design solution j and DP_i is S^{Cj}_i,
System range (S) of Quality for the design solution j and DP_i is S^{Qj}_i,
System range (S) of Time for the design solution j and DP_i for is S^{Tj}_i.

Where, j= {1, 2, 3, 4}
i= {1.1, 1.2, 1.3, 1.4, 2.1, 2.2, 2.3, 3.1, 3.2, 3.3, 3.4}

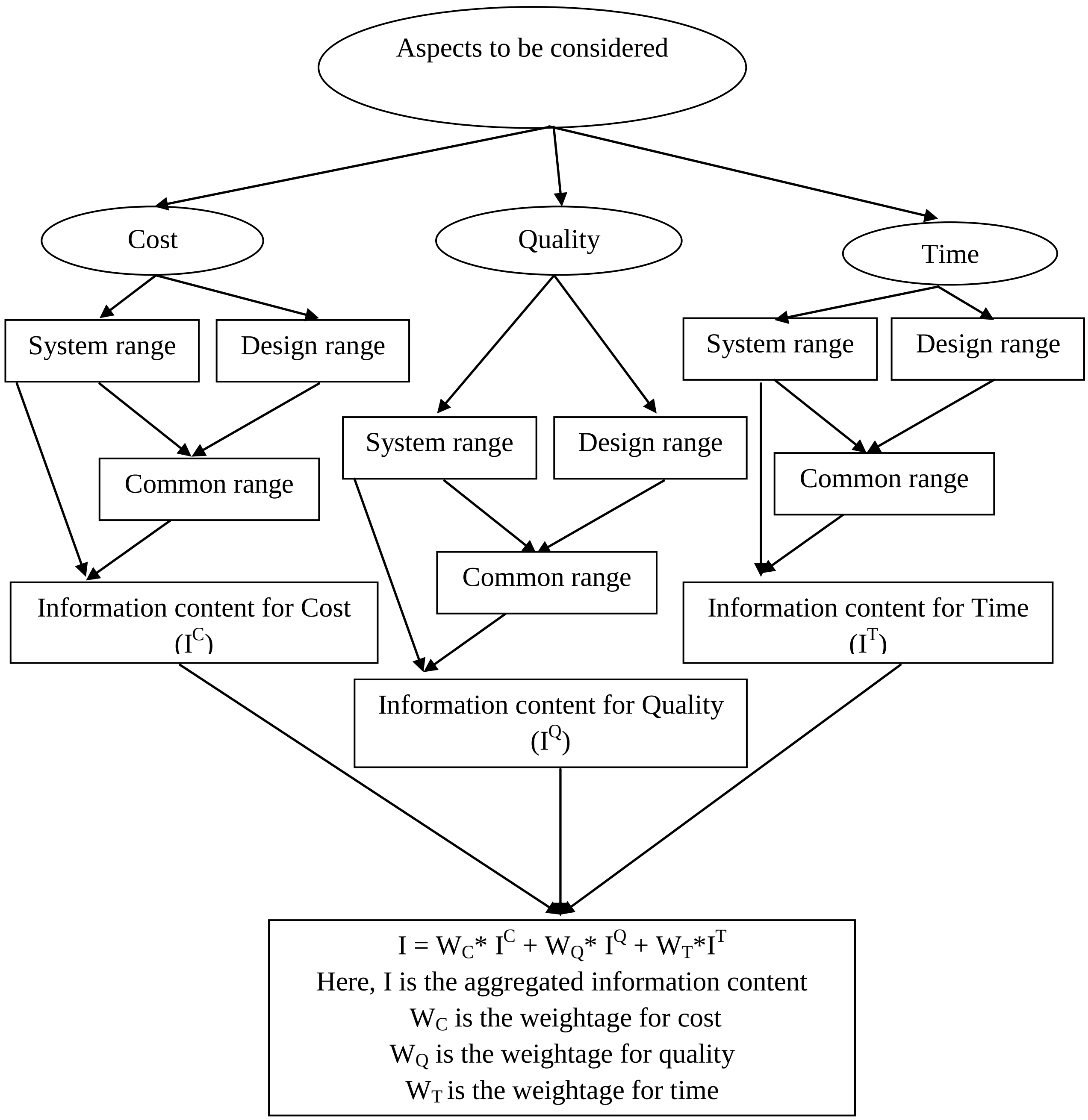

Figure 5.1 Structure to derive the aggregated information content

Table 5.1 Design parameters for valid designs as stated in chapter 4

	Design 1	**Design 2**	**Design 3**	**Design 4**
$DP_{1.1}$	Trays	Trays	Trays	Trays
$DP_{1.2}$	Shelves	Shelves	Shelves	Shelves
$DP_{1.3}$	Closed containers	Closed containers	Closed containers	Closed containers
$DP_{1.4}$	Serological Pipettes	Transfer Pipettes	Serological Pipettes	Transfer Pipettes
$DP_{2.1}$	Thermocouple	Thermocouple	Thermometer	Thermometer
$DP_{2.2}$	Pen type	Pen type	Pen type	Pen type
$DP_{2.3}$	Psychrometer	Psychrometers	Psychrometer	Psychrometers
$DP_{3.1}$	Air-Conditioning	Air-Conditioning	Air-Conditioning	Air-Conditioning
$DP_{3.2}$	Add alakli	Add alkali	Add alakli	Add alkali
$DP_{3.3}$	Sprinkling water	Sprinkling water	Sprinkling water	Sprinkling water
$DP_{3.4}$	Periodic agitation	Periodic agitation	Periodic agitation	Periodic agitation

5.4 Design range

For each of the design parameter of the valid design solution the design range has to be defined for the aspects of cost, quality and time. The design range is defined as follows:

Design range (D) of cost for the design solution j and DP_i is D^{Cj}_i

Design range (D) of quality for the design solution j and DP_i is D^{Qj}_i

Design range (D) of time for the design solution j and DP_i for is D^{Tj}_i

Where, j= {1, 2, 3, 4}

i= {1.1, 1.2, 1.3, 1.4, 2.1, 2.2, 2.3, 3.1, 3.2, 3.3, 3.4}

5.5 Common range

Once the system range and design range are defined the common range for these two can be defined for each valid design parameter. Let

Common range (C) of the cost for the design solution j and DP_i to be C^{Cj}_i

Common range (C) of the quality for the design solution j and DP_i to be C^{Qj}_i

Common range (C) of the time for the design solution j and DP_i for to be C^{Tj}_i.

In the above, j= {1, 2, 3, 4}

i= {1.1, 1.2, 1.3, 1.4, 2.1, 2.2, 2.3, 3.1, 3.2, 3.3, 3.4}

