TABLE OF CONTENTS

PART II APPENDICES

LIST OF EQUATIONS

LIST OF FIGURES

LIST OF TABLES

1. Introduction

1.1 Background

The research area of product development and manufacturing is currently receiving increasing attention to address industry efforts to reduce lead time, cut development and manufacturing costs, increase quality and product performance, and lower total life cycle cost.

In this context, focus has shifted from improving the performance during the later stages of the product development cycle to the front end phases where product development take place at a higher level of abstraction. This shift is motivated by studies and experience showing that design decisions made during the early stages of the product development cycle have the largest impact on total cost of the product (figure 0-1). It is often claimed that up to 80% of the product's total cost is committed during the concept development stage (for example, see [FRED94]).

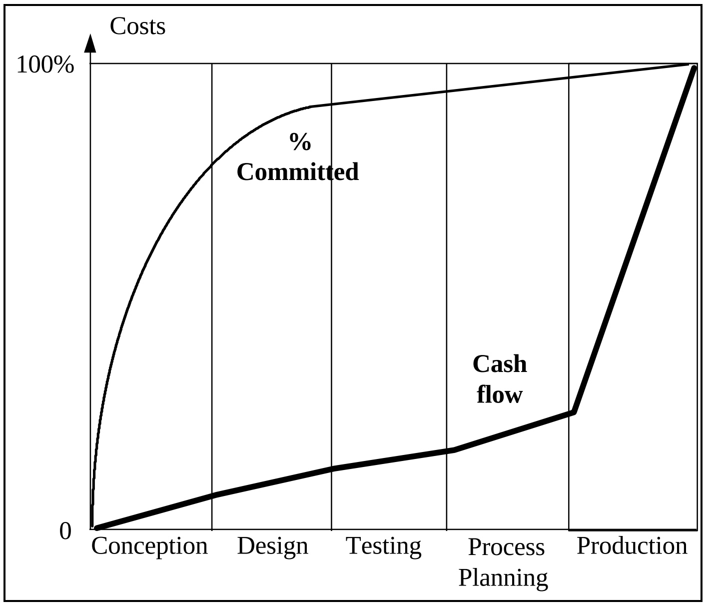

Figure 0-1 Importance of early design decisions

1.2 Engineering design - a form of information processing

Engineering design is an information processing activity. The process begins by inputting information about needs and constraints and ends with a complete description of the system that will satisfy these needs (along with a description of how to realize such system) (Figure 0-2).

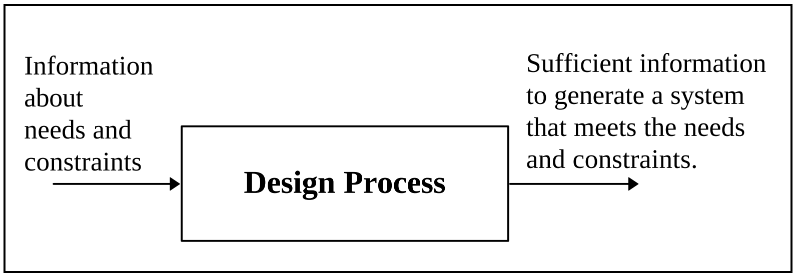

Figure 0-2 Processing information in the design process

During the design process, the designer must access existing information and generate new information. Existing information is found both within and beyond the engineer's current realm of knowledge. For example, information may exist in the designer's immediate surroundings (e.g., in the company) or elsewhere (e.g., with the customer, with a vendor, or at a university). When this information has been entered into the design, we are beginning to build up knowledge (systematized information) about the design object and the process to manufacture it.

Thus, to perform engineering design that quickly leads to high quality products that can be realized at low cost, the company must have:

- access to information, and
- competence and tools enabling them to quickly systematize the information into knowledge about the design object along with knowledge about how to realize it.

Furthermore, in order to build a *sustainable* competitive advantage in the product development process, the company must have one or more of the following

- *useful proprietary information that is easily accessible* to the company's designers,
- *superior methods of accessing and utilizing public information*, and
- *competence and tools to more effectively systematize*.

1.3 Research in engineering design

Systematic research in engineering design began in Germany during the 1850s. Some of these efforts (up until 1983) have been compiled in a list by Bjärnemo [BJÄR83 p. 29]. More recent contributions in the field of engineering design have been added to Bjärnemo's list, demonstrating that research in engineering design is an active research field that has spread from Germany to most industrialized nations around the world (Table 0-1).

To date, most research in engineering design has focused on design methods. As a result, a number of design methods are now being taught and practiced in both industry and academia. However, most of these methods do not provide prescriptive advice where to access information nor how to store such information once the designer has acquired it. Furthermore, there is a lack of theory on how to reuse information that has been systematized and stored.

Accordingly, there is a need for *generalizable* theory on an information infrastructure that will support various design theories enabling designers in industry to more effectively utilize these design methods. Such an information infrastructure will also enable academia to identify new research areas that are complementary to those traditionally pursued in the field of engineering design. Furthermore, theories on information infrastructures will add valuable content to design courses taught at universities.

1.4 Scope and motivation of this thesis

The purpose of thesis is to initiate the effort to establish the *information infrastructure for axiomatic design* [SUH90]. The work is primarily focused on answering the following questions:

- What are sources of information that the designer can use during the axiomatic design process?
- How can information obtained during the design process be of benefit during later stages of the design object's life cycle?

A new information framework was developed to answer the first question, and an extension of the theory presented by Suh in [SUH90] was developed to answer the second question.

It was shown that this framework applies not only to engineering problems, but also to problems outside the field of engineering. Furthermore, the framework and theory that was developed can most likely be fully implemented in a computerized information system. Based on the information framework, it was demonstrated how other design methods (such as Altshuller's theory of inventive problem solving [ALTS88]) can be used to enhance the designers performance within the framework.

It is expected that the information infrastructure for axiomatic design presented here will facilitate the following:

- strategic work to build sustainable competitive advantages in product development for industry choosing to work with axiomatic design,
- identification of research questions related to the development of software supporting axiomatic design, and
- teaching axiomatic design to both students and practitioners.

1.5 Structure of this thesis

The contents of this thesis are as follows:

Section 2 - Scientific method: A framework for conducting scientifically valid research in engineering design is presented and related to the thesis.

Section 3 - Overview of the types of design theories and a general model of the design process: Shows the context of this thesis in terms of other theories in design theory and methodology. This section also contains a model of the design process that provides a useful reference for relating the various theories and activities to the design process.

Section 4 - Expanded framework of information in design: Introduces an expanded framework of information in design, based on Suh’s concept of domains. This framework is shown to be beneficial in identifying and generating design solutions, as well as for capturing design information.

Section 5 - Managing information in the framework: A theory on how the information generated in the framework can be utilized to predict the impact of engineering change orders, search for problems in the design object and feedback information on the performance of previous designs to the design engineers.

Section 6 - Relating Theory of Inventive Problem Solving to the framework: Here it is shown how Altshuller’s theory is complementary to the framework in generating design information.

Section 7 - Applicability of the framework: This section demonstrates that the framework is not strictly limited to engineering problems by presenting an example of how the framework has been successfully used during business planning.

Section 8 - Contributions, conclusions and future work: The contributions of this thesis to academia, industry and the general transfer of knowledge are presented. Conclusions and proposed future work (including how the knowledge developed here could be used in developing a thinking design machine) are also discussed.

Table 0-1. Some work in design theory[1]

Author	Theory or Method	Country	Appr. year
Altshuller	Theory of Inventive Problem Solving [ALTS88]	Soviet	1956
Andreasen	Chromosome model [ANDR92]	Denmark	1992
Bach	Die Maschinelemente	Germany	1881
Boothroyd and Dewhurst	DFM/DFA [BOOT89,BOOT94]	USA	1983
Clausing	QFD [HAUS88, COHE95] Total Quality Development [CLAU94]	USA	1988
Cross	Engineering Design Methods	UK	1989
Dixon and Poli	Engineering Design and Design for Manufacturing [DIXO95]	USA	1995
Erkens	Beiträge zu Konstruktionserziehung	Germany	1928
Hansen	Konstruktionswissenshaft - Grundlagen und Methoden	Germany	1974
Hubka & WDK School	Design Science [HUBK92]	Europe	1973
Kesselring	Die starke Konstruktion	Germany	1942
Kesselring	Technische Kompositionslehre	Germany	1954
Koller	Eine Algoritmisch-physikalisch orienterte Konstruktionsmethodik	Germany	1973
Leyer	Maschinenkonstruktionslehre	Germany	1963-71
Matousek	Konstruktionslehre des allgemeinen Maschinenbaus	Germany	1957
Nieman	Machinelemente	Germany	1950
Olsson	Systematisk Konstruktion	Sweden	1976
Pahl and Beitz	Engineering Design a Systematic Approach [PAHL88]	Germany	1977
Pugh	Total Design [PUGH91, PUGH96]	UK	1985
Redtenbacher	Prinzipen der Mechanik und des Maschinenbau	Germany	1852
Riedler	Maschinenzeichnen	Germany	1913
Reuleaux	Konstruktionslehre für den Maschinenbau	Germany	1854
Reuleaux	Teoretische Kinematik: Gründzüge einer Theorie des Maschinenwesens	Germany	1875
Rodenacker	Methodisches Konstruieren	Germany	1970
Roth	Aufbau und handhabung von Konstruktionskatalogen	Germany	1974
Sohlenius et al	Prodevent (Orderstyrd, kundanpassad produktframtagning) [SOHL76]	Sweden	1976
Suh	Axiomatic Design [SUH90]	USA	1978
Taguchi	Jikken Keikakuho (Eng. trans. *System of Experimental Design)* [PHAD89]	Japan	1977-78
Ullman	The Mechanical Design Process	USA	1986
Ulrich and Eppinger	Product Design and Development [ULRI95]	USA	1995
VDI-GKE	VDI Guideline 2221: Systematic Approach to the design of technical systems and products	Germany	1973
Wögerbauer	Die Technik des Konstruierens	Germany	1943
Yoshikawa	General Design Theory	Japan	1980
Zwicky	The Morphological Method of Analysis and Construction	USA	1948

2. Scientific framework for research in design theory

The purpose of this section is to provide a scientific framework for the research presented in this thesis. It was found that there is a shortage of literature covering the use and validity of research methods and scientific frameworks for design theory research. For this reason, it was necessary to investigate and derive an acceptable, research method or framework for engineering design theory research. This section summarizes the results of this study and outlines a scientific framework for the design theory research (Figure 0-3). Complete results of this study can be found in appendix 1.

The material presented in this section does not indicate that this is the only way to do scientifically valid research in design theory. However, it is concluded to be one scientifically valid way of doing research in this area.

2.1 Definition of scientific theory and discussion on how theories can be used[2]

In this thesis a scientific theory is defined as a theory comprising <u>fundamental knowledge areas</u> in the form of perceptions and understandings of different entities, and the <u>relations</u> between these fundamental areas. These perceptions and relations are combined by the theorist to produce <u>special consequences</u> (which can be, but are not necessarily, predictions of observations) [FØLL93 p. 75-78].

Fundamental knowledge areas (such as mathematical expressions, categorizations of phenomena or objects, models, etc.) are more abstract than observations of real-world data. Such knowledge, and relations between knowledge constitute a theoretical system. A theoretical system may be one of two types (depending on the way in which the fundamental knowledge areas are treated): They may be treated as either

- axioms, or
- hypotheses.

Fundamental knowledge that are not or cannot be tested, yet are generally accepted as true, are treated as axioms. If the fundamental knowledge areas <u>are</u> being tested, they are treated as hypotheses. In this case, the consequences which result are used to support or to refute the hypotheses. So, the distinction between these two theoretical systems is that the axiomatic theory is concerned with derived knowledge; while the hypothetico-deductive theory is concerned with testing the validity of hypotheses.

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[1] This table is neither exhaustive nor categorized, it merely provides the reader with examples of research in engineering design.

[2] This section is based on material presented in [FØLL93].

In either case, the fundamental knowledge areas are combined with information about particular real-world situations to derive logical consequences. The consequences themselves are not the hypotheses. Rather, they can then be used to fulfill three purposes:

- to test,
- to predict, or
- to explain.

Hypotheses lead to consequences which are used either to test or to make predictions (which could be tested). Axioms lead to consequences which are used to explain or to make predictions (which are subsequently not tested). The use of these logically derived consequences to test or to predict is termed applied research. The use of the consequences to explain observed events or facts is pure (or basic) research. The purpose of pure research is to provide ‘true knowledge’ about the world that indirectly will contribute to man’s ability to control and change this world [FØLL93 p. 185].

2.2 Research process model for design theory

In design theory, the role of a design researcher is to develop new design theories and to verify these. In Figure 0-3, a process for such activities is presented.

The purpose of the model in Figure 0-3 is to make explicit one scientifically acceptable research process in design theory research that will serve as the scientific framework for this thesis.

The input to the process is a research question and the output is a theory that can be tested or used for explanation and prediction. The main phases of the research process are data gathering, theory development, and theory validation. Each phase comprises one or more activities that are performed to generate knowledge. In some research projects, an individual researcher works through all phases. In other projects, the work is initiated by one researcher, and the results of this phase are passed to a different researcher who then continues the research by working in a subsequent phase.

Each phase and its activities are described in more detail in appendix 1.

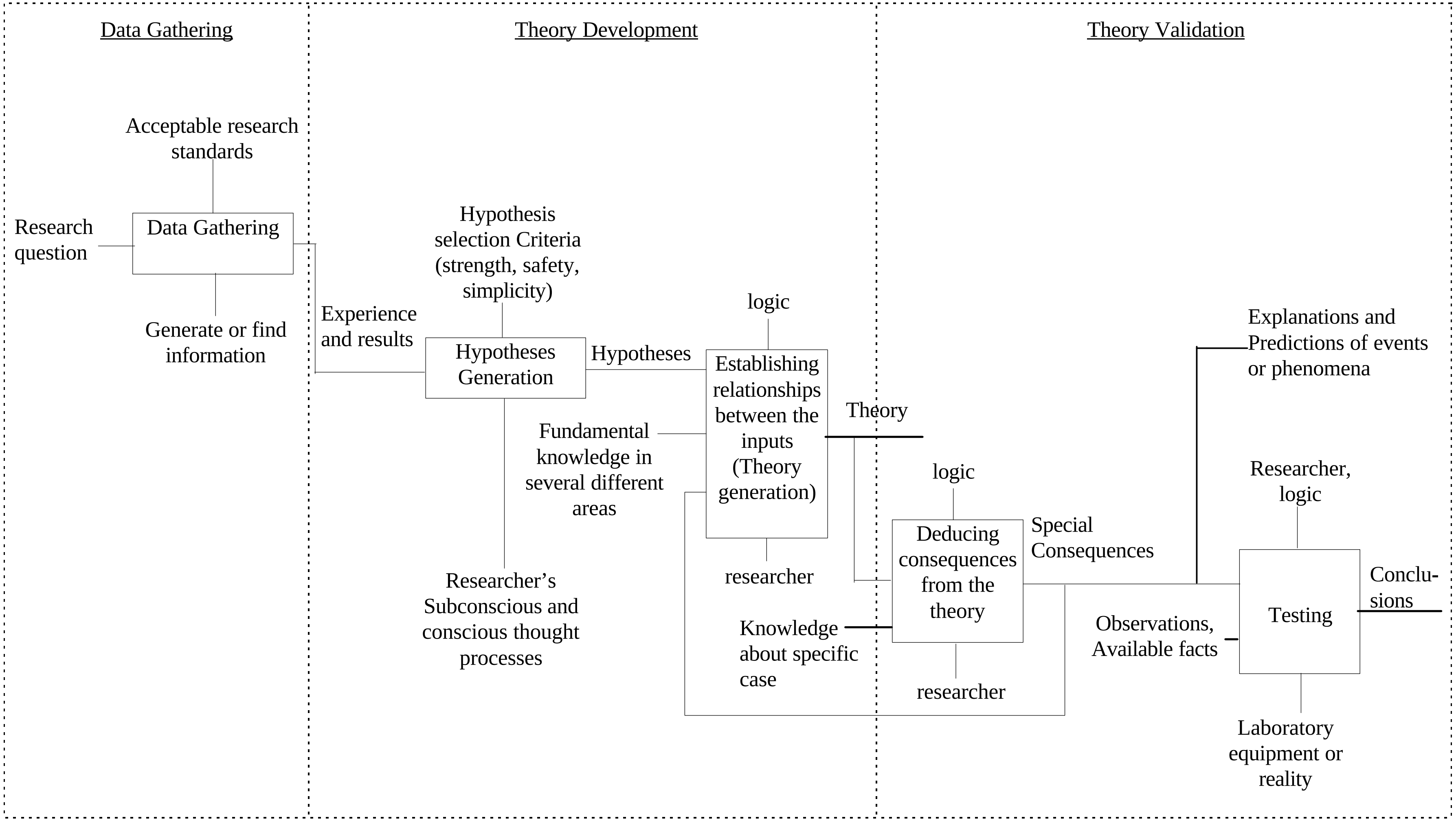

Figure 0-3. Model of the research process for design theory

3. Context of this thesis[3]

The purpose of section 3 is to provide the reader with the industrial and academic contexts for this thesis. The industrial context is the industrial design (product development) process, while the academic context is the existing state of the art in contemporary design theory research.

3.1 Industrial context: The design process[4]

The design process transforms the a customer's perception of a problem into the design object, i.e., any problem solution that the customer finds satisfactory. Designers are able to transform customer perception to design object through their use of design tools/methods, knowledge of discipline-specific information, and a given set of available resources.

Based on discussions with industry, an acceptable design process model that would serve as a context for this thesis, would fulfill the following requirements:

1. Emphasize the importance of making good front-end design decisions.
2. Easy to articulate and understand the results of the approach. Communication of requirements and design solutions among designers, customers, and other stakeholders is critical to the success of the projects.
3. Able to segregate functional and physical space (requirements and solutions). The process must begin by allowing designers to clearly define the requirements in the functional space.
4. Support abstraction, i.e., it is able to handle high-level requirement issues with end users and address realization details with implementors.
5. Helps designers manage complexity by encapsulating unnecessary detail.
6. Accommodates existing systems, organizations and facilities. Most of the product development projects rarely start from scratch with a complete clean sheet of paper. Ignoring these existing factors will lead to unrealistic design processes.
7. Robust, i.e., able to handle a wide variety of customer needs and problem spaces.
8. Analysis and synthesis processes that are easy and intuitive to users.
9. Support iteration of activities, since many activities are either repeated or re-done during a design project.

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[3] The research for section 3 was conducted in close cooperation with Derrick Tate of the department of Mechanical Engineering at MIT.

[4] Much of the material in this section is accepted for publication in [TATE96].

Based on these requirements, a general design process model needed to be flexible enough to cover all instances of the design process, yet specific enough to address specific design activities. To find such a model, a study of existing design process models[5] was conducted. Some models were very broad, and this not helpful in specific design activities. Other models were so restrictive that they were only valid in special cases, if at all.