5.6 Evaluating the aggregated information content

Information content is given in terms of system range and common range for all the three aspects (quality, cost and time). They are (respectively) as follows:

$$I^{Cj} = \sum_{i=1}^{3.4} \log\left(\frac{S_i^{Cj}}{C_i^{Cj}}\right) \tag{5.1}$$

$$I^{Qj} = \sum_{i=1}^{3.4} \log\left(\frac{S_i^{Qj}}{C_i^{Qj}}\right) \tag{5.2}$$

$$I^{Tj} = \sum_{i=1}^{3.4} \log\left(\frac{S_i^{Tj}}{C_i^{Tj}}\right) \tag{5.3}$$

In the above, j= {1, 2, 3, 4}.

i= {1.1, 1.2, 1.3, 1.4, 2.1, 2.2, 2.3, 3.1, 3.2, 3.3, 3.4}.

The overall information content of a particular design solution is given by

$$I_j = W_C \times I^{Cj} + W_Q \times I^{Qj} + W_T \times I^{Tj} \tag{5.4}$$

Where W_C is the weight for the cost, W_Q is the weight for the quality, and W_T is the weight for the time.

In the following, the aggregate information contents of all the valid designs are calculated. It is noted that among the four valid designs, most of the DPs are the same except DP1.4 and DP 2.1. Therefore, the detailed calculation of the aggregate information content for DP1.4 and DP2.1 are presented in the following.

5.6.1 Assumptions while calculating the information content for $DP_{1.4}$ and $DP_{2.1}$

The following are the assumptions while calculating the information content for the design parameters $DP_{1.4}$ and $DP_{2.1}$:

(1) In $DP_{1.4a}$ Serological Pipettes are assumed to be considered.
(2) In $DP_{1.4b}$ Transfer pipettes are assumed to be considered.
(3) The type of thermocouples assumed in $DP_{2.1a}$ is industrial thermocouples 1/2NPT, L400mm class A SS316.
(4) The type of thermometer assumed in $DP_{2.1b}$ V shaped Glass industrial Thermometer LT-092/LT-093.
(5) The information content in terms of quality and time for $DP_{1.4a}$ is assumed to be the same as that of $DP_{1.4b.}$
(6) The information content in terms of quality and time for $DP_{2.1a}$ is assumed to be the same as that of $DP_{2.1b.}$

5.6.2 Aggregated information content for $DP_{1.4}$

DP1.4, it has two solutions i.e., (a) Serological pipette and (b) Transfer pipette, and they are denoted as $DP_{1.4a}$ and $DP_{1.4b.}$ The design ranges for both solutions are assumed to be the same for all the three aspects. Let us denote it as follows:

For cost, $D_{1.4}^{C1} = D_{1.4}^{C2} = D_{1.4}^{C3} = D_{1.4}^{C4}$ (5.5)

Time, $D_{1.4}^{T1} = D_{1.4}^{T2} = D_{1.4}^{T3} = D_{1.4}^{T4}$ (5.6)

Quality, $D_{1.4}^{Q1} = D_{1.4}^{Q2} = D_{1.4}^{Q3} = D_{1.4}^{Q4}$ (5.7)

However, the system range in terms of cost for serological pipette is higher than that for transfer pipette. This is because in this case the cost of the serological pipette ranges from $120-$150, while the cost of the transfer pipettes ranges from $25-$60. Therefore,

$$S_{1.4a}^{C} > S_{1.4b}^{C} \quad (5.8)$$

In the above, $S_{1.4a}^{C}$ is the system range in the cost aspect for $DP_{1.4a}$ and $S_{1.4b}^{C}$ is the system range in the cost aspect for $DP_{1.4b}$. Here, the design range is same for $DP_{1.4a}$ and $DP_{1.4b.}$ In this case the common range is equal to the design range in terms of cost. Therefore,

$$D_{1.4a}^{C} = D_{1.4b}^{C} \quad (5.9)$$

$$C_{1.4b}^{C} = C_{1.4b}^{C} \quad (5.10)$$

In the above, $D_{1.4a}^{C}$ is the design range in the cost aspect for $DP_{1.4a}$, $D_{1.4b}^{C}$ is the design range in the cost aspect for $DP_{1.4b,}$ $C_{1.4a}^{C}$ is the common range in the cost aspect for $DP_{1.4a}$, $C_{1.4b}^{C}$ is the common range in cost aspect for $DP_{1.4b}$.
Therefore, the information content in terms of cost for serological pipette is higher than transfer pipette i.e.,

$$I_{1.4a}^{C} > I_{1.4b}^{C} \quad (5.11)$$

However in the aspects of time and quality, serological pipette and transfer pipettes are always ready in the market for supply. When considered in terms of quality, both transfer and serological pipette would be the same, and thus they possess the same system and design ranges. Therefore, information contents in terms of time and quality for $DP_{1.4}$ of all these designs are the same. Therefore,

$$I_{1.4a}^{Q} = I_{1.4b}^{Q} \quad (5.12)$$

$$I_{1.4a}^{Q} = I_{1.4b}^{Q} \quad (5.13)$$

The aggregated information contents are thus:

$$I_{1.4a}= (I_{1.4a}^{C} + I_{1.4a}^{Q} + I_{1.4a}^{T})/3 \quad (5.14)$$

$$I_{1.4b}= (I_{1.4b}^{C} + I_{1.4b}^{Q} + I_{1.4b}^{T})/3 \quad (5.15)$$

From equations (5.11), (5.12) and (5.13) it can be found that

$$I_{1.4a} > I_{1.4b} \quad (5.16)$$

In the above equations,

$I_{1.4a}^{C}$ is the Information content in cost aspect for $DP_{1.4a,}$

$I_{1.4b}^{C}$ is the Information content in cost aspect for $DP_{1.4b}$,

$I_{1.4a}^{Q}$ is the Information content in quality aspect for $DP_{1.4a}$,

$I_{1.4b}^{Q}$ is the Information content in quality aspect for $DP_{1.4b,}$

$I_{1.4a}^{T}$ is the Information content in time aspect for $DP_{1.4a}$,

$I_{1.4b}^{T}$ is the Information content in time aspect for $DP_{1.4b}$,

$I_{1.4a}$ is the aggregated Information content for $DP_{1.4a}$ and

$I_{1.4b}$ is the aggregated Information content for $DP_{1.4b}$.

5.6.3 Aggregate information content for $DP_{2.1}$

The $DP_{2.1}$, has two of designs, that is thermocouple ($DP_{2.1a}$) and thermometer ($DP_{2.1b}$)
The design ranges is the same for the $DP_{2.1a}$ and $DP_{2.1b}$ in terms of cost, quality and time are the same. They are as follows:

For cost, $D_{2.1}^{C1}= D_{2.1}^{C2}= D_{2.1}^{C3}= D_{2.1}^{C4}$ (5.17)

Time, $D_{2.1}^{T1}= D_{2.1}^{T2}= D_{2.1}^{T3}= D_{2.1}^{T4}$ (5.18)

Quality, $D_{2.1}^{Q1}= D_{2.1}^{Q2}= D_{2.1}^{Q3}= D_{2.1}^{Q4}$ (5.19)

For the system range, the only difference is the cost. The cost of thermocouple is higher than that of thermometer. In particular, the cost for a single thermocouple would range around $28-$120 while for the thermometers the cost would range around $18-$26. Therefore,

$$S_{2.1a}^{C} > S_{2.1b}^{C} \quad (5.20)$$

Here, the design range is same for $DP_{2.1a}$ and $DP_{2.1b.}$ In this case the common range is equal to the design range in terms of cost. Therefore,

$$D_{2.1a}^{C} = D_{2.1b}^{C} \quad (5.21)$$

$$C_{2.1b}^{C} = C_{2.1b}^{C} \quad (5.22)$$

Therefore, the information contents in terms of cost for thermocouple are higher than the thermometer, since the system range is higher for it. That is,

$$I_{2.1a}^{C} > I_{2.1b}^{C} \quad (5.23)$$

However in the aspects of time and quality, thermocouples and thermometers are always ready in the market for supply. When considered in terms of quality, both thermocouples and thermometers would be the same, and thus they possess the same system and design ranges. Therefore, information contents in terms of time and quality for $DP_{1.4}$ of all these designs are the same. Therefore,

$$I_{2.1a}^{Q} = I_{2.1b}^{Q} \quad (5.24)$$

$$I_{2.1a}^{T} = I_{2.1b}^{T} \quad (5.25)$$

The aggregated information contents for the two design parameters are

$$I_{2.1a} = (I_{2.1a}^{C} + I_{2.1a}^{Q} + I_{2.1a}^{T})/3 \quad (5.26)$$

$$I_{2.1b} = (I_{2.1b}^{C} + I_{2.1b}^{Q} + I_{2.1b}^{T})/3 \quad (5.27)$$

From equations (5.23), (5.24) and (5.25) it can be found that

$$I_{2.1a} > I_{2.1b} \tag{5.28}$$

In the above equations,

$I_{2.1a}^{C}$ is the Information content in cost aspect for $DP_{2.1a}$,

$I_{2.1b}^{C}$ is the Information content in cost aspect for $DP_{2.1b}$,

$I_{2.1a}^{Q}$ is the Information content in quality aspect for $DP_{2.1a}$,

$I_{2.1b}^{Q}$ is the Information content in quality aspect for $DP_{2.1b}$,

$I_{2.1a}^{T}$ is the Information content in time aspect for $DP_{2.1a}$,

$I_{2.1b}^{T}$ is the Information content in time aspect for $DP_{2.1b}$,

$I_{2.1a}$ is the aggregated Information content for $DP_{2.1a}$ and

$I_{2.1b}$ is the aggregated Information content for $DP_{2.1b}$.

5.6.4 Overall information content for each design

Design 1:

The overall information content for the design 1 would be as follows:

$$I_1 = I_{1.1}^{1} + I_{1.2}^{1} + I_{1.3}^{1} + I_{1.4a}^{1} + I_{2.1a}^{1} + I_{2.2}^{1} + I_{2.3}^{1} + I_{3.1}^{1} + I_{3.2}^{1} + I_{3.3}^{1} + I_{3.4}^{1} \tag{5.29}$$

This can be simplified to:

$$I_1 = I_{1.1} + I_{1.2} + I_{1.3} + I_{1.4a} + I_{2.1a} + I_{2.2} + I_{2.3} + I_{3.1} + I_{3.2} + I_{3.3} + I_{3.4} \tag{5.30}$$

Let,

$$I' = I_{1.1} + I_{1.2} + I_{1.3} + I_{2.2} + I_{2.3} + I_{3.1} + I_{3.2} + I_{3.3} + I_{3.4} \tag{5.31}$$

Therefore,

$$I_1 = I' + I_{1.4a} + I_{2.1a} \tag{5.32}$$

Design 2:

The overall information content for the design 2 would be as follows:

$$I_2 = I_{1.1}^2 + I_{1.2}^2 + I_{1.3}^2 + I_{1.4a}^2 + I_{2.1a}^2 + I_{2.2}^1 + I_{2.3}^2 + I_{3.1}^2 + I_{3.2}^2 + I_{3.3}^2 + I_{3.4}^2 \quad (5.33)$$

This can be simplified to:

$$I_2 = I_{1.1} + I_{1.2} + I_{1.3} + I_{1.4a} + I_{2.1b} + I_{2.2} + I_{2.3} + I_{3.1} + I_{3.2} + I_{3.3} + I_{3.4} \quad (5.34)$$

From equation (5.32)

$$I_2 = I' + I_{1.4a} + I_{2.1b} \quad (5.35)$$

Design 3:

The overall information content for the design 3 would be as follows

$$I_3 = I_{1.1}^3 + I_{1.2}^3 + I_{1.3}^3 + I_{1.4b}^3 + I_{2.1a}^3 + I_{2.2}^3 + I_{2.3}^3 + I_{3.1}^3 + I_{3.2}^3 + I_{3.3}^3 + I_{3.4}^3 \quad (5.36)$$