This apparent contradiction was solved by segmenting the design process into a collection of generic activities and making the relationships between these activities explicit (an activity is defined as the transformation of inputs to outputs). From such a collection of activities, the designer can structure a unique design process. Using this idea, it is possible to describe the activities with sufficient specificity to be useful (for example, to support the designer in selecting design tools and methods for each activity, to clearly identify the decision points, and to create a good information infrastructure for the process). However, this collection of design activities is still general enough to assemble any design process.

The design activity collection presented in this section came about as an abstraction and generalization of several industrial design processes that were studied during this thesis research and in cooperation with Tate [TATE97].

3.1.1 Introduction to the design process roadmap

The design activity collection consists of several distinct activities with clear starting and end points. These activities can be conducted in several different sequences. Each design project will have its own unique sequence, depending on its specific status, scope, and goals. Figure 0-1, shows all activities that are currently in the design activity collection and the possible links between them. From this roadmap it is possible to assemble a project specific process that can begin with any activity. The arrows entering an activity show what information is required to perform the activity. Arrows that do not originate from or end in one of the activities in this roadmap interface with activities other than those in the design process, e.g., customer surveys.

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[5] The models reviewed were found in [HUBK92, PAHL88, PUGH91, WILS80].

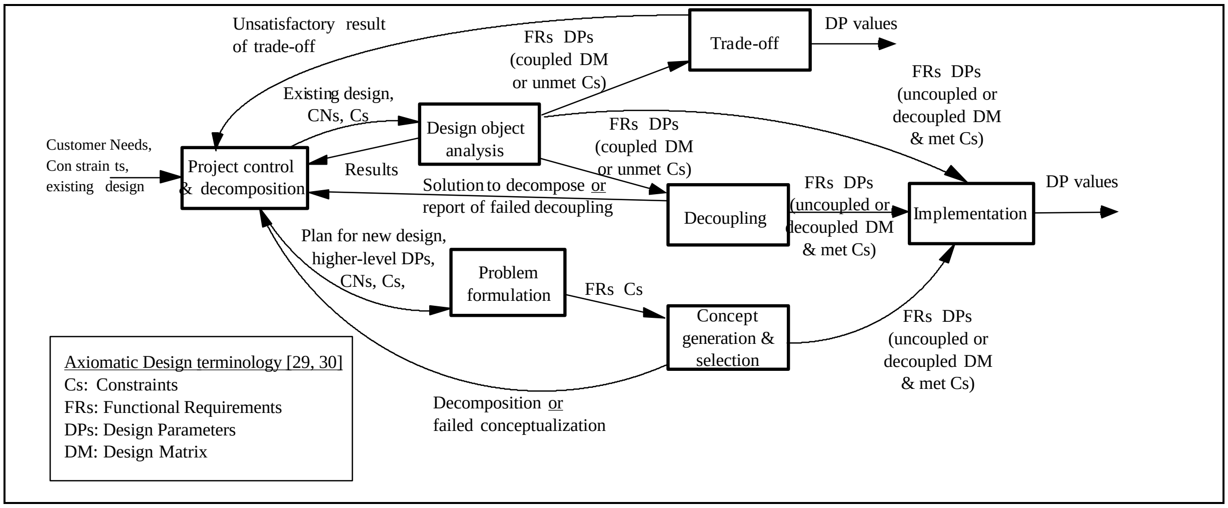

Figure 0-1. The design process roadmap (from [TATE96]).

3.1.2 Putting together a project specific design process from the activities in the roadmap

A design process (project) generally begins with the project control and decomposition activity (at the left side of Figure 0-1). A design process that yields a design object ends with either an implementation or a trade-off activity (at the right of Figure 0-1), where a design object is described in terms of its physical parameters and their implementation (drawings, models, etc.), and manufacturing processes. Design processes that fail to yield a design object end in the project control and decomposition activity, when a decision to terminate the project is made.

The specific path which is followed is the responsibility of the design team. Each time an activity is completed, a decision is made about how to proceed with the design process. The preferred outcome of the project is to successfully complete implementation as quickly as possible. By understanding the desired outcomes of the various activities as described in Figure 0-1 (FRs, DPs, uncoupled/decoupled DM, etc.) and comparing these with the actual outcomes, decisions about how to proceed with the design process can be based firmly on concepts of independence and minimum information content (maximum probability of success) [SUH90]. Often, the choice to perform one activity over another will allow the design team to reach its goal in fewer steps. For example, the choice to decouple a design object, as opposed to conducting the trade-off activity, will (if successfully done) allow the designer to quickly implement a design satisfying the independence axiom. Trade-off, on the other hand, is a much more involved, iterative process which may not always yield a design object that satisfies all functional requirements.

3.1.3 Description of the generic activities in the design activity collection

This section contains a description of each activity shown in the design process roadmap (Figure 0-1). Each description explains the activity's purpose, inputs, outputs, and typical questions that arise during the activity.

3.1.3.1 Project control and decomposition

Project control and decomposition places controls on the design project and establishes its scope. During a design project, this activity is revisited multiple times. It will be performed when it is necessary either to plan and decompose for work at a more detailed level of the design, or to plan activities in response to an inability to solve a previous problem.

During project control, possible courses of actions are evaluated and decided upon. The scope of the design project and other project management issues such as a budget, milestones, etc. are also established. Typical questions that arise during this activity include the following:

- What resources are available to solve the problem?
- Will a project be a new design or an adaptation of an existing design?
- How can the project be decomposed into sub-problems?

The inputs of project control and decomposition can vary. At the beginning of a "clean slate" project, the inputs are customer needs and constraints. At the start of a re-design, or evolutionary design project, the inputs will include customer needs, constraints, and additionally a representation of the existing design object. When this activity occurs as a part of an on-going design project, the inputs will be descriptions of the design object at the current level of abstraction and a description of any problems which have occurred.

Outputs of the project control and decomposition activity are project goals, constraints, and plans describing how to put subsequent activities together in a sequence.

3.1.3.2 Design object analysis

The design object analysis activity presupposes an existing design object requiring an analysis of functionality or feasibility. The analysis may follow one or more specific approaches, such as axiomatic design [SUH90], functional analysis (value engineering) [MILE72], or Theory of Inventive Problem Solving [ALTS88]. Design object analysis is often a central activity in feasibility studies. The results of this activity can be fed back into the project control and decomposition activity to allow a detailed planning and control of the design process. Design object analysis can also be conducted to identify areas for improvement in existing designs. Typical questions that arise during this activity include the following:

- What are the FRs of this design?
- What improvements can be made to the design object?
- Does the design object meet all its constraints?
- How do I reduce cost, number of parts and assembly time?
- Are there couplings in the design?
- Are off-the-shelf, or other existing, solutions acceptable for this project?
- Is a new solution needed for the problem?

In design object analysis, there are two inputs: an understanding of the customer needs, and an existing design object that must be analyzed. The output of this activity is a description of the design object in terms of its functions, constraints, physical implementation, and functional dependencies (or independence).

3.1.3.3 Problem formulation

Problem formulation is performed when the designer's objective is to create a new or innovative solution to a design problem. This activity requires designers to have the flexibility to select a new or innovative solution. A new solution may be required because a previous design problem that was never solved. Or, a new solution could be sought because customer needs have changed and an analysis of the existing solution has shown that the current solution was unacceptable to the customer. Typical questions of problem formulation include the following:

- What does the customer want?
- What is the customer willing to pay for?
- What is the ideal function?
- What are the constraints (e.g., those imposed by the company) on an acceptable solution?

Problem formulation involves translating information from the customer—in terms of customer needs and constraints—into functional description of a design object which will meet these needs. During this activity, the functional description will be produced (for problems not at the highest level of the hierarchy). Accordingly, it is necessary to consider decisions made at the previous level about the physical embodiment of the design object.

Inputs for problem formulation are customer needs and constraints pertaining to the current level of the design hierarchy. In addition, if the design is not at the highest level of abstraction, then decisions about the physical embodiment of the design (from previous levels of the hierarchy) are required. The outputs of problem formulation are a set of FRs and constraints which then serve as input for the conceptualization activity.

3.1.3.4 Decoupling (conflict resolution)

Decoupling is one possible activity that will follow the problem analysis activity. This will occur when problem analysis shows that the design is coupled or fails to meet its constraints. Otherwise, the trade-off activity will follow. The aim of the decoupling activity is to achieve an uncoupled or decoupled design that meets all constraints. This is achieved by applying one or more problem solving strategies specific to conceptual design (e.g., Suh's theorems, Altshuller's principles, Su-field analysis, etc.). The preferred result of this activity is a design that is acceptable for implementation or further decomposition. However, the decoupling activity does not always lead to a solution suitable for implementation. In such instances the result must be used for a new project control and decomposition activity and an alternative course should be selected.

Very often, the decoupling activity is performed when the designer must improve the design object's performance, yet is not free to make major changes to the design object. Typical questions that this activity is intended to answer include:

- How can this design object be modified to resolve the problems we are experiencing?
- How can the design parameters be better integrated to meet the constraints?

Inputs to the decoupling activity are descriptions of a design object or concept that fail to satisfy the independence axiom [SUH90], or a design object that fails to satisfy the constraints. In the first case, the design object does not perform its functions satisfactorily. In the second case, the design object may perform its functions satisfactorily, but the physical solution is unacceptable for some other reason (e.g., it is too big or too heavy, it does not meet some legal requirement, etc.).

The output of this activity is normally a description of a design object (or concept), that is functionally uncoupled or decoupled and meets all its constraints. In cases when a successful result is not produced, the output will be a coupled design or a design that does not meet its constraints. A report will also be produced explaining why the activity failed.

3.1.3.5 Concept Generation and Selection

The concept generation and selection activity always follows the problem formulation activity. The objectives of concept generation and selection are:

- to develop concepts that satisfy the specifications derived in problem formulation, and
- to determine which of these concepts to implement.

Hence, this activity is supported by concept generating (synthesis) tools and analysis tools. Suh illustrates this activity as a feedback control loop (see figure 0-2), and concludes that analysis is an important part of concept generation because "if we cannot analyze a design solution, then we cannot rapidly generate the best design since we cannot distinguish good design from bad design. In the absence of a criterion for selecting a good design, we cannot make good *design decisions.*" Concept generation tools include brainstorming, databases, etc., while analysis tools include design axioms, group decision making, and other design rules.

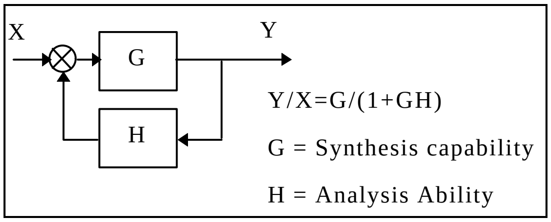

Figure 0-2 Feedback control loop depicting the synthesis and analysis during the concept generation and selection activity (from [WILS79])

Typical questions addressed during this activity include the following:

- Given a set of functions, what are possible solutions? How can these functions be realized?
- How many ways can I solve this problem? How creative can I be?
- Will this concept work? How do I choose between concepts?
- How can these design parameters be physically integrated while achieving their functions?

Inputs to the conceptualization activity are a set of functional requirements (FRs) and constraints. Outputs are a set of FRs, constraints, design parameters (DPs) (including physical implementation in the form of sketches or models), and design matrices (DMs) that show the functional dependencies in the design object.

3.1.3.6 Trade-off

The objective of the trade-off activity is to get the best possible performance out of a design object that does not satisfy the independence axiom (see implementation activity for design objects that do satisfy this). A typical situation in which a trade-off activity is conducted is when there is an existing design that has been found to have some inherent problems, yet it is impossible to anything but small changes to some DP values. Accordingly, this activity entails setting the design parameters to values that best achieve the desired functionality given the circumstances. Typical questions answered during this activity include the following:

- How should the values of these parameters be set to provide the best possible functionality?
- What is the best functionality I can get with this design object?

Inputs to this activity are functional requirements, constraints, design parameters, and design matrices. Outputs from this activity are functional requirements, constraints, design matrices, and design parameters (set at their optimal values).

3.1.3.7 Implementation

Implementation is the final activity for any design project that has yielded a design object that satisfies the independence axiom and accordingly should achieve all functional requirements. A typical question for this activity is:

- How should the values of these parameters be set to provide optimal functionality?

Inputs to the implementation activity are functional requirements, constraints, design parameters, and design matrices.

Outputs from this activity are functional requirements, constraints, design matrices, and design parameters that are tuned to provide optimal functionality for this design object.

3.2 Academic context: Contemporary design theory research[6]

Several contemporary European and US research programs were reviewed to understand

- the motivation behind conducting research in design theory,
- the scope of such research, and
- how these methods were developed.

The research programs examined were those put forth by Altshuller [ALTS88], Clausing [CLAU94], Suh [SUH90], and the WDK school (Hubka, Eder and Andreasen) [HUBK92].

These programs represent a cross-section of contemporary research in design. They are widely taught at universities, actively researched around the world and writings on these programs are readily available in English.

3.2.1 Motivation and Scope[7] of selected design methods

3.2.1.1 Altshuller's motivation and scope

Altshuller recognized the need for a scientific approach to invention after listening to scientists and inventors speak of design as "sudden enlightenment." They complained that it was impossible to control the creative process much less understand what it is and how it comes about. Such discussions made Altshuller question why everything but creativity should be open to scrutiny and why this process, unlike all others, should not be subject to control. According to Altshuller, failure to control the creative process results in many inventions coming too late, frequent mistakes, and inventors dreaming up unrealistic solutions. [ALTS88 p. ix-x].

Accordingly, Altshuller strived to make creativity a controlled process. Here, creativity refers to the activity of generating new designs, not selecting from among existing designs. Creativity is required when formulating problem statements identifying and analyzing key conflict areas, and applying solution guidelines to the specific situation at hand.

Altshuller's program is intended to enhance the engineer's thinking during innovative work thereby contributing to the overall design process. However, the scope of his method of creative or innovative thinking is general, despite being mainly aimed at engineers [ALTS88 p. xi]. Applying this method in

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[6] This section is a modified subset of [TATE95].

the context of a design project should provide benefits in the form of a reduced number of iterations and better solutions (based on Altshuller's definition of what is a good product). Furthermore, Altshuller describes how solve technical conflicts in his algorithm for solving inventive problems.

3.2.1.2 Clausing's motivation and scope

The driving force behind Clausing's work has been a very broad one—to improve industrial performance. It appears as if Clausing's approach is to use results of different product design research to improve the overall product development process. He incorporates the work of other researchers into his framework, which he calls "total quality development".

In Clausing's own words, Total Quality Development is the "modern way of developing new products that will be competitive in the global economy. It combines the best engineering, the best management, the best strategy, and especially, the best teamwork. The resulting improvements are greatly reduced development time, a reduction in all costs, higher quality, and increased product variety. Combined, these improvements greatly increase customer satisfaction" [CLAU94 p. 3].

3.2.1.3 Suh's motivation and scope

Suh's primary motivation for developing axiomatic design is education; i.e., educating designers to make good design decisions. Suh seeks to establish an academic discipline for design and manufacturing [SUH78a, SUH78b, SUH90 p. 21-22], i.e., fundamental, correct principles and methods that will guide *decision making in design.* According to Suh, without such discipline the ad hoc nature of design can not be improved" [SUH90 p. 5]. To be effective "the student must be taught to see the big picture and [be taught] the ability to conceptualize a solution, as well as how to optimize an existing product or process" [SUH90 p. 22].

Suh's view of the scope of design may be summarized by the following: "Design, as the epitome of the goal of engineering, facilitates the creation of new products, processes, software, systems, and organizations through which engineering contributes to society by satisfying its needs and aspirations" [SUH90 p. 5]. In contrast to Clausing, Suh does not describe how to connect design activities to the company's general activities; rather, Suh's theories and methods are focused on decision making in the design process.

In his book [SUH90], Suh primarily considers designs from three fields: manufacturing process design, product design, and organizational design. Although the bulk of his personal experience in applying

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[7] The definition of scope which we are using is the following: "extent covered" [MERR89 p. 650].

axiomatic design is limited to these three areas, he recognizes the potential for its application in other fields. Industrial use and acceptance of axiomatic design has been growing in a variety of fields. Recent applications of the theory have included product design, manufacturing process design, the design of software configuration control systems, organizational design, and corporate planning.

3.2.1.4 The Workshop Design Konstruktion (WDK) School's motivation and scope

Hubka and Eder focus on systematic design methods, and "independent auditing" in order to improve the efficiency of the designer [HUBK92 p. iii]. According to these researchers, design become more efficient "by scientifically reducing or eliminating waste of labor, time, or materials" [HUBK92 p. 45].

Looking at the beginnings of the design process, Hubka and Eder state that design can be considered broad enough to include defining needs and product planning as well as the narrow view of "designing" [HUBK92 p. 49]. Clearly though, they do not feel that this is *necessarily* within the scope of design. The design sequence begins when an engineering design team receives a set of requirements (either from a customer or another sponsor) [HUBK92 p. 74]. The end point of the design process is a description of a technical system, specifically a "full and complete description of an optimal product (i.e. a technical system) [HUBK92 p. 46].

3.2.1.5 Discussion on scope of design methods

In general, the European schools (such as WDK) of design tend to separate out and concentrate on a portion of the total product development activity. This is also explained by Clausing in the following: "The undergraduate engineering curriculum typically…includes one or two design courses. These concentrate on creative concepts and feasibility, the assurance of a first-order compatibility with the laws of nature. Let us call this *partial* design" [CLAU94 p. 5]. However, this term "partial design" is unsatisfactory because it is misleading. The activity is not partial in the sense that it is incomplete; rather it covers only a small, well-defined fraction of design. It is proposed to use the Germanic word "konstruktion" for this narrow, detailed activity [TATE95].

3.2.2 Approaches to develop new design methods

This section describes, in more detail, how the four theories and methods discussed above were developed.

3.2.2.1 Altshuller's approach

Altshuller identified a need for new methods to manage the creative process. Such methods would be capable of radically reducing the number of 'empty' trials [ALTS88 p. 3] during a trial-and-error approach. Furthermore, the creative process needed to be recognized to permit the effective application of new methods. All this required a scientifically based theory (for the solution of inventive tasks) capable of being implemented in practice [ALTS88 p. 3].

In order to develop such a theory, three requirements were established. If these requirements were satisfied, it would be possible to guarantee a solution to any technical problem. The requirements were 1) “information about the whole of physics,” 2) “tables linking the type of problem to the respective physical effects,” and 3) “control of psychological factors that inhibit the thinking of the inventor” [ALTS88 p. 35].

Altshuller begun work on an algorithm[8] for the solution of inventive problems [ALTS88 p. 36] in 1946. He studied the experience of inventive creativity from a fundamental point of view and brought out the characteristic features of good solutions (i.e., those characteristics that distinguished them from bad solutions). As a result of these studies, Altshuller discovered that “the solution of inventive problems turned out to be good if it overcame the technical contradiction[9] contained in the problem presented, and bad if the technical contradiction was not revealed and eliminated” [ALTS88 p. 40].

3.2.2.2 Clausing’s approach

As was described in section 0, the motivation behind this approach is pragmatic; if a technique works (that is, improves the design process or design object), it is more important to put it into use than to understand exactly why it works. Thus this school consists almost entirely of methods, not theories.