This can be simplified to:

$$I_3 = I_{1.1} + I_{1.2} + I_{1.3} + I_{1.4b} + I_{2.1a} + I_{2.2} + I_{2.3} + I_{3.1} + I_{3.2} + I_{3.3} + I_{3.4} \quad (5.37)$$

From equation (5.32)

$$I_3 = I' + I_{1.4b} + I_{2.1a} \quad (5.38)$$

Design 4:

The overall information content for the design 4 would be as follows:

$$I_4 = I_{1.1}^4 + I_{1.2}^4 + I_{1.3}^4 + I_{1.4a}^4 + I_{2.1a}^4 + I_{2.2}^4 + I_{2.3}^4 + I_{3.1}^4 + I_{3.2}^4 + I_{3.3}^4 + I_{3.4}^4 \quad (5.39)$$

This can be simplified to:

$$I_4 = I_{1.1} + I_{1.2} + I_{1.3} + I_{1.4b} + I_{2.1b} + I_{2.2} + I_{2.3} + I_{3.1} + I_{3.2} + I_{3.3} + I_{3.4} \quad (5.40)$$

From equation (5.32)

$$I_4 = I' + I_{1.4b} + I_{2.1b} \quad (5.41)$$

5.7 Evaluating the best design

According to Axiom 2 of ADT, the design with the least information content would be the best possible design solution.

Let us compare the information contents for all the design solutions. The results are:

$$I_1 > I_2 \quad (5.42)$$

$$I_1 > I_4 \quad (5.43)$$

$$I_3 > I_4 \quad (5.44)$$

$$I_2 > I_4 \quad (5.45)$$

$$I_1 > I_3 \quad (5.46)$$

Therefore the fourth design solution has the least information content among all the designs. According to Axiom 2, the design solution no.4 would be the best design solution.

5.8 Conclusion

The application of Axiom 2 of ADT was discussed in this chapter. The aggregate information content along with the modified Axiom 2 was applied to each design solution. First, the concept of information content has been extended to consider the cost, time and quality. This extension leads to so called aggregated information content. Accordingly, Axiom 2 of ADT is extended to: "the best design is the one with the minimum aggregate information content."

Then for the SSF, it was demonstrated that the effectiveness of Axiom 2; in particular, for the SSF under design, the fourth design solution is the best. Coincidentally, this conclusion is the same as the one with SDP. At this point, it is interesting to notice that if the original Axiom 2 is used, one may conclude that among the four designs, no one stands out significantly.

One can conclude that the modified Axiom 2 of ADT is meaningful and it shall give a complete picture of the pros and cons of each design.

Chapter 6 COMPARISON OF ADT AND SDP

6.1 Introduction

This chapter deals with the relationship between ADT and SDP and attempts to provide an answer to questions 2 and 3, respectively, proposed in Chapter 1. This chapter also describes the nature of the zigzag method in the context of these two methodologies.

6.2 ADT versus SDP

There is no doubt that design is a cognitive activity to synthesize elements in a physical domain to form a physical entity that performs required functions under required conditions and subject to required constraints. The required conditions and constraints are the basis to lead to a bounded physical domain. To achieve a design task, there are several generic tasks. The first generic task is to form a design problem from required functions, conditions and constraints. The second generic task is to decompose the design problem into a set of smaller problems (if necessary). The third generic task is to find candidate solutions to all problems. The fourth generic task is to evaluate the candidate solutions and select the best one. The design activity may iterate among these tasks. Sometimes, activities among different tasks may be coupled strongly so that a design model may be formulated to complete these activates simultaneously (e.g., a design model may be a constrained optimization model).

The SDP provides guidelines for all the tasks except the fourth task, that is, the SDP does not provide any guideline for evaluation and selection. More precisely speaking, in the SDP, the evaluation and selection task is delegated to the subjective evaluation such as the evaluation based on the cost and manufacturability. It is perhaps in the mind of the SDP developer, there is no sense to have a body of generic knowledge (or one index) such as information content in the ADT.

The ADT provides guidelines for the last three tasks, namely, the second, third, and fourth tasks. The ADT provides guidelines for the second and third tasks in that Axiom 1 of the ADT must be done after completing the second and third tasks. That is, Axiom 1 is employed to the design situation where FRs and DPs are found. However, the role of Axiom 1 is a post-check process in particular from a perspective of coupling, uncoupling, and decoupling; Axiom 1 is never used for decomposing a function into a set of sub-functions or smaller functions and for generating designs or solutions or DPs to fulfill the sub-functions. Axiom 1 has its role in developing the function structure and solution structure in that once a design (a set of FRs and a set of DPs) is deemed to violate Axiom 1, the FR set and/or the DP set may need to be revised and thus from that point of view, the FR and DP structures are changed.

Axiom 2 of the ADT provides a guideline for the fourth task, that is, to evaluate and select the candidate designs that have passed Axiom1. The key is the information content tied to each design and then the best design is the design with the minimal information content.

It may clear that the two design methodologies, ADT and SDP, are complementary to each other in the context of the four generic design tasks; see Table 6.1. They have an overlapping in the second and third tasks, that is, if a function cannot be fulfilled by any DP, then the function needs to be decomposed into several small ones to explore whether there are DPs which fulfill these small functions. The two do not have any conflict on this overlapping area.

Table 6.1 Complementary relationship of ADT and SDP

Task		ADT	SDP
1			√
2	2.1 Generation		√
	2.2 Evaluation	√	
3	3.1 Generation		√
	3.2 Evaluation	√	
4		√	

6.3 Remark on the ZigZag process in ADT and SDP

The ZigZag process describes the design process of finding DPs and decomposing FRs with a particular focus on the intertwining nature of these two processes. The term is often used in conjunction with ADT. In ADT, suppose that there is an overall function FR and no DP is found. As such, the FR is decomposed into FR11 and FR12 (for example), where the first subscript "1" refers to the level (1^{st} level) in hierarchy, and the second subscript "2" to the number. Suppose that DP11 is found for FR11 but no DP for FR12. FR12 then needs to be further decomposed. In ADT, Axiom 1 is used to evaluate the FR-DP structure. Suppose that the result of evaluation is such that DP11 may not only affect FR11 but also FR12 (for example). There are two cases: (1) modify DP11 to or find new DP11', and (2) modify FR11 and FR12 to FR11' and FR12' such that DP11 only affects FR11' but not FR12' (and thus Axiom 1 is satisfied). For case (2), the FR and DP structures are developed simultaneously.

In fact, the zigzag process is also followed in SDP. In SDP, an overall function is decomposed into a set of functions or is developed into a function structure in the term of SDP. After that, solution principles (or solutions) are found for all functions. In the SDP literature, it does not seem to say that in what a situation a function may be further decomposed, it does show that the function structure may not only stop at the one level, that is, overall function into a set of functions. It can reasonably be assumed that in SDP, the motivation to further decompose a function must be such that there is no solution principle found for that function. However, in SDP, there is no evaluation of the FR-DP structure (DP corresponds to solution principle) and therefore, the function dependency may present in the FR-DP structure.

6.4 Comparison between ADT and SDP based on their final results

The following are the common grounds for the comparison. First, both methodologies were applied to the same task (i.e., design of the SSF). Second, three main functions were defined. The following are the results of running both methodologies.

1) From these 3 main functions, 11 sub-functions are derived with ADT and SDP, respectively, and the sub-functions are the same for both ADT and SDP.
2) SDP has a set of valid design solution variants. ADT also has a set of design solutions and then a set of valid design solutions after applying Axiom 1 of ADT. The set of valid solutions of ADT is different from the set of valid solutions of SDP. For instance, solution variant 2 of SDP, that is SP 10 (evaporative cooling), not only satisfies SF 10 (moisture content) but also

SF 8 (Maintain T) (see Chapter 3 for details), and this design is not valid according to Axiom 1 of ADT.

3) SDP has an evaluation procedure with the criteria such as simple manufacturing, operation, easy maintenance, accessibility, safety, simple assembly, low complexity and few operation errors. Though there seem to be more aspects to be evaluated than the only criterion - information content of ADT, they seem to be aggregated into the three aspects: quality, time and cost, which are considered in ADT (with a modified notion of information content). It is noted that in the case of quality, it makes sense to say a sort of combination of the product quality and ease with manufacturing or assembly or maintenance and so on in ADT. In fact, having all these aspects considered should be what the information content represents in the context of manufacturing.
4) In SDP, when combining the solution principles, the compatibility among the solutions is analyzed to screen out any incompatible solutions. This compatibility analysis is not present in ADT. As such, the valid design from a point of view ADT may not be a valid design from a point of view of SDP. For instance, consider FR1.1 (Hold substrate) and FR 1.2 (Support structures) and let DP 1.1 be trays and DP 1.2 be drum holders. These designs are valid by applying Axiom 1 of ADT. However, practically, the drum holders can never be the support structures for the trays to act as substrate holders. The compatibility analysis with SDP is able to eliminate this wrong combination – i.e., wrong design solution.
5) The final best design solution is the same with the application of ADT and SDP.