In developing his approach to design, Clausing has been using two primary sources: personal experience from industry and benchmarking the best practices around the world. He then integrates the best components into a holistic approach to design [CLAU94 p. xix].

This approach of developing a design method is different in that it is totally goal oriented (to improve industrial performance). Clausing doesn’t make any claims to be scientific in his approach, but implicitly claims that it works better than any other approach (that he is aware of) in an industrial setting. Clausing’s contributions are mainly: 1) pragmatically analyzing the different design methods and placing them in the context of the total development process in a corporation, and 2) integrating the best design theories and methods with management and strategy to form a cohesive approach to design.

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[8] Altshuller defines an algorithm as any sufficiently clear program of action [ALTS88 p. 36].

[9] A technical contradiction exists “if [when using] certain methods [to improve] one part (or one parameter) of a technical system, it is inadmissible for an other part (or other parameter) to deteriorate in the process” [ALTS88 p. 28].

By its evolutionary nature, this program will continually change and improve as Clausing continues to search for new components that complement or improve his approach.

3.2.2.3 Suh's approach

Suh started the development of his program by asking the following: "Given a set of functional requirements for a given product, are there generally applicable axioms which yield correct decisions in each step of manufacturing (i.e., starting from the design stage to the final assembly and inspection stages) so as to devise an optimal manufacturing system?" [SUH78a]

A heuristic approach was used to develop the axioms. This approach involved positing an initial set of axioms that were subject to trial and evaluation in manufacturing case studies. This evaluation would then be used in order to expand, redefine, and refine the original set of axioms, until the process converged on a comprehensive set of axioms [SUH90]. Based on such a set of axioms, many specific methods for analysis and problem solving could be developed [SUH90 p. 171]. Out of this exercise evolved twelve hypothetical axioms which later have been reduced into two and a set of corollaries and theorems [SUH90 p. 20].

Suh started his search for design axioms by observing that that there are both good and bad design solutions. Accordingly, there are features or attributes that distinguish each type of solution. The first axiom defines an acceptable design as one where the design parameters and functional requirements are related such that a specific design parameter can be adjusted to satisfy its corresponding requirement without affecting other functional requirements. The second axiom states that the best design (of several proposed) is the one that has the lowest information content (i.e., the highest probability of success) [SUH90 p. 47-8].

3.2.2.4 The WDK School's approach

In contrast with the other programs discussed here, this school, as presented by Hubka and Eder, primary focuses on developing descriptive models both for technical systems and the design process [HUBK92 p. 71-102]. When such descriptive theories are established, "it would be desirable if the [prescriptive] statements (of advice and compulsion) could be derived from the descriptive [theories]" [HUBK92 p. 116].

Based on this general procedural model of the design process, a procedural plan for a specific situation could be "derived and adapted from the ideal model" [HUBK92 p. 59].

Andreasen, has further evolved Hubka and Eder's work, based on his belief that designers are, in general, unable to describe large parts of their work, because "it takes place in unnamed patterns of ideas, rapid experimental patterns of association, and partly sub-consciously." Therefore, Andreasen determined that "the task of design research must be to create the conceptual framework and the patterns of thought." In order to support design of mechanical systems, Andreasen concludes that the design theory[10] must be based on a theory of the design process and a theory of mechanical systems [ANDR92a p. 1-2]. He also believes that if "we are to make progress in design science, we have to create a theoretical apparatus so that we can discuss design and attempt to derive laws, models and methods" [ANDR92a p. 10].

3.2.2.5 Discussion on approaches to develop design methods

Both Altshuller and Suh established a set of principles or axioms from which a variety of methods or algorithms to solve specific problems can be developed. Both also attempt to define what is a "good" solution or design, *and* interestingly, they arrive at very similar definitions independently of one another.

Based on their principles or axioms, Altshuller and Suh have developed different but complementary approaches to arrive at a good design. Altshuller developed a system of methods to separate contradictory properties through clever synthesis and integration of parameters, while Suh developed a metric and analysis rule that warns the designer if he or she is creating a bad design.

The approach that Hubka and Eder followed to develop the WDK school is based on observation and systematizing what designers already do, complemented with a theory for modeling technical systems. This, appears to yield an after-the-fact approach to design. As such, it will only provide a scientific description of what the designers do without stating whether this is the right thing to do. The models of the technical system will be used by the designer to describe how the technical system will function; however these models will not provide any fundamental reason why it will or will not work.

Furthermore, the WDK school of Hubka and Eder does not appear to directly define what constitutes a good design—something that is central to both Altshuller and Suh. Instead, Hubka and Eder refer to the ISO 9000 definition of quality, which is "the totality of those properties and characteristics (of a product or an activity) that relate to its suitability to fulfill the stated requirements" [HUBK92 p. 21]. The quality is evaluated against a set of criteria, and a composite quality number (representing e.g., technical and economical value) is calculated. Hubka and Eder recognize that this method has

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[10] Theory here is defined as a system of concepts, rules, axioms and models.

problems, but implicitly defend it in that all methods have their disadvantages. In comparison to Suh and Altshuller it appears as a weakness of this school to lack a clear definition of what constitutes a good design.

Clausing provides an important technology transfer link from the academic research community to the community of users in industry. Clausing's unique approach applies a concept selection method, that combines useful features from several different methods to create a holistic method. Then benchmarking is used to ensure that the new method is superior indeed.

Clausing's way of evolving a design approach requires a number of properties: a broad network of contacts that can provide information on new developments; more focus on pragmatic value than scientific value; and an open mind which is not committed to any individual component of the approach, but rather is willing to replace components with new ones that are better. Perhaps Clausing is the only researcher in this field who has found a way to satisfy the following challenge by Ullman: "If only we could use a sound design [method] to approach the problem of designing a theory..." [ULLM91 p. 801]. Even if Clausing's approach by some would be called unscientific, it is nevertheless effective.

The differences in approaching the development of knowledge in this field is captured by the following statement where Sohlenius expands on thoughts presented by Von Karman: "The engineer creates what has never been, the scientist analyses what is… and the engineering scientist analyses what is, imagines what should be, creates what has never been, and analyses the results of the creation" [SOHL90].

3.2.2.6 Approach followed to develop the method presented in this thesis

The research presented in this thesis is prescriptive in its nature and is primarily based on Suh's work, and therefore follows a similar approach to that of Suh. This is especially evident in sections 5 and 6 where Suh's and Altshuller's axioms and principles are used to derive further theorems and theories. However, some descriptive research is done in section 4 to establish how designers work when following the axiomatic design method. The results of this research was used to create a *prescriptive* information framework presented in section 4. Section 7 also provides some descriptive research to demonstrate that the prescriptive models derived in section 4 were applicable outside the field of engineering.

4. Expanded Framework of Information in Design

4.1 Research question

What are sources of design information in the context of axiomatic design?

4.2 Research method

This research has followed the process outlined in chapter 2. Information gathering was conducted through literature studies and studies of how designers work when following the axiomatic design method. This information was then used as a basis for forming hypotheses that would answer the research question. Finally, the hypotheses were tested in an industrial case study.

4.3 Literature studies

The scope of this literature study has been to answer the following question: What outside sources of innovation are available to the designer? In the context of axiomatic design, innovation is interpreted as generating the design information necessary to map from the functional to the physical domain or from the physical to the process domain. Identifying these sources of innovation will facilitate the development of an extended framework around the domain model proposed by Suh [SUH90 p. 128]. Such a framework will enable the designer to effectively utilize available sources of design information during the axiomatic design process.

Utterback has found that, often, the most radical innovations are made by industry "outsiders" rather than the leading companies in a particular industry [UTTE94 p. 160]. The reason for this phenomenon has to do with risk and commitment. "Outsiders" have everything to gain and nothing to loose with the introduction of radical innovations. In contrast, "industry insiders" are often committed to an existing technology due to large investments that cannot be easily divested (for a detailed discussion on commitment and its implications on corporate strategy, see Ghemawat [GHEM92]).

Von Hippel presents a more detailed categorization of the functional sources of innovation: users, manufacturers, and suppliers [HIPP88 p. 4]. Users are defined as those who benefit from using an innovation. Manufacturers are those who benefit from manufacturing the innovation. Finally, suppliers are those who benefit from supplying the materials or components necessary to build the invention [HIPP88 p. 3]. Von Hippel concludes that innovation is likeliest to occur in the category where the expected rent from the innovation is highest [HIPP88 p. 117]. In order to acquire the desired design information von Hippel proposes several mechanisms:

- Field service organizations can gather information about user modifications on the products they service.
- Sales departments can obtain information on new product needs, ideas and prototype solutions.
- Marketing research groups can seek possible sources of new product solution data as well as need data.

These mechanisms mainly address the information transfer from users to manufacturers. A novel way to effectively transfer design information between suppliers and manufacturers is the JIT II system (Just in Time II) proposed and implemented by Lance Dixon [DIXO94]. With JIT II a manufacturer provides its suppliers' employees with almost completely free access to the manufacturer's plant in order to facilitate a high level of interaction with the manufacturer's engineers. Dixon points out that there are risks associated with allowing outside people to influence the design [DIXO94 p. 69]. However, with careful management, these risks can be outweighed by the benefits. According to Dixon there are clear benefits with having "consistent access to in-house supplier expertise-even when the supplier does not ultimately win a program. JIT II may also spawn innovation as design engineers press suppliers for solutions. Managed with care, it is possible for a JIT II customer to maintain inflow of leading-edge technologies to [its design groups]" [DIXO94 p. 70-71].

4.4 Empirical Study of how engineering information is synthesized in a design project

This section describes a design project from the medical industry where using Suh's method of axiomatic design [SUH90] was used to design a new medical device. A total of four designers from the company were involved. The researcher's role was to facilitate the application of axiomatic design during the project and learn how the designers worked when trying to apply axiomatic design.

The task was to design a manufacturing system that would insert a small rubber disk into a plastic tube (sealed at one end) as illustrated in figure 0-1. Upon completion of the assembly sequence, the rubber disk should touch the membrane seal without trapping any air. Besides cost constraints, designers were not allowed to puncture the membrane seal or tube during the manufacturing process.

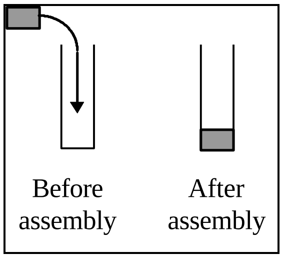

Figure 0-1 Manufacturing Requirements

The functional requirements (FRs) for this product were established as follows:

FR1: position the disk, and
FR2: remove all air trapped between the disk and the seal.

Next, the design group had to identify design parameters (DPs) to satisfy these FRs. For this study, the researcher was most interested in identifying the types of information that designers generate along with the possible sources of such information.

In generating DP1, it was reasoned that some force was needed to position the disk. The design group proceeded to generate a list of all potential forces. This list included mechanical force, pressure/vacuum, centrifugal force, gravitation, magnetic force, and electric force. It appeared as if the engineers followed two approaches in generating this list of DPs: brainstorming and structured reasoning. During brainstorming, the designers listed any force that came to mind, without criticizing any of the suggestions. Using structured reasoning, the engineers carefully analyzed what was known about the design and its environment, and then tried to identify potential sources of force that existed in this environment. When analyzing the feasibility of each DP (primarily comparing them to constraints), it became clear that the DPs generated from the environment were likely to have both lower cost and lower information content (as per axiom 2 [SUH90]). In contrast, when DPs are generated from outside the existing environment, it is often necessary to create a new [technical] system, which may have a high information content. Following this logic, gravitation was chosen for DP1 as it is always present (zero information content) and it is free.

A number of ways to remove trapped air were also generated for DP2. These included making a small hole to release air through the disk, once inserted, temporarily changing the disk's geometry to enable air to escape, and positioning a small straw between the disk and inside of the tube, through which the trapped air could escape (once the disk is positioned, the straw would be removed). Evaluating these alternatives, it was estimated that the straw was the most complex solution, and that the hole violated one of the constraints. Thus, temporary changing the geometry (size) of the disk was chosen as DP2. Again, a DP from the existing environment (the disk) was chosen rather than introducing a new device to perform the function.

At this point, the design must be analyzed (Equation 0-1) to ensure it satisfies the independence axiom:

Equation 0-1

$$\begin{Bmatrix} \text{FR1 Position Disk} \\ \text{FR2 Remove Air} \end{Bmatrix} = \begin{bmatrix} X & X \\ O & X \end{bmatrix} \bullet \begin{Bmatrix} \text{DP1 Gravitation} \\ \text{DP2 Change disk geometry} \end{Bmatrix}$$

This is a decoupled design. It shows that the manufacturing system must first change DP2 (disk geometry), and then implement DP1 (gravitation) in order to successfully achieve FR1 (positioning of the disk). Since it is possible to satisfy the independence axiom with this design, the design group proceeded to identify the process variables.

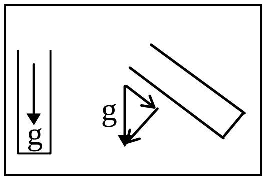

Figure 0-2 Gravitation components depend on orientation of tube

The following options for PV1 (how to generate gravity) were identified: locate on different planet, locate in orbit, use centrifuge to enhance or reduce gravitation, change orientation of tube to reduce the gravitation component toward the bottom of the tube. Only one of the proposed concepts was deemed as feasible by the design group: PV1 orientation of tube (Figure 0-2). The tube has to be oriented vertically to maximize the effect of gravitation in positioning the disk.

Suggestions for PV2 (how to temporarily alter the disk’s geometry) included: using a tool to hold the disk from the sides, hitting the disk, Shrinking the disk by freezing it and the re-heating it to resume the original shape. Of these proposed PVs, only room temperature existed in the environment, but several different ways of freezing the disk could be identified in the customer domain, i.e., at the company site. The group decided to select temperature as PV2. This meant introducing a freezing system (e.g., a freezer or liquid nitrogen) to freeze (and shrink) the disks, drop them into the tubes, and then utilize the existing room temperature to warm the disks up so that they would retake their original shape.

Finally, the proposed DP-PV mapping was analyzed (Equation 0-2) to ensure the independence axiom was satisfied:

Equation 0-2

$$\begin{Bmatrix} \text{DP1 Gravitation} \\ \text{DP2 Change disk geometry} \end{Bmatrix} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \bullet \begin{Bmatrix} \text{PV1 Orientation of tube} \\ \text{PV2 Change disk temperature} \end{Bmatrix}$$

This is an uncoupled design, hence the independence axiom is satisfied.

Based on the design equations described here, a system that stores the disks in some type of freezer, before dropping them into the vertically oriented tubes was conceptualized. Based on the evaluation in the design group, this design met all constraints and would provide the required functions. The concept was then handed off to the CAD and calculation groups responsible for either implementing or discarding the project.

The important result from this study was the realization that useful information about potential DPs and PVs exists in the environment where the design will exist and in the customer domain.

During the synthesis phase of the product development process, it is important for the designer to systematically investigate the environment where the design will exist as well as the customer domain. In doing so, the designer can identify potential DPs and PVs. In the project described above, important DPs and PVs came from the environment (e.g., gravitation) and the customer domain (e.g., freezing).

4.5 Results

Based on sections 0 and 0, the framework in Figure 0-3 is proposed to provide a representation of the internal and external sources of design information available within the context of axiomatic design.

The proposed framework is based on Suh’s idea that the design world consists of four domains: the customer domain, the functional domain, the physical domain and the process domain [SUH90 p. 128]. Suh’s model of the design world is adequate to capture the information required for analyzing the design in terms of the independence axiom, realizing the design object and implement the process required to manufacture the design object. However, Suh’s model does not explicitly describe the sources of information necessary to synthesize, analyze and realize the design object. The framework shows that information about both potential design solutions (DPs and PVs) as well as constraints can come from both inside and outside the design project. Furthermore, it makes the consequences of design decisions explicit.

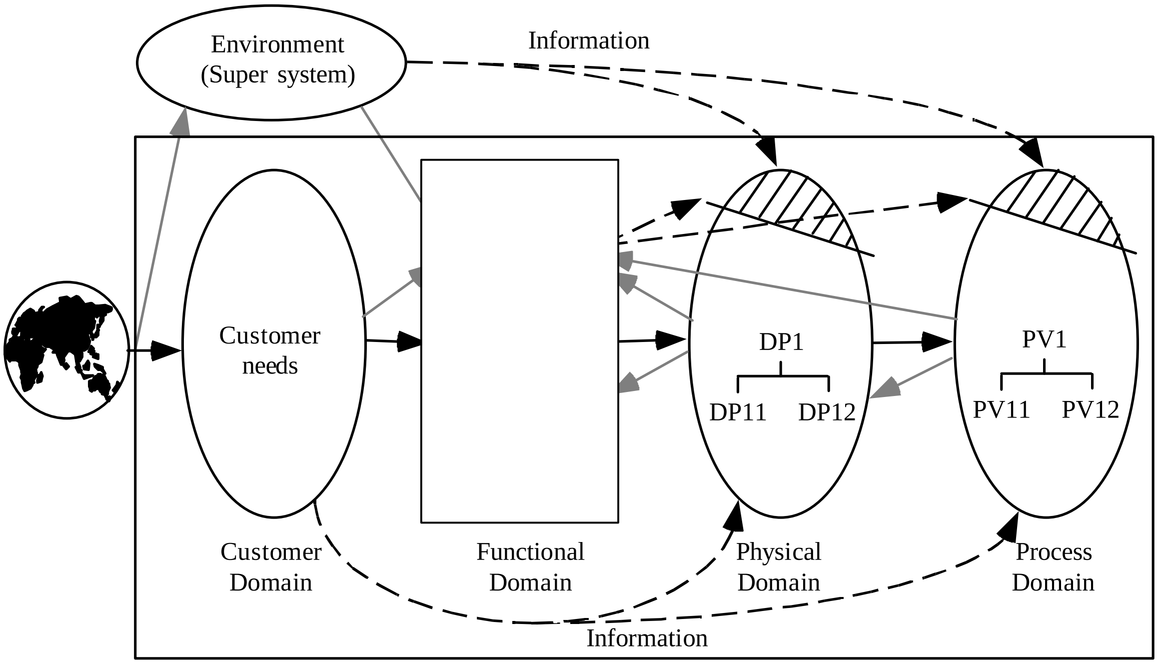

Figure 0-3 Information Framework

Legend to Figure 0-3:

- A black arrow represents a decision.
- An arrow with gray head represents a consequence.
- A dashed arrow represents useful information that can be transferred from a source to a domain.

The framework captures the following characteristics about information in the design process. In the list below, items marked with an asterisk (*) indicate contributions of this research.

- Every time the designer moves right, (i.e., from one domain to another) the designer has to decide how to satisfy either the customer need, functional requirement or design parameter in the previous domain (derived from [SUH90 p. 26-7]).
- Each domain contains a characteristic vector of FRs, DPs, or PVs that can be decomposed [SUH90 p. 36].
- The design can only be decomposed through a reiterative zigzag process, where the designer makes a decision, decomposes the problem as a consequence of previous decisions, and makes new decisions based on the decomposition (continuing until the design is sufficiently decomposed) [SUH90 p. 36].

- Constraints limits the number of DPs and PVs available to the designer [Suh p. 39].

* As a consequence of every decision made in the framework, new constraints are introduced.

* In the environment and the customer domain, resources exist that the designer can draw upon when generating DPs and PVs (for example, energy sources, existing manufacturing facilities, etc.)

* Every piece of information in the design framework is traceable through the abstraction levels and decisions to a customer need derived from the world.

* Selection of a customer domain, generates an environment in which the design object must reside. This environment can generate constraints for the design process (e.g., geometrical and legal constraints).

Detailed description of decisions (black arrows) in the framework and their consequences (gray arrows):

World → Customer Domain. The designer (or the designer's superiors) must decide which customer domain to select from an infinite number present in the world. Decision criteria applied in this selection include company strategy, capabilities, and marketing. This decision is made before the project controlling activity is initiated in the design process roadmap (Figure 0-1).

As a *consequence* of this decision, an environment (or super-system) in which the design object will reside is established. The environment has both a technical and social component. The technical component describes the technical system that the design object will be a part of (e.g., an aircraft fuselage is the technical super-system for a flight control system). The social component describes the social system that the design object will be a part of (e.g., a specific market, organization or country). Each environment will introduce constraints, for example geometry (from technical super-system), or regulation (from social super-system). Each environment will also contain a set of resources that can be used in the generation of DPs and PVs. For example, the aircraft engine residing in the environment of the flight control system may provide a good source of energy for the flight control system, thereby avoiding unnecessary complexity by having to introduce a new system. The social system may also provide solutions (for example people or infrastructure) for some design problems.

Customer Domain → Functional Domain. The designer, or preferably multifunctional design team, must decide how to formulate functional requirements at the highest level of abstraction based on the information in the customer domain. This is a critical step in the design process, represented in the problem formulation activity in the design process roadmap (Figure 0-1). If a mistake is done during this step, the entire design process will be set up to achieve the wrong goal.

A *consequence* of mapping from the customer domain to the functional domain is that the design team must also capture whatever constraints the customer may have that are relevant to the design process (for example, cost).

Functional Domain → Physical Domain. The design team must generate a set of possible design parameters (DPs), and decide which DPs to implement in order to satisfy all functional requirements. Suh's independence axiom is used as criteria for making this decision. This takes place during the concept generation activity in the design process roadmap in Figure 0-1.

A *consequence* of establishing DPs is that they introduce new constraints that affect all decisions at lower abstraction levels of the design. For example, deciding to use an electronic flight control system (fly-by-wire) (FCS) as a DP to control the aircraft, introduces the constraint that any other system in the aircraft must not interfere with the electronics of the FCS.

Physical Domain → Process Domain. The designer or design team must generate and decide which process variables (PVs) to allocate to the DPs established in the previous domain. Again the independence axiom is used as criteria to select which PV to implement. This decision also takes place in the concept generation activity in the design process roadmap (Figure 0-1).

Similar to the establishment of DPs, the *consequence* of establishing a PV can also be the introduction of new constraints. Selecting a specific manufacturing system or plant at a high level of abstraction, only allows the designer to select DPs that can be manufactured in this system or plant at a lower level.

4.6 Hypotheses H1 and H2

Two hypotheses were derived from the framework:

H1: The framework provides an accurate representation of the sources of design information in the context of axiomatic design.

H2: The information framework is not a useful tool and does not provide the designer with an effective framework for structuring, searching and managing design information.

The following consequences are derived from the hypotheses and can be tested:

- If hypothesis H1 is valid, then this framework should be useful when following axiomatic design.
- If hypothesis H2 is valid, then teaching the framework to designers, who will subsequently use it should impair their ability to produce good designs quickly.

4.7 Testing Hypotheses H1 and H2

In order to test the validity of hypotheses H1 and H2, a comprehensive course in Axiomatic Design was taught to designers at Saab Military Aircraft in 1993. The proposed framework was included as an integral part of this course. The participants were asked to consult with the instructor and apply the methods and tools taught in the course as appropriate to the projects they were currently working on. This section presents one of these projects which specifically tested the application of the proposed framework.

4.7.1 Case study background [11]

The task is to design an initiator that sends a signal to the detonator only when the depth charge hits a target and is intended to explode. The customer requires a unit that is cheaper and more reliable than the existing one.

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[11] This design project was conducted by Anders Swenson with the support of Mats Nordlund. Mr. Swenson is employed by Saab Dynamics. Mr. Swenson's report of this project can be found in [SWEN94].

A schematic drawing of an initiator is shown in Figure 0-4.

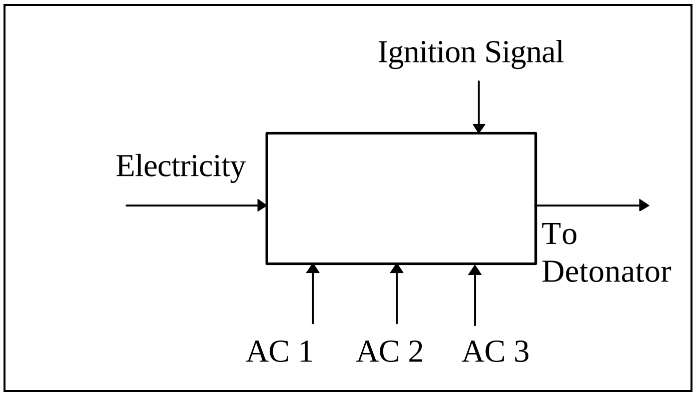

Figure 0-4 Initiator

The initiator requires the following inputs before signaling to the detonator

1. Electrical energy,
2. Three independent arming conditions (AC's), and
3. Ignition signal.

When all are present, the detonator will detonate the warhead. The functional requirement of the design object is to provide the initiator with these signals to detonate the depth charge.

Safety regulations mandate that at least one of the ACs should be satisfied by a state (e.g., under water, upside-down, etc.). The state should be constant from its first occurrence until detonation. This means that the system will prevent detonation if the state changes or disappears. Furthermore, the system's sensors must not erroneously react to humidity, electromagnetic radiation, darkness, vibrations, accelerations or temperature.

4.7.2 Effectively searching for potential design solutions

The information axiom states that the designer should select the design with the minimum information content (i.e., have a maximum probability of success). This axiom has been interpreted in many different ways. One common interpretation is that the simplest design is the best, while another interpretation is that the minimum number of parts is the best (provided that the independence axiom is still satisfied). The last statement is not true if the total information content in the new system is higher than it was in the old system.

The framework in Figure 0-3 was used to effectively generate information for the design process. This framework shows that from the world around us we can identify a set of Customer Requirements (CRs) and the environment where the customer intends to use the design (e.g., a specific country). This in turn will introduce important constraints such as the laws and regulations for this specific country. Other information about the environment may be that the customer intends to fit the design into a larger system, in which case geometry, weight or vibrations could be constraints that the designer must introduce. The framework shows that the constraints affect the selection of acceptable DPs and PVs.

The environment also provides the designer with a set of environmental factors that can be used in the physical or process domains. Environmental factors are matter or force fields already existing in the environment where the design is intended to be used. Examples of common environmental factors are gravity, vibrations, thermal fields, electromagnetic radiation, hardware structures, air, and humans.

4.7.3 Design of the Depth Charge Initiator[12]

4.7.3.1 Problem definition

Based on the general problem description, a more concrete description of the customer requirements (CRs) was developed to help focus the thinking process. Three CRs were established:

CR_1 = Lower cost
CR_2 = Simpler concept (lower part count if information content is reduced, as per axiom 2}
CR_3 = More reliable concept

4.7.3.2 Top level design.

The highest level functional requirements (FRs) are to initiate detonation of the warhead, and convey the driving gas pressure in the barrel to the entire depth charge causing it to accelerate and begin its ballistic trajectory. DPs were chosen according to Equation 0-3 and Equation 0-4.

Equation 0-3

$$\begin{Bmatrix} \text{FR1 Initiate detonator} \\ \text{FR2 Launch Depth Charge} \end{Bmatrix} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \bullet \begin{Bmatrix} \text{DP1 Electrical system} \\ \text{DP2 Launcher} \end{Bmatrix}$$

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[12] Due to the nature of this product, specific numbers as well as some specific requirements and constraints that were part of the original design report can not be included. However, this does not make any difference to the conclusions presented here.

Equation 0-4

$$\begin{Bmatrix} \text{FR21 Provide force to launch device} \\ \text{FR22 Send device in desired direction} \\ \text{FR23 Convey force to entire device} \end{Bmatrix} = \begin{bmatrix} X & O & O \\ O & X & O \\ O & O & X \end{bmatrix} \bullet \begin{Bmatrix} \text{DP21 Explosive} \\ \text{DP22 Barrel} \\ \text{DP23 Chassis} \end{Bmatrix}$$

These equations show that the independence axiom is satisfied, i.e., the independence of the FRs is maintained and the design process continues. However, design of the launcher (including the explosive, barrel and chassis) is already complete and will not be further decomposed here.

At this level, a number of constraints are introduced that will apply to all DP choices later in the design process.

Constraints

C_1 = Safety
C_2 = Weight
C_3 = Position of the center of gravity
C_4 = Outside measures (geometry) has to fit within chassis
C_5 = Environmental endurance

4.7.3.3 Decomposing the initiator (FR1)

FR1 must now be decomposed into the lower level FRs. The decomposition must take into consideration that an electrical system was chosen as DP1.

$$\begin{Bmatrix} \text{FR11 Provide electricity} \\ \text{FR12 Activate AC1} \\ \text{FR13 Activate AC2} \\ \text{FR14 Activate AC3} \\ \text{FR15 Send Ignition Signal} \end{Bmatrix}$$

4.7.3.4 Environmental Analysis

Based on the framework in Figure 0-3, the different environments this product would encounter while at the customer/users must be investigated in the research. Figure 0-5 shows the result of this analysis, outlining all the different environments the depth charge will experience before it is expected to detonate. Within these environments are factors that can be used as arming conditions (DPs).

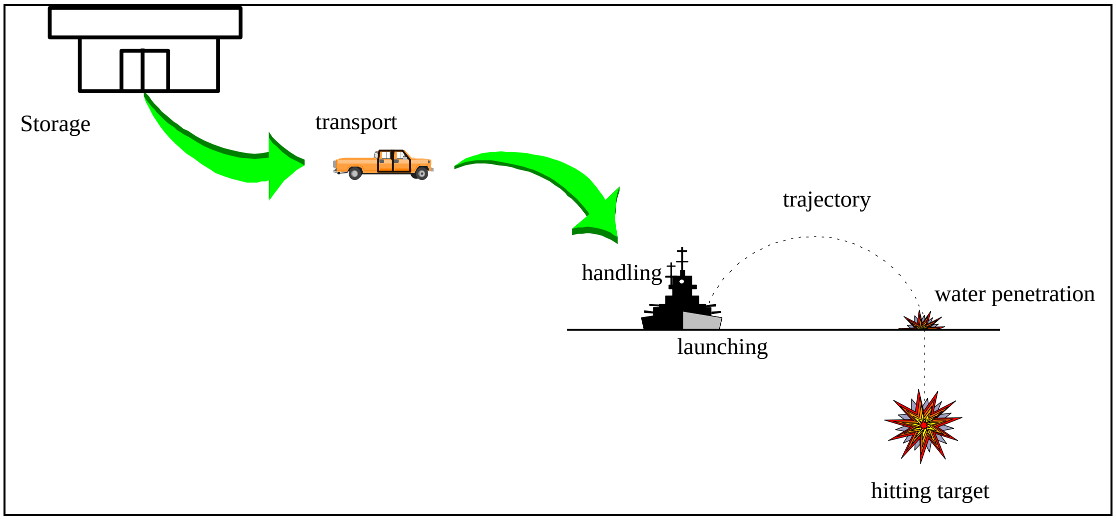

Figure 0-5 Analyzing the environment

4.7.3.5 Searching for DPs in the environmental phases

In Figure 0-5, seven phases are identified in the environment:

1. Storage and transport
2. Loaded in launcher
3. Launching
4. Air trajectory
5. Penetrating water
6. Sinking
7. Hitting target

It was decided that the armament conditions should be satisfied by factors from phases 2 - 6, and the initiation condition should be satisfied during phase 7.

Environmental factors

Environmental factors are characteristic events and states that can be selected as DPs to generate the signals required for the arming conditions (FRs). Possible environmental factors are listed below. In order to be suitable as an arming condition (AC), the environmental factor has to be a unique characteristic of the phase. Furthermore, acceptable factors have to be independent of each other.

Loaded in launcher

Characterizes a unique state of the depth charge. Exists in two phases (2 and 3). This state can not be used as a DP because it is not present just before detonation. However, the event when the depth charge leaves the launcher through the muzzle can be detected as an event.

Air presence

Not useful as it does not distinguish between the phases storage and transport or loaded in launcher.

Dynamic air pressure

When launched, dynamic air pressure will exist. However, this will be in the same order of magnitude as dynamic water pressure, which means that dynamic pressure can not distinguish between dynamic water pressure or dynamic air pressure. Therefore dynamic air pressure cannot be used in this design.

Gas pressure (in the launcher's barrel)

Exists only when launching, which means it is a unique and independent event.

Water presence

Clearly distinguishes between the air and the water phases, making it suitable as a state to detect.

Water pressure

Clearly distinguishes between the air and the water phases.

Dynamic water pressure

Same order of magnitude as dynamic air pressure, which means that dynamic pressure can not distinguish between dynamic water pressure or dynamic air pressure. Therefore dynamic water pressure cannot be used in this design.

Rotation

The launcher is not rifled, hence launching generates no rotation. However, rotation is generated when penetrating water as well as during storage and transport, therefore rotation cannot be used as an environmental factor.

Hitting the target

When the depth charge hits the target there will be some negative acceleration that can be detected as an event.

Time

Time is not a good factor, as the time required for each phase will be different for each situation.

4.7.3.6 Choosing DPs.

Based on the analysis above, the following environmental factors were determined to be unique and independent. Therefore they could be used to trigger the ACs (the FRs) and set off the ignition signal (IS) to the detonator.

- Gas pressure
- Passage of the launcher muzzle
- Presence of Water
- Water pressure
- Hitting target

The design equation (Equation 0-5), for this system at this level is shown below.

Equation 0-5

$$\begin{Bmatrix} \text{FR11 Provide Electrity} \\ \text{FR12 Generate AC1} \\ \text{FR13 Generate AC2} \\ \text{FR14 Generate AC3} \\ \text{FR15 Send Ignition Signal} \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O \\ X & X & O & O & O \\ X & O & X & O & O \\ X & O & O & X & O \\ X & X & X & X & X \end{bmatrix} \bullet \begin{Bmatrix} \text{DP11 Battery with electrolyte in ampoule} \\ \text{DP12 Leave barrel (event 1)} \\ \text{DP13 Entering water (event 2)} \\ \text{DP14 Water pressure (state)} \\ \text{DP15 Impact on target (event 3)} \end{Bmatrix}$$

The constraints at this level are:

Constraint	**Implication**
C_{11} = Safety	- Create a partially decoupled design to ensure the events have happened in a desired sequence. The ignition signal must not be possible to detect before all other FRs are satisfied!
C_{12} = Probability of function	- Use simple mechanisms (“solid state”)

4.7.3.7 Design of sub-systems

The five FRs are then decomposed to arrive at a detailed design of each sub-system that will produce the ACs. Only the decomposition of FR11, FR12 and FR15 can be disclosed in this case study. However, the approach to decomposing FR13 and FR14 is no different than the approach followed in decomposing the other FRs.

<u>FR11 Provide electricity</u>

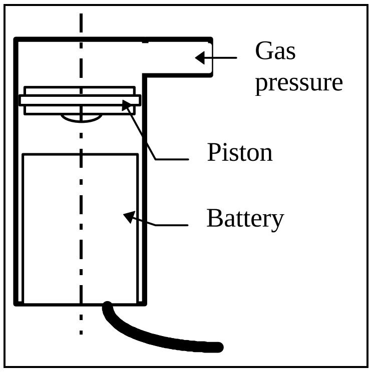

Figure 0-6 Supplying Electricity

The decomposition of FR11 (provide electricity) yields:

Equation 0-6

$$\begin{Bmatrix}\text{FR111 Sense activation time}\\ \text{FR112 Supply electrolyte}\end{Bmatrix} = \begin{bmatrix} \text{X} & \text{O} \\ \text{X} & \text{X} \end{bmatrix} \bullet \begin{Bmatrix}\text{DP111 Gas Pressure}\\ \text{DP112 Impact piston}\end{Bmatrix}$$

A concept realizing this solution is shown in Figure 0-6. Gas pressure enters the rear end of the depth charge. The gas is led to a chamber where an impact piston is forced to hit one end of a battery. This impact should suffice to break a glass ampoule containing an electrolyte. When the electrolyte diffuses, the battery becomes active.

<u>FR12 Generate Arming condition 1</u>

The design equations resulting from decomposing FR12 (generate AC1) are:

Equation 0-7

$$\begin{Bmatrix}\text{FR121 Sense launch}\\ \text{FR122 Activate circuit after leaving barrel}\end{Bmatrix} = \begin{bmatrix} \text{X} & \text{O} \\ \text{X} & \text{X} \end{bmatrix} \bullet \begin{Bmatrix}\text{DP121 Rod sensing barrel}\\ \text{DP122 Switch activated by rod}\end{Bmatrix}$$

Equation 0-8

$$\begin{Bmatrix} \text{FR1211 Push rod toward barrel} \\ \text{FR1212 Extend rod when leaving barrel} \\ \text{FR1213 Prevent rod from moving back after launch} \end{Bmatrix} = \begin{bmatrix} X & O & O \\ X & X & O \\ O & O & X \end{bmatrix} \bullet \begin{Bmatrix} \text{DP1211 Gas pressure} \\ \text{DP1212 Piston} \\ \text{DP1213 Latch mechanism} \end{Bmatrix}$$

A mechanism to integrate this design is shown in Figure 0-7. Also in this case, the gas pressure is led into a chamber that has a piston. On the low pressure side of the piston, there is a rod sliding along the barrel. When launching, gas pressure builds up in the chamber forcing the rod towards the barrel. When the depth charge leaves the launcher, the rod can move further out. This causes an electric switch to close. In order to ensure that the switch does not open again later, a latch mechanism to hold it in place must be introduced. This latch mechanism could be either mechanical or electrical.