6.5 Conclusion with discussion

In this chapter, the comparison of the ADT and SDP was made. The following conclusions can be drawn. First, ADT and SDP are complementary to each other in design especially in developing the FR-DP structure. In particular, SDP is used to guide the function structure generation and solution finding, while ADT is used to evaluate the FR-DP structure. Further, the SDP can be applied to evaluate the compatibly among DPs to remove any solution that includes incompatible solutions. A new design process which integrates ADT and SDP is proposed in Figure 6.1. Second, the zigzag process makes sense to both the ADT and SDP. Third, the best design solutions obtained by the application of SDP and ADT may not be the same in spite of the same best design solution obtained for the SSF in this thesis.

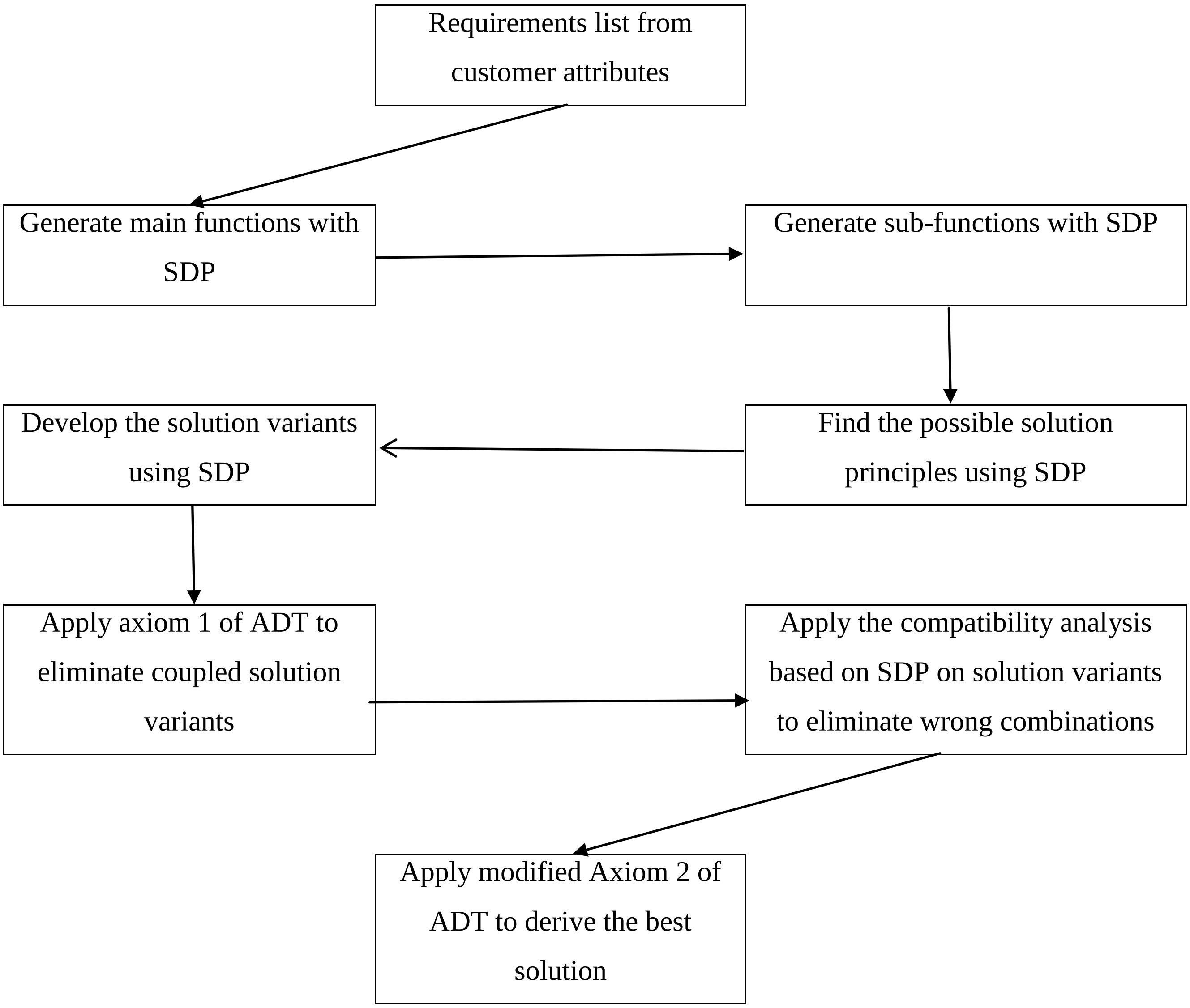

Figure 6.1 New design process that integrates ADT and SDP

Chapter 7 CONCLUSIONS AND FUTURE WORK

7.1 Overview

Jatropha curcas is one of the best recourses for the bio-diesel production in future. Its characteristics such as a weed, drought and pest resistance makes it very desirable. While biodiesel is the main product of Jatropha, the seed cake remains after the extraction of oil from these seeds which contain a rich source of proteins. Many anti-nutrients present in the seed cake can be significantly removed, However phorbal esters cannot be removed using these processes. Phorbal esters have a complex structure. Phorbal esters were successfully removed from the seed cake by solid state fermentation (SSF) with fungi in the laboratory scale. The next step was then to extend the laboratory scale system to an industrial scale system.