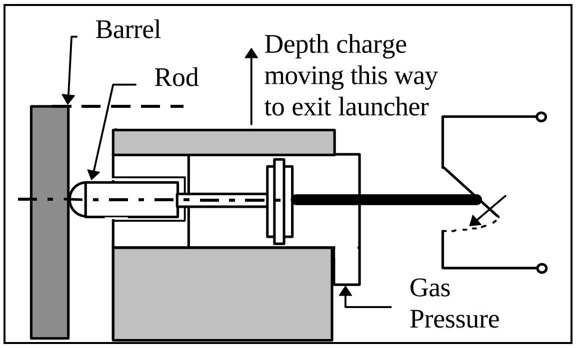

Figure 0-7 Generating arming condition 1

<u>FR15 Provide Initiation Signal</u>

The decomposition of FR15 (provide initiation signal) is

Equation 0-9

$$\begin{Bmatrix} \text{FR151 Sense target impact} \\ \text{FR152 Send signal to detonator} \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \bullet \begin{Bmatrix} \text{DP151 Accelerometer} \\ \text{DP152 Switch activated by accelerometer} \end{Bmatrix}$$

As this design can be realized using standard off-the-shelf components, it is not discussed further.

4.7.4 Final comments on the case study

The result of this case study was a more reliable and robust system where the part count was reduced from more than 350 to less than 100. This system is now in serial production.

4.8 Conclusion

The case study introduced in section 4.7 shows that the framework was useful for a designer following the axiomatic design method. Therefore, hypothesis H1 can not be rejected. The case study also shows that the designer was not impaired by the framework. Therefore, hypothesis H2 must be rejected.

In conclusion, there is now evidence supporting the hypothesis that the *framework provides an accurate representation of the sources of design information in the context of axiomatic design*. Furthermore, it must be concluded that the framework (at least in this special case) is *a useful tool that provides the designer with an effective framework for structuring, searching and managing design information*.

5.

Managing Information in the framework

The first part of this section contains a development of new theory on how to utilize design information once it has been captured. The second part shows the results of two projects aimed at creating computer systems that realize some of the functions outlined in the theory development (one developed independently of this research project [GOLD94] the other in close cooperation with this research project).

5.1 Research Question

How can design information, obtained using the proposed framework, be of benefit during later stages of the design object's life cycle?

5.2 Research Method

A theory on how to utilize design information in the framework during later stages of the design object's life cycle is developed. The feasibility of creating a computer system able to implement this theory is also discussed.

5.3 Theory Development

Information captured in the functional, physical and process domains of the framework follows the format of axiomatic design. The following can be stated about the information captured in the framework:

- FRs, DPs and PVs are organized in hierarchical structures in the functional, physical and process domains respectively [SUH90 p. 37-38].
- At each level of the hierarchy, the FRs, DPs, and PVs form characteristic vectors [SUH90 p. 54].
- A characteristic vector at any specific level of the design hierarchy in one domain (functional, physical or process domain) is related to the characteristic vectors at the same level in the other domains. The relationships are described by the [A] and [B] matrices [SUH90 p. 129].
- A characteristic vector at a certain level of abstraction is related to the characteristic vectors at the higher and lower levels of abstraction in the same domain. These relationships are found in the hierarchical structure of the functional, physical and process domains.

This section will show how this knowledge can be put into practice. The goal is to develop a prescriptive theory for utilizing design information to develop a computerized system. Such system would support the search for problem sources in a design object, facilitate field service of the design object, enable effective management of engineering change orders, and allow design decisions to be traced.

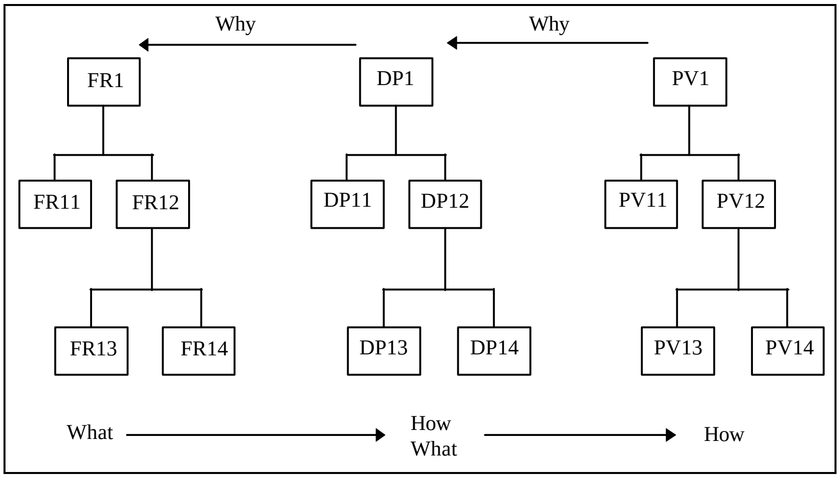

Figure 0-1 Hierarchies of FRs, DPs, and PVs.

Figure 0-1 shows a simple information structure and the relationships between the elements of this structure. Moving from left to right in the structure takes the designer from "what" to "how" [SUH90 p. 25-26]. Going from right to left helps the designer answer the question "why." Vertical movements bring the designer to different levels of abstraction. The lower levels in the hierarchy contains the most specific information while the highest levels contains the most abstract information. This simple structure, and the implications of moving within the structure will be used as a basis for the theory developed in this section.

5.3.1 Finding problem sources in a design object

When a system, subsystem, or prototype malfunctions, the framework can be very useful in determining whether the problem is rooted in the product or process.

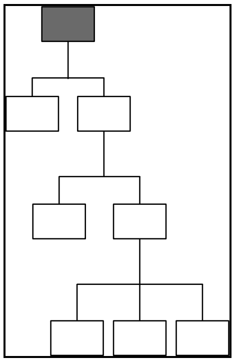

Figure 0-2 Unsatisfied top level FR

Assume that the top level FR (i.e., FR1) of a design is not satisfied (Figure 0-2). Since every FR is decomposed (unless it is a leaf FR at the lowest level of abstraction), the first step in localizing the source of the problem is to identify the FRs at the next lower level in the hierarchy below FR1. Next, it is necessary to investigate which of these FRs is not met. Since FR1 is achieved when all the FRs in the hierarchy below FR1 are achieved, it is assumed that if FR1 is not achieved, at least one lower level FR must also not be achieved. This process is then repeated until an unsatisfied leaf FR is found (Figure 0-3).

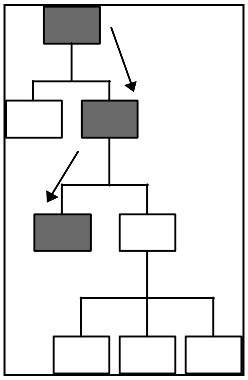

Figure 0-3 Tracing unsatisfied FRs

When an unsatisfied leaf FR is found, its corresponding DP must be investigated. This DP is found in the same place of the DP hierarchy as the corresponding FRs place in the FR hierarchy (see Figure 0-4).

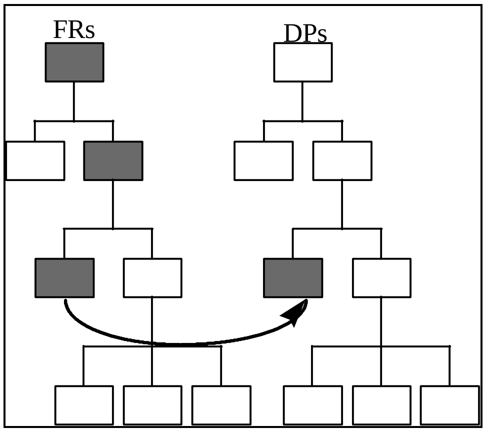

Figure 0-4 Finding an FR's corresponding DP

The result of this investigation will show whether the DP meets its specifications.

In the cases when the DP meets its specifications, the designer can conclude that the manufacturing process performs as intended, but the DP does not perform as intended, i.e., the problem is in the product. This means that the DP is not appropriate for the FR, and a new design must be sought. This leads to the following theorem:

Theorem A: *If a design parameter (DP) meets its specifications, but fails to provide the intended function, then the DP must be replaced by another DP. Consequently, its corresponding process variable (PV) must also be changed* (the consequence is derived from theorem 5 [SUH90]).

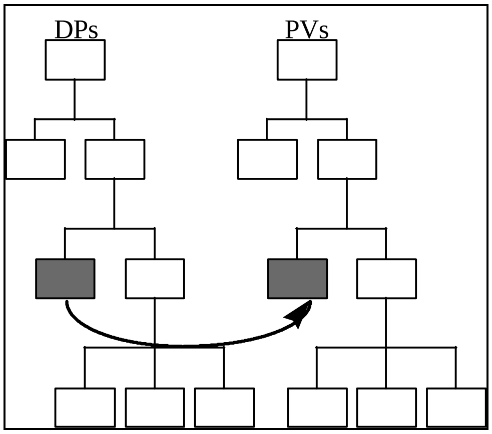

Figure 0-5 Finding a DP's corresponding PV

The problem is in the process when the DP does not meet its specifications. This occurs when the corresponding PV is incorrect or has not been adjusted correctly (see Figure 0-5). Theorem B provides insight into this situation:

Theorem B: *When a design parameter (DP) does not meet its specifications, its corresponding process variable (PV) must be either replaced or adjusted.*

This investigation of the information structures that were developed during the design process, made it possible to derive two theorems that apply when locating flaws in a design. These theorems provide the designer with a rationale for changing the specifications of the design object (the DPs) (and accordingly the process (PVs) intended to realize the new DPs) or only changing the process (PVs).

5.3.2 Proposing an information system for field service

An analog reasoning to the analysis in section 0 can be used to derive how the information generated during the design process can be used to create an information system that will support (field) service[13] of a design object.

A field service information system would guide the technician to the lowest level FR that is not satisfied (this process was illustrated in Figure 0-2 through Figure 0-4). When this FR has been identified, the system would present information about and prescribe changes to the specific DP (or DPs if the design is decoupled) that were implemented to generate the function.

Besides supporting the service department, such a system would facilitate statistical analysis of the failure rate of various systems and components in the field (or elsewhere). This information can be fed back to the design department for consideration in future design projects (this feedback idea is also disussed by Stadler, Nordlund et al, in Ericsson Telecom’s vision for hardware testing in 1999 [STAD93]).

5.3.3 Tracing the impact of an Engineering Change Order (ECO)

The information structure can also be used to predict the impact of an engineering change order (ECO). An ECO is a decision to change one of the DPs in the hierarchy, without changing DPs at levels above this DP. Clearly, if a DP is changed, all DPs in the structure below it may also change since they were decompositions of the higher level DP that was changed.

Figure 0-6 shows a DP hierarchy which contains one DP that potentially should be changed. This section explains how engineers can investigate the impact this proposed change will have on the rest of the design.

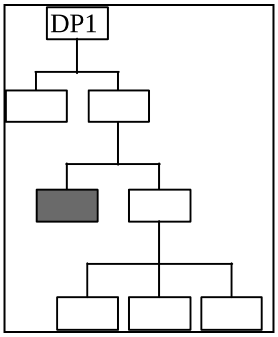

Figure 0-6 Proposed engineering change order in DP hierarchy.

All available information about the design is located in the FR, DP and PV hierarchies, as well as the design matrices. The design matrices contain information about how FRs and DPs, as well as DPs and PVs are related. Figure 0-7 illustrates how the design matrices are used to trace the impact of an ECO.

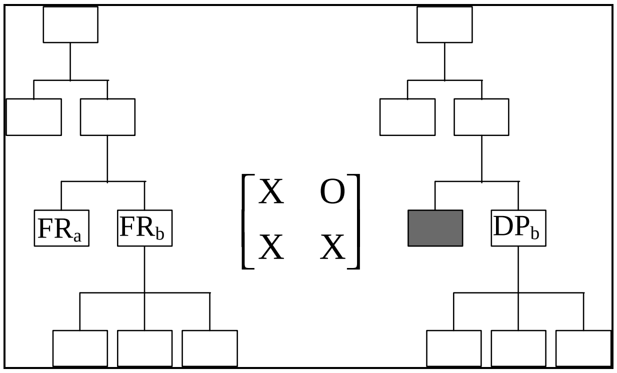

Figure 0-7 Relating FR and DP hierarchies through the design matrix.

The design matrix in Figure 0-7, shows that the design in this example is decoupled at this level of abstraction. This means that a change to DP_a (gray in this figure) will affect both FR_a and FR_b. DP_a will be set to satisfy FR_a, but will also impact FR_b as is illustrated by the off-diagonal element in the design matrix. In order to ensure that FR_b is still satisfied, it is likely that DP_b must also be adjusted.

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[13] Field service is defined as servicing a design object that has been delivered to a customer's site, whereas service is a more generic term, not referring to where the design object is located.

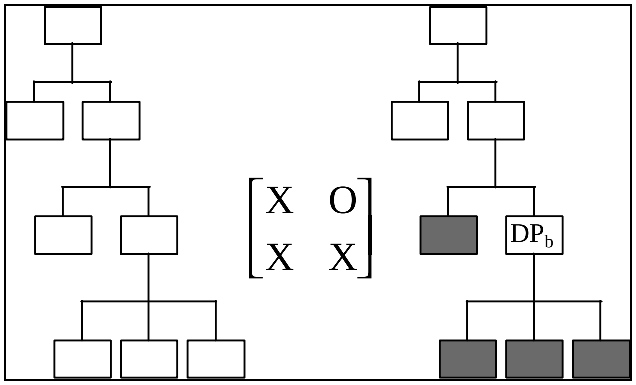


Figure 0-8 Impact of an engineering change order

Since DP_b is decomposed further (i.e., is made up of more specific DPs), the designer must go to the lowest level of the hierarchy to find which specific DPs must be changed in order to ensure that FR_b is satisfied.

The ECO should not impact higher levels of the design because DPs at higher abstraction levels of the design remain unchanged. Higher level DPs impose a number of constraints on all lower level DPs. These constraints ensure that an ECO that is within the constraints does not impact the higher level DPs in the hierarchy.

Theorem C: *An engineering change order can only affect the design parameters at the same level and lower abstraction levels in the design hierarchy. As a consequence of this, process variables (PVs) corresponding to the changed DPs may also need to be changed* (the consequence is derived from theorem 5 [SUH90]).

Theorem D: *When the design is decoupled or coupled, an engineering change order will impact more than one FR. Consequently, it is likely that more than one DP must be changed as a part of the engineering change order.*

5.3.4 Tracing design decisions

As was shown in Figure 0-1, the relationship between adjacent design domains can be described as a “what” - “how” relationship. The domain to the left contains *what* should be achieved, while the domain to the right contains information about *how* this will be achieved. This implies a motion from left to right across the domains during development of a design object.

Moving across the design domains from the right to the left is possible when a design object already exist. This process traces what a PV or DP was supposed to achieve. Through this process one can learn *why* a specific PV or DP became part of the process or design object (see Figure 0-1).

Based on this observation, it should be possible to devise a system for capturing design history. Some initial studies on how to capture design history related to axiomatic design have been presented by Lindholm [LIND96] and Malmqvist [MALM95].

Lindholm's paper focuses on capturing rationale and history of decisions made during the design process and facilitate discussions in the design teams. Lindholm outlines the types of information (especially about functional requirements (FRs) and design parameters (DPs)) that should be captured as part of the design history. Finally, he suggests that it would be useful to link FRs and DPs to CAD drawings.

Malmqvist's paper proposes a computerized approach to capturing design history. This approach is a combination and extension of Function Means Trees [ANDR80] and the Chromosome Model [ANDR92]. The Extended Function Means Tree serves as a tool to guide the synthesis process while the Chromosome Model provides a consistent product modeling template capable of capturing design rationale as the design process progresses. Malmqvist recommends that designers work with these two models concurrently to ensure that both models contain up-to-date design information. Malmqvist provides examples where this approach has been tested. He also suggests linking this system to CAD or word processing programs.

5.4 Computer systems that realize some of the functions in the above theory

This section summarizes the results of two projects aimed at capturing design information. The first project was performed by engineers at Tetra Pak Research and Development AB in Lund, Sweden, with theory support from this research project. This work is part of an on-going product development project at Tetra Pak. The second project by Goldis [GOLD94] was conducted in parallel to and completely independent from this research project. Goldis' system is similar to that developed in the first project and is discussed here to address the feasibility of implementing information infrastructures to support design methods in computer software.

5.4.1 Background

In industry, design information is normally captured in the form of specifications, design meeting protocols and models. The models are either physical models (prototypes, etc.), or abstract models, e.g., drawings or computer models (like the CAD model of a subsystem in a packaging machine shown in Figure 0-9).

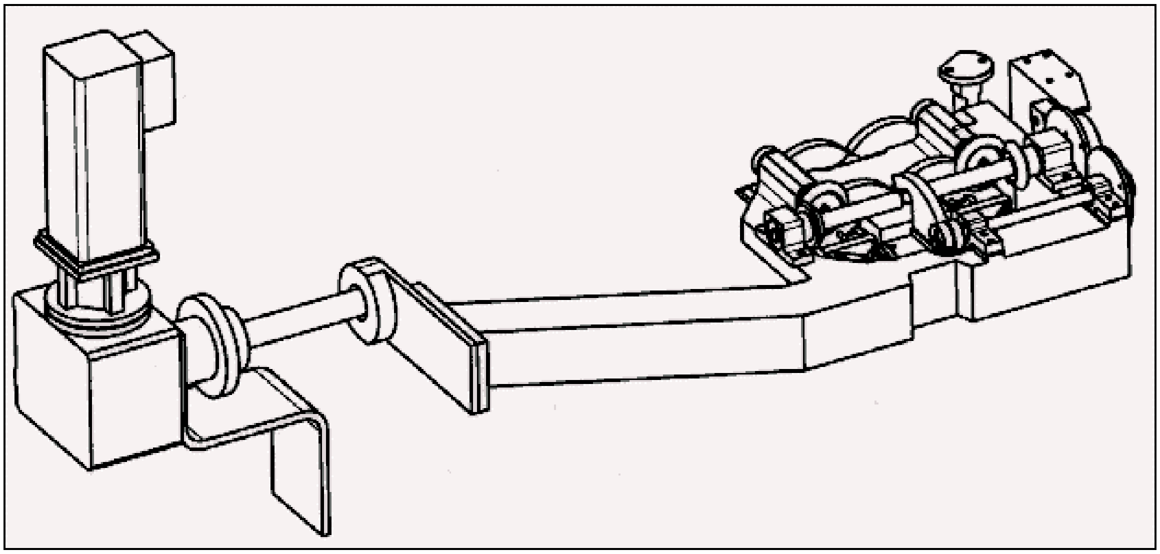


Figure 0-9 CAD model of subsystem in packaging machine (from Tetra Pak)

Such models (both physical and abstract) only capture information from the physical domain in the proposed framework. Accordingly, when presented with pure CAD models, individuals other than the original designer have difficulty determining the exact functions of each component and problems establishing the functional relationships between the components.

To enable designers to utilize the theory developed in the earlier parts of this section, a new type of design information system is required. The first step in designing such a system is to determine its functional requirements and constraints. These are presented below:

FR1: Capture information prescribed by the proposed framework, and
FR2: Model the design object as the design process progresses.

C1: Must be closely linked to the company's product development process.

Section 0 discusses a realization of a design information system based on axiomatic design [SUH90] while section 0 discusses a realization of a design information system based on total quality development (TQD) [CLAU94].

5.4.2 Design information system based on axiomatic design

5.4.2.1 Analyzing the design process and information flows

The design process used in this project is illustrated in Figure 0-10.

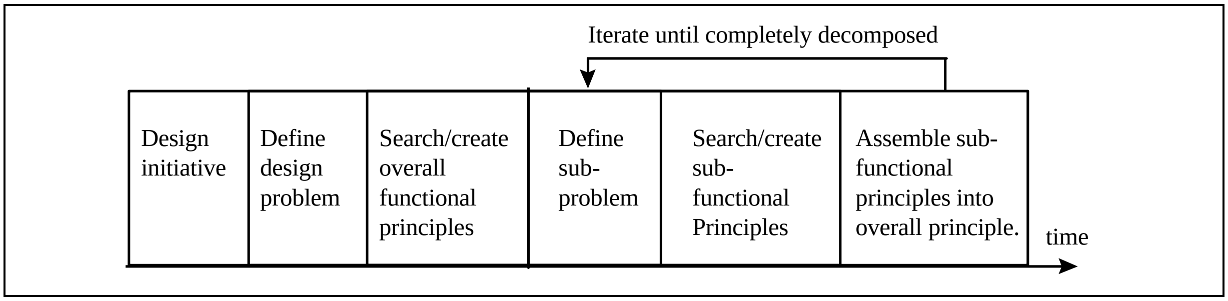


Figure 0-10 Design process model showing the main design phases

(adapted from P. Andersson, Tetra Pak)

The first task in this project was to investigate the design information produced during different phases in the design process model. Next, this information was related to the framework and a CAD product modeling tool in order to understand how information flows during the design project. The result of this analysis is presented in Figure 0-11.

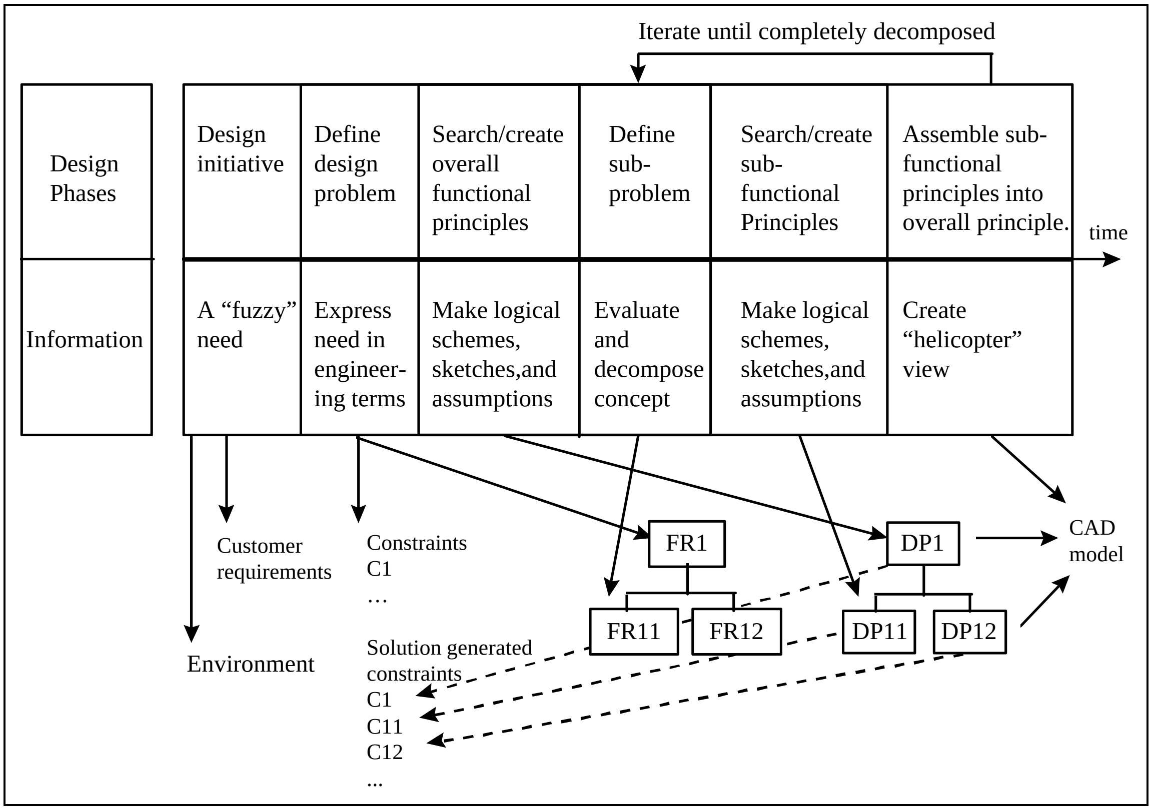


Figure 0-11 Relating the design process to information infrastructure

(adapted from P. Andersson, Tetra Pak)

5.4.2.2 Finding existing tools that satisfy the requirements

In this project, extensive, in-house software development resources could not be expended on a new information system. Therefore, it was desirable to find existing software solutions that would satisfy the FRs (ideally, software that was already used within the company in order to avoid new investments). After evaluating several available software packages, it was concluded that Microsoft Project and a word processor would enable designers to capture the information prescribed by the framework. Specifically, Microsoft Project has the ability to create the large tree structures, required by the framework.

To model the design object, the team selected Pro Engineer, a commercially available CAD software.

Equation 0-1 shows the design equation for this system.

Equation 0-1

$$\begin{Bmatrix} \text{FR1 Capture information according to framework} \\ \text{FR2 Model design object} \end{Bmatrix} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \bullet \begin{Bmatrix} \text{DP1 MS Project} \\ \text{DP2 Pro Engineer} \end{Bmatrix}$$

The equation shows that this is an uncoupled design, implying that the two software packages can be treated as independent modules and can be replaced by other software packages independently of one-another. This makes the system easy to upgrade and change.

5.4.2.3 Implementation - Case study

The feasibility of the proposed system was tested during the development of a new packaging machine at Tetra Pak. This case study shows how design information for one of the subsystems of this packaging machine was captured. The function of this subsystem is to form the package during the filling process.

To begin, the highest abstraction level functional requirements (FRs) and their corresponding design parameters (DPs) were established by the project management. Next, these FRs were decomposed to the next level of the hierarchy by the project management. At this level, the FRs were assigned to project engineers who were responsible for realizing the desired function. One such FR (FR 3.5: form/define the package during filling) and its subsequent decomposition are illustrated in Figure 0-12. The corresponding DP hierarchy is presented in Figure 0-13.

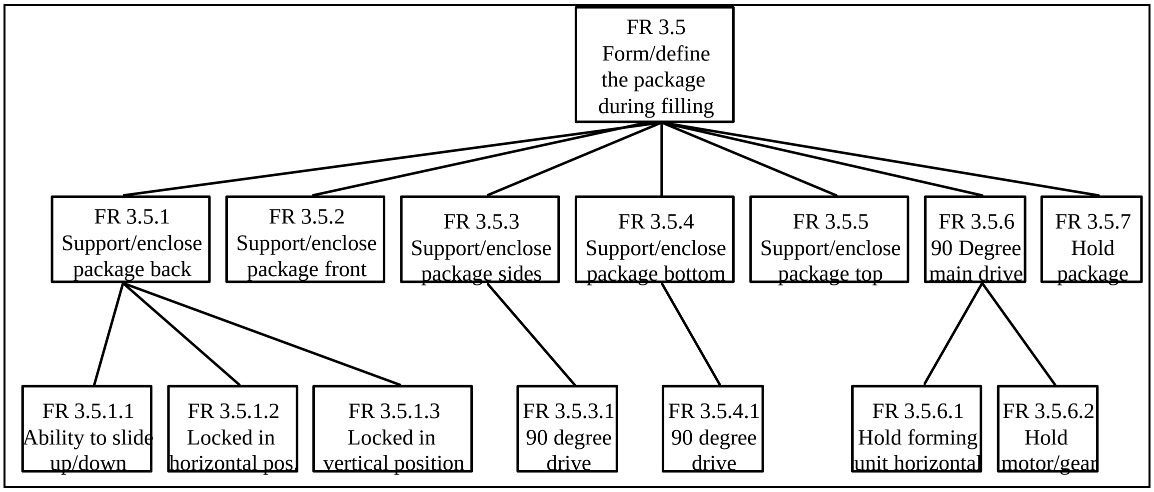


Figure 0-12 FR tree for part of packaging machine

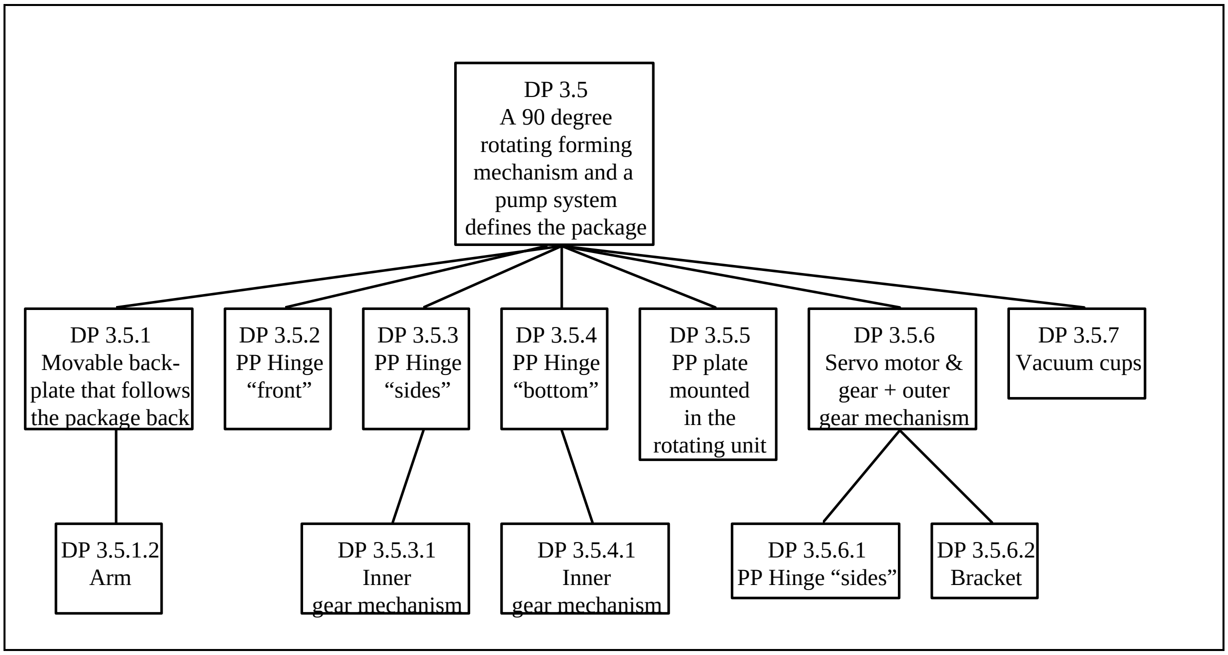


Figure 0-13 DP tree for part of packaging machine

Figure 0-14 was created to capture the design information in Figure 0-12 and Figure 0-13, in a format that was found to be easier for the engineers to read.

Note that either representation formats are acceptable provided the properties of the information structure (i.e. the vertical and horizontal relationships in the framework) are maintained to enable utilization of the theory developed in the early parts of this section.

In parallel to the development of these information structures, CAD models of the design object were also developed. Figure 0-15 shows a CAD model for a packaging machine at the highest level of abstraction (A-level layout). The top level FRs are inserted on the model, in this case they are: “To form, fill and seal a package.” The applicable constraints, as well as their sources (e.g., the project’s steering committee, the market or the package) are identified. Some of these constraints are then translated into geometries shown in the drawing on the right (e.g., machine length).

In accordance with the framework, DPs are selected and illustrated on the drawing, first at a conceptual level then at a more detailed level (called “ultimate solution” in the drawing). Finally, as was shown in the framework, each selection of a DP introduces new constraints that apply at lower levels. These are captured in the left part of the figure under the heading “Solution generated constraints.”

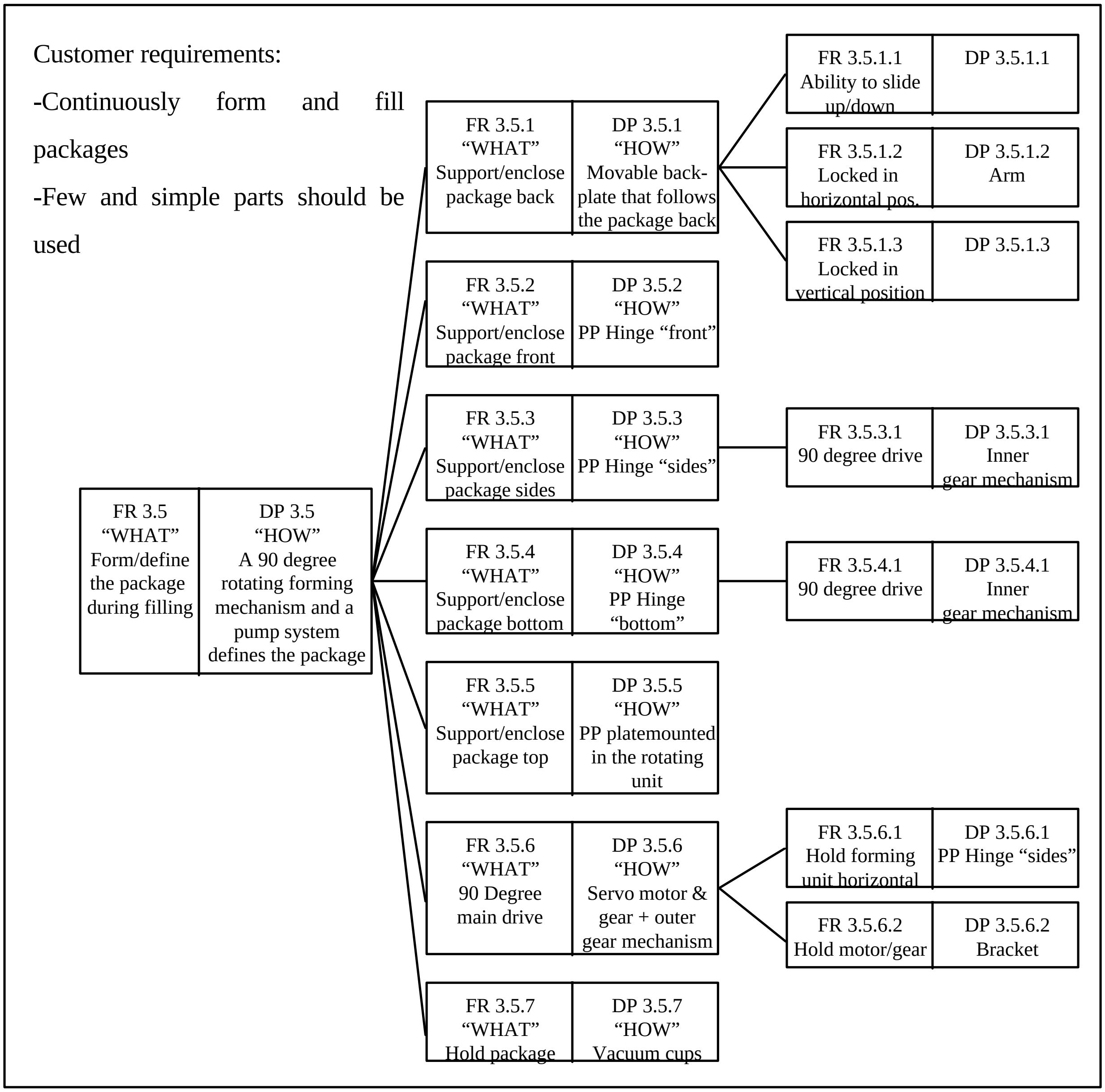
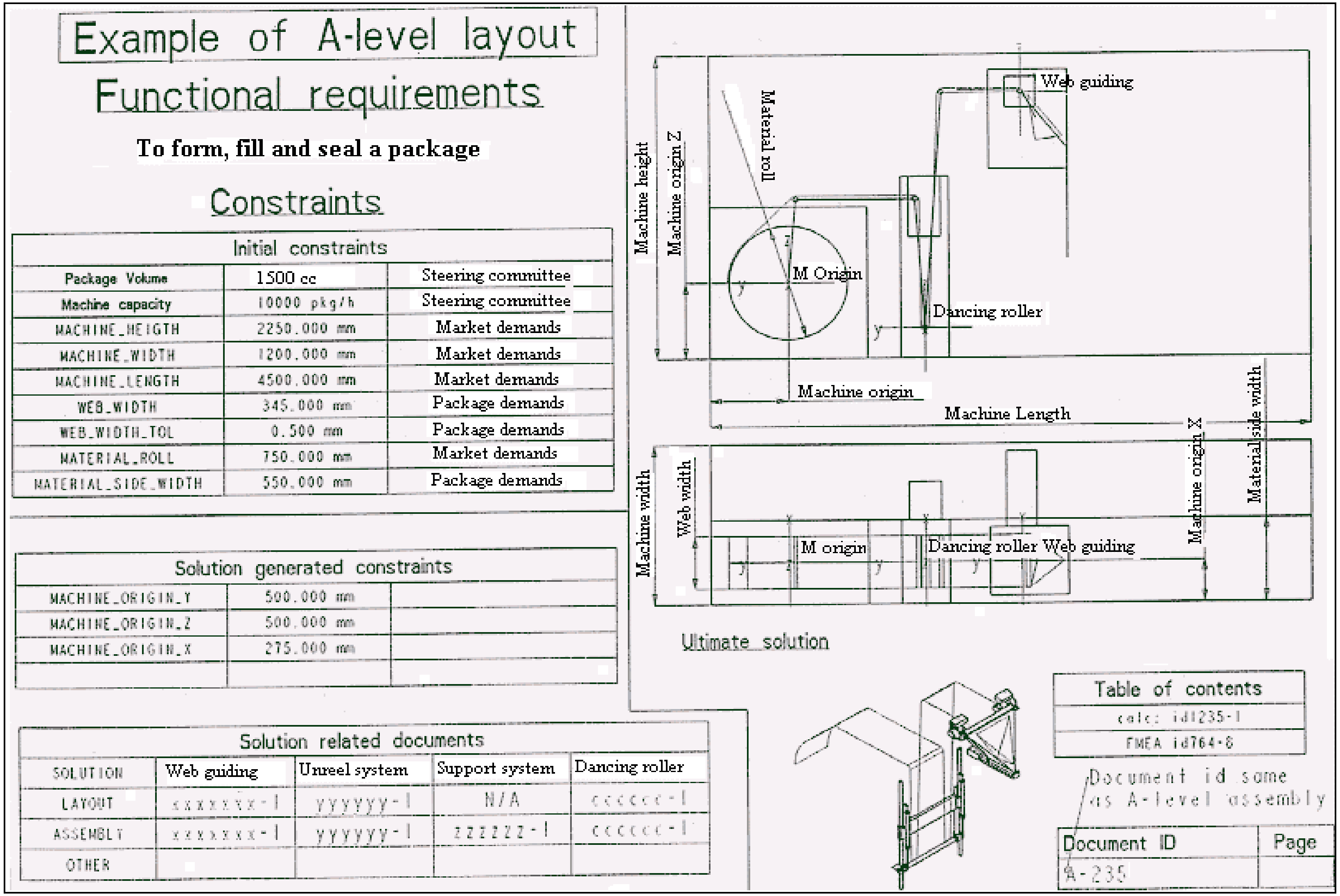