This thesis presented a study towards the application of design theory and methodology (ADT) on designing the design solutions for the SSF. The focus of the study was to provide the best design through for a particular SSF a rational process along with a deep investigation of two well-known design schools or approaches in the design community, namely ADT and SDP. Therefore, the research faced three questions:

> Question 1: What is the best design for the industrial scale solid state fermenter?
> Question 2: What is the relationship between ADT and SDP?
> Question 3: What are some specific obstacles in the application of ADT and SDP in industrial design practice?

The specific research objectives were then defined and they are re-visited herein.

Objective 1: Apply the SDP to the design of an industrial scale solid state fermenter for the detoxification of *Jatropha* seed cake. Specifically, the work should (1) find all possible design solutions and (2) find the best one.

Objective 2: Apply the ADT to the design of an industrial scale solid state fermenter for the detoxification of *Jatropha* seed cake. Specifically, the work should (1) find all possible design solutions and (2) find the best one.

Objective 3: Application of Axiom-2 of the ADT for obtaining the best design based on the design solutions generated from the first two objectives.

Objective 4: Compare ADT and SDP to lead to a more effective guideline for design.

In chapter 2, the background for SSF was explained, and overview of the key concepts of ADT and SDP were presented.

In chapter 3, the SDP was applied to develop the design solution for SSF. Finally, the fourth design solution (i.e., variant 4) was found to be the best design solution. In chapter 4, the ADT was applied and led to four design solutions. In chapter 5, Axiom 2 of ADT was applied to the four design solutions of SSF which resulted from the application of ADT, which led to the same best design solution as concluded by the application of SDP. In Chapter 6, the relationship between ADT and SDP was analyzed and discussed. The discussion was not only based on the first principle of each of them but also on the result after applying them (respectively).

7.2 Limitations of design solutions

The following are the limitations with regard to the proposed design solutions:

(1) The design solutions may not be valid outside the assumptions stated in the previous chapters.
(2) The design solutions are mainly aimed to compare the design theories and methodologies.
(3) The design solutions proposed in this thesis may not be used to design a fermenter, but can be used as guidelines in developing the design solutions.

(4) The design solutions proposed in this thesis are restricted to conceptual phase of design, whereas further refinement has to be done in order to develop the industrial level fermenter.

7.3 Conclusions

The study presented in the thesis concludes:

1. Both SDP and ADT are an effective design methodology, including function decomposition and solution finding, and they each have their methods for ensuring a better design. They are complementary to each other and can be well integrated to lead to a better design process.
2. Axiom 2 of ADT misses the information of the cost and time of a design, and therefore, it is difficult to be used in design practice, which partially answers Question 3 to be answered by the current thesis.
3. Both SDP and ADT follow a zigzag process in developing the FR-DP relation and both follow a divide-and-concur strategy to cope the complexity of design problem.

7.4 Research Contributions

The main contributions of the thesis are discussed below:

1. Provision of a rational design solution for industrial scale SSF system that can detoxify the phorbal esters in the Jatropha seed cake, which makes the industrial utilization of the *Jatropha curcas* as on the source for bio-diesel.
2. Proposal of a new design process that integrates SDP and ADT. In principle, the new design process can overcome the shortcomings in SDP and ADT, respectively.
3. Proposal of the modified information content for Axiom 2 of ADT, that is, the aggregate information content. The aggregate information content allows considering three aspects of design, which are quality, cost, and time in the context of manufacturing.

7.5 Future work

This thesis work could potentially be improved through several future endeavors and they are discussed in the following:

1. These design solutions should further be elaborated and applied in order to get a fully workable SSF. That may further imply the proceeding of the embodiment and detail designs of SSF.
2. It is widely agreed in the design community that design can be divided into three phases: conceptual design, embodiment design, and detail design. The finding and scope of this thesis are mostly about the activities at the conceptual design phase. It may be interesting to look into the applicability of the findings of this thesis to the subsequent design phases, namely embodiment design and detail design phases.
3. It is known that there are different types of design, such as new design, redesign, and configuration design, and so on. The finding of this thesis is mostly about the new design type. It is interesting to study the suitability and applicability of ADT, SDP and ADT-SDP to different types of design.

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