Figure 0-14 Design information about part of packaging machine represented in a form of function means tree (adapted from M. Sjögren, Tetra Pak)



Example of A-level layout

Functional requirements

To form, fill and seal a package

Constraints

Initial constraints		
Package Volume	1500 cc	Steering committee
Machine capacity	10000 pkg/h	Steering committee
MACHINE_HEIGTH	2250.000 mm	Market demands
MACHINE_WIDTH	1200.000 mm	Market demands
MACHINE_LENGTH	4500.000 mm	Market demands
WEB_WIDTH	345.000 mm	Package demands
WEB_WIDTH_TOL	0.500 mm	Package demands
MATERIAL_ROLL	750.000 mm	Market demands
MATERIAL_SIDE_WIDTH	550.000 mm	Package demands

Solution generated constraints		
MACHINE_ORIGIN_Y	500.000 mm	
MACHINE_ORIGIN_Z	500.000 mm	
MACHINE_ORIGIN_X	275.000 mm	

Solution related documents

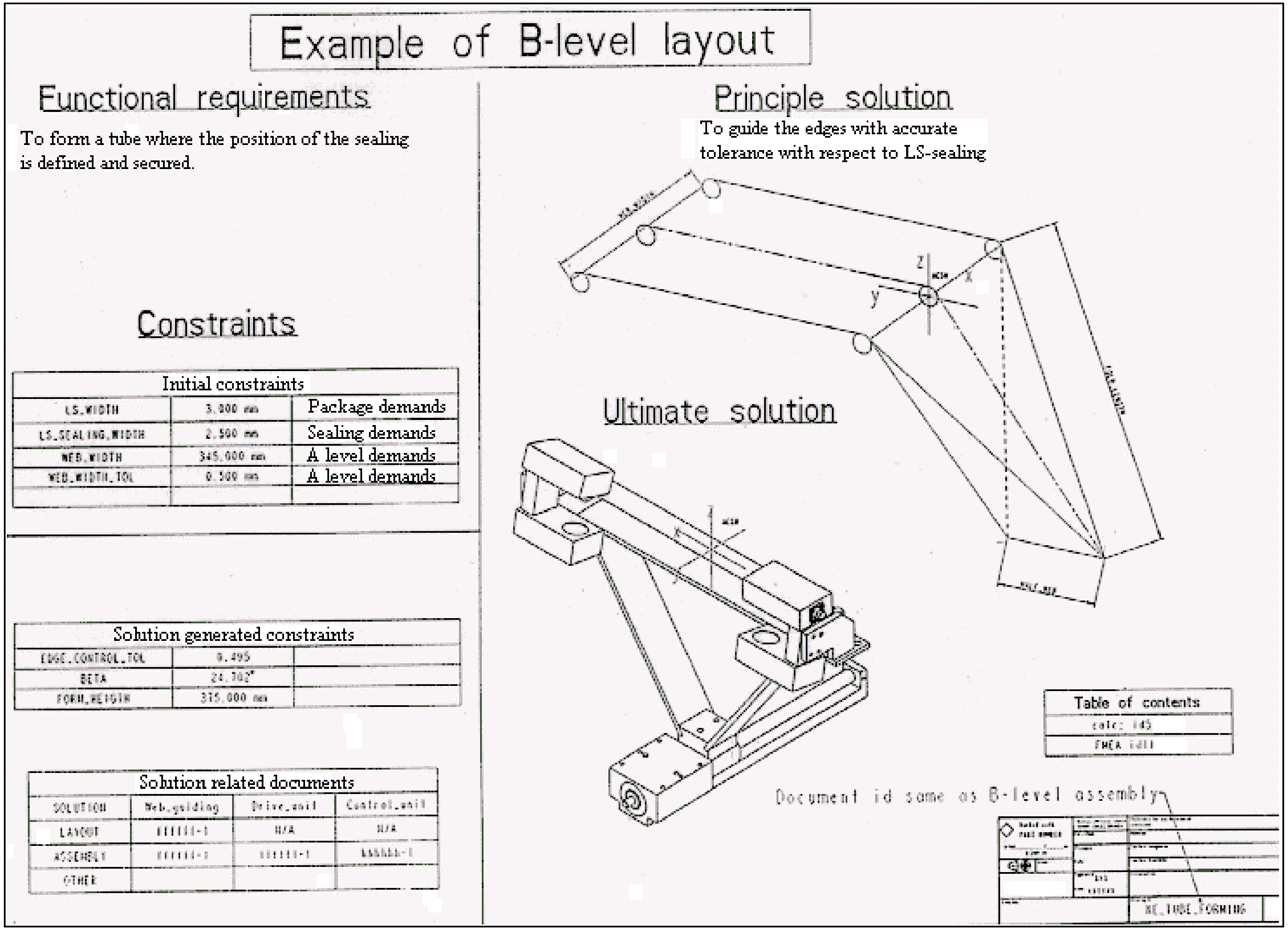
SOLUTION	Web guiding	Unreel system	Support system	Dancing roller
LAYOUT	xxxxxxxx-1	yyyyyy-1	N/A	cccccc-1
ASSEMBLY	xxxxxxxx-1	yyyyyy-1	zzzzzz-1	cccccc-1
OTHER				

Table of contents
calc: id1235-1
FMEA id764-8

Document id same as A-level assembly

Document ID	Page
A-235	

Figure 0-15 CAD model at A-level showing the product model as well as information generated at a high level of abstraction. (From Tetra Pak)



Example of B-level layout

Functional requirements

To form a tube where the position of the sealing is defined and secured.

Constraints

Initial constraints		
LS_WIDTH	3.000 mm	Package demands
LS_SEALING_WIDTH	2.500 mm	Sealing demands
WEB_WIDTH	345.000 mm	A level demands
WEB_WIDTH_TOL	0.500 mm	A level demands

Solution generated constraints		
EDGE_CONTROL_TOL	0.495	
BETA	24.702°	
FORM_WEIGTH	375.000 mm	

Solution related documents			
SOLUTION	Web_guiding	Drive_unit	Control_unit
LAYOUT	[illegible]-1	N/A	N/A
ASSEMBLY	[illegible]-1	[illegible]-1	[illegible]-1
OTHER			

Principle solution

To guide the edges with accurate tolerance with respect to LS-sealing

Ultimate solution

Table of contents
calc: id5
FMEA id11

Document id same as B-level assembly

XE_TUBE_FORMING

Figure 0-16 CAD model at B-level showing the product model as well as information generated at a sub-system level of abstraction.

(from Tetra Pak)

Figure 0-16 shows the next level of abstraction for a subsystem of the same packaging machine. This subsystem's functional requirement is "to form a tube where the position of the sealing is defined and secured." Its corresponding design parameter (called "Principle solution" in the figure) is "to guide the edges with accurate tolerance with respect to the LS-sealing." This DP is visualized in the right part of the figure. The constraints that apply at this level are found under the heading "Constraints." The specific constraints generated at this level as a result of the chosen solution are found under the heading "Solution generated constraints."

Eventually, the design progresses to a level where all subsystems can be implemented. At this point it is possible to extract drawings of each subsystem and equip them with references to the functional requirements and design parameters that were documented in the tree structures. An example of such a drawing is found in Figure 0-17. This figure shows the implementation of the function means tree in Figure 0-14. This is also the same information as is found in the FR and DP trees in Figure 0-12 and Figure 0-13.

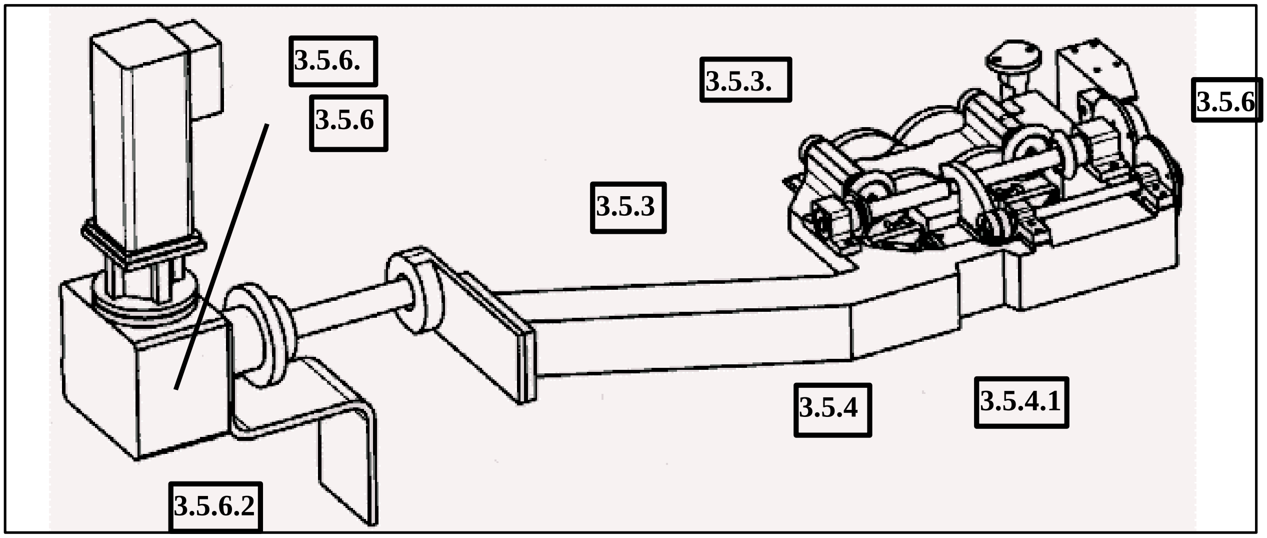


Figure 0-17 CAD model of mechanism in packaging machine with references to the FR/DP structures in Figure 0-12 and Figure 0-13 as well as the function means tree in Figure 0-14.

(Adapted from M. Sjögren, Tetra Pak)

5.4.3 QCAD - Quality Computer Aided Design

QCAD - a system for coordinating design information among different parts of the product development process - was developed and implemented in software by Yale Goldis [GOLD94]. It was primarily developed for use with the total quality development (TQD) approach which follows the EQFD method [CLAU94]. QCAD combines the concept of domains [SUH90] and QFD analysis [CLAU94] with the product model programming in [ICAD93]. This combination yields an information system able to link functions with the hardware parts that realize those functions [GOLD94 p. 55].

The information system supports the designer to develop three hierarchies (function hierarchy, hardware hierarchy, and process hierarchy). Information relevant to each hierarchy is captured as specified below:

Functional hierarchy [GOLD94 p. 74-85].

- Functions - describe what need the product meets.
- Constraints - based on the use environment or customer needs
- House of quality (HoQ) - provides a tool to combine engineering metrics with abstract requirements
- Function diagrams - based on design structure matrices [ULRI95], and showing information flows between functions in order to determine the relationships between these functions.
- Concept generation - a list of the ideas generated that can be reused in the future
- Concept selection - uses the metrics in the HoQ to evolve concepts in the Pugh Concept Selection matrix [PUGH91].
- Concept review - a matrix displaying the relationships between functions and parts, enabling the product development team to avoid interactions that are “too complex” [GOLD94 p. 84].

Hardware hierarchy [GOLD94 p. 85-93]

- Product structure diagram - based on design structure matrices [ULRI95] showing information flows in a set of design activities.
- House of quality (HoQ) - provides a tool to relate hardware design parameters to engineering metrics identified in the HoQ in the functional hierarchy.
- Hardware parameters - variables such as dimensions, material choice, geometries, etc.
- Product parameter design - optimized parameter values.
- Materials and process selection - uses the Pugh Concept Selection matrix [PUGH91] to select materials and processes for piece-parts.
- Concept review - evaluates the relationship between the hardware and process to avoid unnecessary complexity.

Process hierarchy [GOLD94 p. 93-95]

- Bill of materials - itemization of all parts in an assembly
- Process parameters - detailed values of the production process, e.g., assembly sequences, speeds or feeds of a milling operation.
- Process parameter design - the optimal setting of parameters for the production process
- House of Quality (HoQ) - translating hardware characteristics to process requirements

These information structures can be displayed in the same computer window as a CAD model of a product, enabling the designer to view more information than is possible in a pure CAD model.

Goldis points out that QCAD is very useful not only during the design process, but also when the designer wants to change a function, as the system will then identify all hardware affecting this function [GOLD94 p. 74]. This is achieved through the function diagram and concept review matrices. The function diagrams indicate functions affected by or affecting the function that the designer wishes to change. The concept review matrix shows all hardware parts affecting those functions that may be part of the change.

During redesign, the designer can study the existing hardware implementation of a function to generate new ideas [GOLD94 p. 74]. QCAD facilitates this in two ways: by showing the current design, and by providing a list with all ideas generated during *concept generation* (a part of the functional hierarchy).

5.4.4 Discussion on the differences between the two computer implementations

The main difference between the two projects described in sections 0 and 0 is that they are based on two different *design processes:* Tetra Pak's system (TPS) is based on axiomatic design's process [SUH90] while QCAD is based on EQFD [CLAU94].

QCAD uses function diagrams (design structure matrices) to make relationships between functions explicit. Then, concept review matrices are used to find the hardware component related to these functions. Using these two matrices, QCAD can provide a link from functions, to hardware and processes, but not necessarily the other way.

Goldis concludes that this system can identify what hardware and processes must be changed when the designer changes a function. This is consistent with theorem 5 in axiomatic design. This theorem states that *when a given set of FRs is changed, the design solution given by the original DPs cannot satisfy the new set of FRs. Consequently, a new design solution must be sought.*

It seems straightforward to implement a function in the current version of QCAD that would realize the theory discussed in sections 0 and 0 (finding problem sources and providing feedback to the product development team). However, since the links between the hierarchies in QCAD only go in one direction (from the functional hierarchies to the hardware and process hierarchies) it is not clear how the theory on engineering change orders (maintaining the functional requirements but changing the design parameter) described in section 0 could be easily implemented in QCAD. Some small modifications, especially on how relationships are captured should increase QCAD's ability to also support axiomatic design and the proposed framework.

The big advantage of QCAD over TPS is that it is implemented in *one* computer software system thereby eliminating the need to manually link information structures with the CAD models. Furthermore, QCAD currently implements many more functions than TPS.

5.5 *Conclusions*

A new theory was developed to show how design information (developed using the proposed framework) can be of benefit during later stages of the design object's life cycle. This theory shows how this design information can be used to accomplish the following:

- Guide a search for problem sources in a design object,
- facilitate field service of the design object,
- enable effective management of engineering change orders, and
- allow design decisions to be traced.

Four new theorems were stated that would support the designer in this work:

Theorem A	**<u>The design parameter meets is specification but do not deliver the function</u>** If a design parameter (DP) meets its specifications, but fails to provide the intended function, then the DP must be replaced by another DP. Consequently, its corresponding process variable (PV) must also be changed.
Theorem B	**<u>The design parameter does not meet its specification</u>** When a design parameter (DP) does not meet its specifications, its corresponding process variable (PV) must be either replaced or adjusted.
Theorem C	**<u>Impact of an engineering change order in the design hierarchies</u>** An engineering change order can only affect the design parameters at the same level and lower abstraction levels in the design hierarchy. As a consequence of this, process variables (PVs) corresponding to the changed DPs may also need to be changed.
Theorem D	**<u>Impact of an engineering change order</u>** When the design is decoupled or coupled, an engineering change order will impact more than one FR. Consequently, it is likely that more than one DP must be changed as a part of the engineering change order.

Two projects that implement information infrastructures to support design methods were described, one based on axiomatic design, the other on EQFD. The first project was conducted by one industry in close cooperation with this research project. The second project was completely independent from this research project.

The results from these projects clearly demonstrate that it is practical and useful to develop a system capable of capturing more information than pure CAD models developed during design processes. They also show that it is feasible for such system to utilize the theory developed in this section.

Both projects also showed that it is possible to concurrently develop and link information captured in the FR, DP, and PV hierarchies with CAD models. Such linkage helps designers visualize the design object and facilitates its implementation in systems and components. A CAD system with the ability to link models to the tree structures can provide visual models (rather than text models) that would guide the search for problem sources in a design object and facilitate field service of the design object. The system would also visually represent all components that are affected by an engineering change order.

6.

Utilizing principle-based methods and tools to effectively generate the design object within the framework

Thus far, this thesis has introduced an extended information framework around Suh's domain concept, and shown where sources of information in this framework are located. Furthermore, it has been demonstrated how information generated and captured in this framework can be used to improve various design related activities, such as engineering change orders and problem searching.

In a previous paper [NORD94], the theory of inventive problem solving [ALTS88, SUSH95], was proposed as a complement to axiomatic design [SUH90]. Specifically, this section investigates how Suh's independence axiom [SUH90] and the theory of inventive problem solving can be used within the framework introduced in section 4, under the hypothesis that these theories are complementary.

The following statements about the independence axiom and the theory of inventive problem solving are the basis for the hypothesis:

> <u>The independence axiom</u>[14] [SUH90 p. 9] should be used during pre-CAD design to analyze a proposed set of design parameters in order to avoid a functionally coupled design.
>
> <u>The theory of inventive problem solving</u> (TIPS)[15] among other things contains laws of engineering system evolution [ALTS88 p. 223-231] and a collection of problem solving techniques. The problem solving techniques include generalized knowledge for generating a desired function by identifying a set of appropriate physical, chemical, and geometrical effects [ALTS88 p. 309-314] and a set of 40 principles for solving technical contradictions [ALTS88 p. 151-168].

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[14] For a more in-depth description of axiomatic design, see appendix 2, or [SUH90]

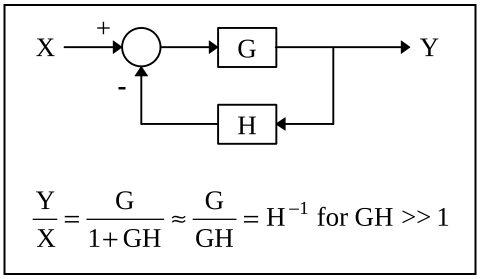
[15] For a more in-depth description of TIPS, see appendix 3, or [ALTS88, SUSH95, MAZU96a, MAZU96b]

6.1 Hypothesis - H3

H3: Working within the proposed framework, the theory of inventive problem solving provides a synthesis tool complementary to the analysis rule provided by the independence axiom within the proposed framework. More specifically, when dealing with the design of a mechanical system in the proposed framework, Altshuller's principles for resolving technical contradictions can sometimes be applied to resolve a situation where a design parameter (DP) or a process variable (PV) does not meet a constraint.

6.2 Theory Generation

The design process can be modeled as a feedback control loop (Figure 0-18) where X represents the input and Y represents the desired output. G represents the synthesis capability and H represents the analysis capability. Wilson et al [WILS79] show that when GH is very large, the gain is equal to 1/H. According to Suh [SUH90 p. 7], when there is a lack of analysis capability, the "[designer] can not rapidly generate the best design" since a good design can not be distinguished from a bad one. Furthermore, Suh points out that "in the absence of a criterion for selecting a good design, we can not make good *design decisions*" [SUH90 p. 7]. The design axioms were developed to provide this analysis capability.



$$\frac{Y}{X} = \frac{G}{1+GH} \approx \frac{G}{GH} = H^{-1} \text{ for } GH >> 1$$

Figure 0-18 Design Process as a feedback loop (from [WILS79])

The framework proposed in section 4 provides the engineer with an infrastructure to capture information that is generated during the design process. The framework also provides a context within which the analysis and synthesis methods and tools can be placed.

Table 0-1 summarizes the contribution of each component of the theory to the over-all design process. This table shows that the design axioms provide analysis support, TIPS provides synthesis support and the framework provides an information infrastructure. Figure 0-19 incorporates TIPS and the design axioms in the proposed framework. The remaining portion of this section explores in greater detail the role of TIPS in the framework.

Table 0-1 Identifying complementary properties between axiomatic design, TIPS and the framework.

	Design axioms	**TIPS**	**Frame work**
Decision-making support (Analysis)	**Yes**	No	No
Synthesis Support	No	**Yes**	No[16]
Information Infrastructure	No	No	**Yes**

6.3 Using axiomatic design and TIPS in the framework

After top-level FRs have been established, there are several information generating activities the designer must perform. First, DPs and PVs must be generated. As was shown in section 4, the designer should investigate both the environment and the customer domain for potential DPs. To effectively search for DPs, the designer can also employ Altshuller's proposed database that matches technical functions with physical, chemical, and geometrical effects[17].

Next, the designer must select an appropriate set of DPs from those generated. All DPs selected must meet all constraints as well as satisfy the design axioms.

A technical contradiction exists whenever a DP does not meet a constraint. It is important to distinguish between a technical contradiction (from TIPS) and a functional coupling (from axiomatic design). Technical contradiction are modeled as contradictions between two technical parameters, while functional couplings are modeled as an interdependence between FRs and DPs. Functional coupling may exist without a technical contradiction and vice versa.

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[16] The framework does provide some support for synthesis in that it prescribes certain areas in which the designer should look for potential DPs and PVs. However, this support is not in the form of rules or principles.

[17] Such databases exist in commercially available software packages.

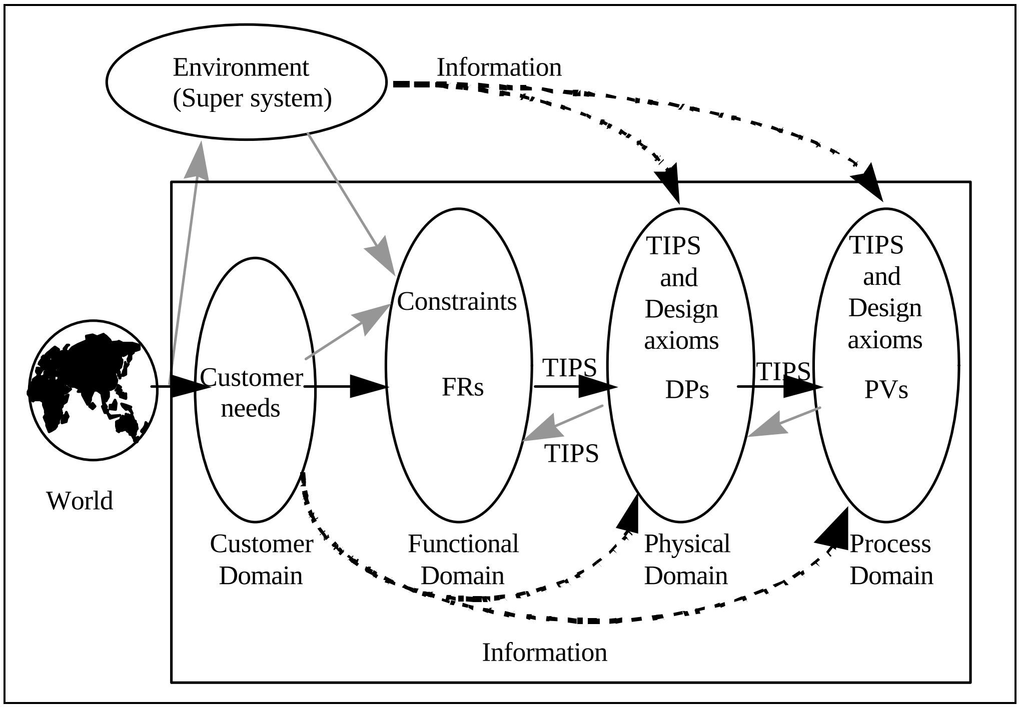

Figure 0-19 TIPS and axiomatic design in the framework[18]

To resolve a technical contradiction (DP-Constraint contradiction, or a PV-constraint contradiction) Altshuller postulated 40 inventive principles. Figure 0-20 illustrates how DPs are checked against the constraints (Cs). This activity takes place in either the physical domain or the process domain. During this process, every DP is systematically checked against each constraint (e.g., DP1 vs. C1, DP1 vs. C2, … DP1 vs. Cn). Whenever a DP or PV violates a constraint the designer can attempt to apply one or more of Altshuller's 40 principles to overcome this problem.

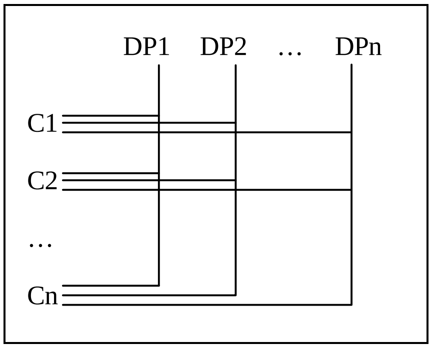

Figure 0-20 Checking DPs against constraints

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[18] For increased clarity, some information found in section 4 has been removed from this figure.

The last step in a design cycle (before the next level DPs are generated) is the decomposition of FRs. In order to decompose an FR, the designer must know its corresponding DP. Altshuller has developed trends of technology evolution that can be applied when decomposing the FRs. This practice would ensure that designers state FRs to achieve the highest possible performance.

6.4 Example: An engineering change order utilizing axiomatic design and TIPS within the framework

The switch pictured in Figure 0-21 has been designed to fit within a small volume and manage a current of 50 A. The design equation for this switch is shown in Equation 0-1.

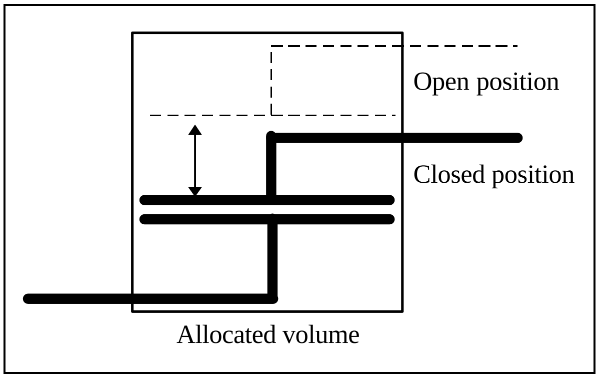

Figure 0-21 Schematic drawing of a switch

Equation 0-1

$$\begin{Bmatrix} \text{FR1 Conduct Current (50A)} \\ \text{FR2 Break Current (50A)} \end{Bmatrix} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \bullet \begin{Bmatrix} \text{DP1 Area of plates} \\ \text{DP2 Mechanical movement} \end{Bmatrix}$$

C1: Maximum power losses in switch = 1%
C2: Max volume X*Y*Z mm

In this example, it is assumed that the switch’s plate areas are of a size that causes exactly 1% power loss at 50A. It is also assumed that the plates fit exactly within the allocated space.

Now, the FRs for the switch are changed so that FR1 becomes: *FR1 Conduct Current (100A)* (at the same voltage).

According to theorem 5 [SUH90 p. 392], a new design solution should be investigated. First, the existing DPs are investigated. The existing area of the plates will allow 100A current as well as 50A, and since the voltage is unchanged, the same mechanical movement will suffice to break 100A and 50A.

Next, the DPs are checked against the constraints. The physics of the switch are studied to provide the answer to how the power loss is affected by a change in current. The physics of the switch are defined by Equation 0-2 and Equation 0-3.

Equation 0-2

Power $P=RI^2$ (where I is the current and R is the resistance in the switch)

Equation 0-3

Resistance $R=\rho l/A$ (where ρ is resistivity, l is length and A is area of the conductor).

Equation 0-4 shows how power loss (P) can be expressed as a function of current (I) and plate area (A):

Equation 0-4

$$P=I^2\rho l/A.$$

Equation 0-4 shows that when the current is increased, power losses in the switch will increase in proportion to the square of the increase in current. Based on the assumption above, this will bring the power losses over 1%. To ensure that *C1* is satisfied, *DP1 Area of plates* must be increased. Since DP2 has no effect on power losses, *C1* is satisfied.

Next DP1 is checked against C2, concluding that DP1 no longer satisfies C2 (any increase in dimensions will exceed the allocated space). In this case, there is a technical contradiction between DP1 and C2. The area must be increased, but the volume is fixed.

According to the hypothesis, it should be possible to utilize Altshuller’s principles to resolve this technical contradiction. The contradiction was modeled as

Improving parameter: 5 - *Area of moving object*

Worsening parameter: 7 - *Volume of moving object*

Altshuller’s matrix for matching technical contradictions to the applicable inventive principles (see appendix 3), was used to identify the following four inventive principles (Table 0-2) that could solve the technical contradiction identified above.

Table 0-2 Inventive principles for solving the technical contradiction in the switch

(from [ALTS88])

Principle 4 *Asymmetry*	• Switching from symmetrical to asymmetrical forms, • If the object is already asymmetrical, increase the degree of asymmetry.
Principle 7 *Nesting*	• One object is contained inside another which in turn is placed inside a third, etc., • One object passes through a cavity in the other object.
Principle 14 *Spheroidality*	• Switch from direct linear to indirect linear, from flat surfaces to spherical, from cubical or parallelepipod parts to spherical structures, • use rollers, balls, spirals, • switch from linear to rotating motion, use centrifugal forces.
Principle 17 *New dimension*	• move an object in two- or three-dimensional directions (increase the degree of freedom), • use a multi-layered arrangement of objects instead of a single-layered arrangement, • Incline or tilt the object, lay it on it's side, • use the reverse side of an available area.

Based on these principles, several conceptual solutions of how to increase the area while meeting the volume constraint can be generated (Figure 0-22). Concept A is an implementation of principle 7 (*Nesting)*. Concept B implements principle 14 (*Spheroidality)*. Finally, concept C combines principle 7 and 14.

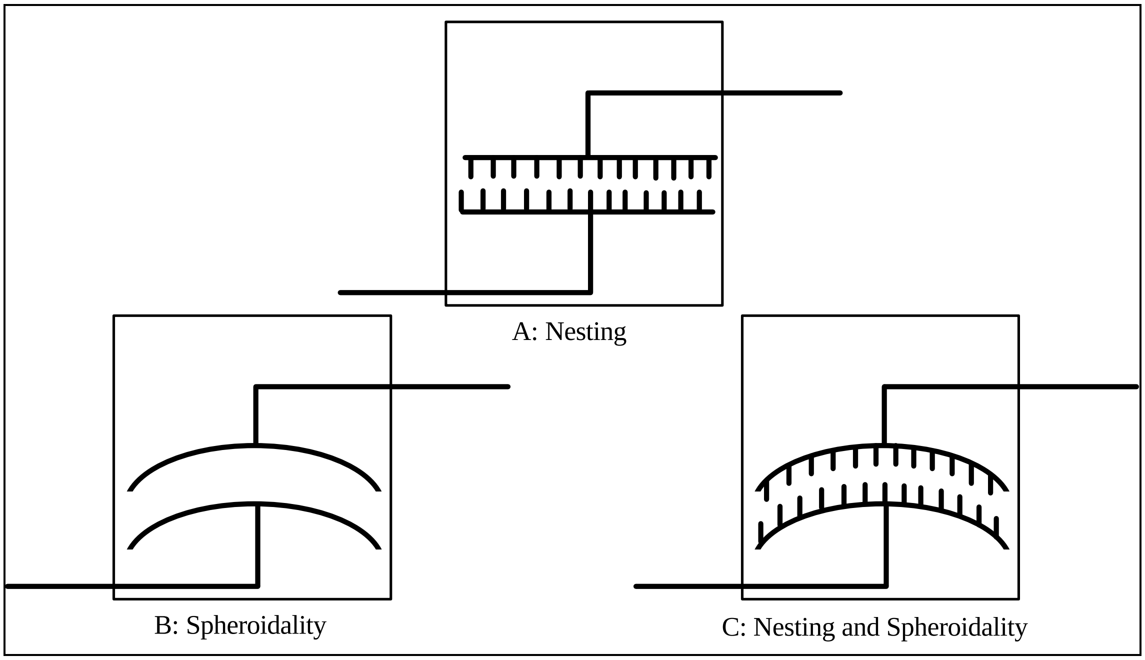

Figure 0-22 Different design concepts that increase the contact area of a switch

6.5 Conclusions

The example supports the hypothesis (H3) that (at least in special cases of mechanical systems design) Altshuller's inventive principles can be used within the proposed framework to resolve a situation where a DP does not meet a constraint.

It is also proposed that

- Altshuller's inventive principles can be used within the proposed framework to resolve a situation where a PV does not meet a constraint.
- the collection of effects can support the designer in satisfying the functional requirements by identifying possible design parameters (in addition to scanning the environment, the customer domain, and the designer's own knowledge), and
- the trends of technology evolution may be applicable during the zigzag decomposition process.

The findings in this section are based on purely academic work. Neither the hypothesis, nor the proposals were tested in industry case studies. Nevertheless, these findings can be used to derive questions for future research relating axiomatic design and the theory of inventive problem solving. For example:

- Are the results valid also for constraint-PV contradictions?
- For which types of constraint-DP or constraint-PV contradictions can Altshuller’s principles not be applied?
- Which trends of technology evolution are applicable during the decomposition process?
- How does the algorithm of inventive problem solving relate to the framework and axiomatic design?

7.

Limitations on the applicability of the framework

This section explores the applicability of this framework for problems outside the field of engineering.

7.1 Research Question

Is this framework applicable to non-engineering problems?

7.2 Hypothesis

H4: *The framework is only valid for designing engineering systems (e.g., products or manufacturing systems).*

The following consequence is derived from the hypothesis and can be tested:

- If hypothesis H4 is valid, then this framework should not provide any guidance to the designer of a non-engineering design object.

7.3 Testing hypothesis H4

An opportunity to test this hypothesis was provided when Saab Service Partner AB wanted to try a new approach to corporate business planning. The process that was proposed and implemented was as follows:

1. Using the framework, analyze parts of the previous year's business plan[19] to determine whether the hypothesis is supported.

If the hypothesis is not supported (i.e., the framework seems applicable) then

2. Establish a common terminology for the company business plan
3. Teach the framework and the approach to the company's executive leadership
4. Facilitate the executives in conducting an analysis of the previous plan
5. Develop a new plan based on the result of the analysis.

Since the framework proved to be useful in analyzing the previous year's plan, the team moved on to steps 2-5. First, the terminology of the framework was changed as follows: FRs were renamed to *Goals*, DPs became *Strategies* and PVs were changed to *Activities*. It seemed feasible to analyze the business plan in these terms. For example (from appendix 4) note how the following statement contains both a goal (FR written in italics) and a strategy (DP, underlined): “Continuous improvement of our business is a precondition to *maintain and improve the quality level compared to our environment*.” However there is no specific activity (PV) specified in the activity plan (in appendix 4) to realize this strategy. This may indicate that the goal will not be implemented, or that no specific plans for implementation exist. For the feasibility study, a number of similar examples were investigated and presented to the company management. Based on this study, the company management decided to proceed and conduct a business planning activity following the framework.

To begin this effort, a common terminology was established. Words including mission, vision, goals, strategy, quality, and customer satisfaction had to be defined to ensure efficient communication during the planning activity.

The planning activity consisted of a half day course in how the framework works, and some exercises applying it to prepared examples. Next, the previous business plan was analyzed in terms of the framework to identify current goals, activities and strategies, but also to realize what potential DPs and PVs already existed in the customer domain and the environment (the company).

The executives were divided into three groups who worked in parallel. The chief executive officer, chief financial officer and the facilitator were rotated between the groups. Each group also had a group facilitator who had received thorough training in using the framework before the exercise. At the end of this activity, the groups began identifying deficiencies in the design information. For example the groups found goals without strategies and activities (FRs without DPs and PVs), as well as strategies and activities that had no goals (DPs and PVs without FRs). The groups then proceeded to generate information for these deficiencies. This information was primarily taken from the customer domain (e.g. cooperate with customers) and the environment (use existing facilities or staff in the company). When all the groups had completed their work, each presented their results, and a smaller group with members from each of the three groups was formed to merge the three different plans into one.

7.4 Conclusions

The framework is valid for designing non-engineering systems. The framework has been shown to be useful in designing a company business plan, and an equal opportunity plan. Therefore hypothesis H4 (that the framework is limited to engineering problems) must be rejected. There is currently not enough evidence to state that the framework is generally applicable. However, there is no evidence at this point that rejects such an hypothesis.

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[19] An abbreviated translation of this document can be found in appendix 4.

It was also found during the case study that information captured about non engineering problems can be managed in the same way as described in chapter 5, i.e., to support analysis of the impact from changing one or more strategies or activities.

Based on Saab Service Partner's experience with this framework, the parent company, Saab-Scania, decided to develop its equal opportunity plan in the same way. This plan is published in [JÄMS94]. Saab Service Partner is still using the framework to conduct its business planning.

Since the first business plan (see section 0) was developed as a part of this research project, the leadership of Saab Service Partner has conducted new business planning sessions following the same process, this time without the involvement of the researcher. Therefore, it is concluded that the results are not arrived dependent on the researcher's involvement in the process.

Limited experiments were also conducted applying the framework to marketing problems (both academic examples conducted on Harvard business schools cases and industry problems conducted with AGA AB). Results from these experiments indicate that the framework also is applicable in designing marketing strategies.

There are many areas outside the engineering field where the validity of the framework remains to be tested.

7.5 Saab Service Partner’s Business Plan.

8. Contributions, Conclusions and Future work

8.1 Summary of this research project's contributions to the academic community

As a result of this research, new knowledge was developed and validated, and new graduate courses in design were developed and implemented. Contributions to the knowledge base were:

- An extended framework describing the information flows during axiomatic design.
- A theory for how to manage information captured during the design process. This theory shows how to use this information to manage engineering change orders, facilitate field service, and conduct problem shooting in a design object.
- A theory relating axiomatic design to the theory of inventive problem solving (TIPS). It was explained how components of TIPS can be used within the proposed framework to facilitate generation of design information.
- It was shown how the framework and theories can be used during business planning.

8.2 Summary of the effects on industry and knowledge transfer

In addition to the contribution in knowledge, this project has also impacted industry practice and contributed to knowledge transfer from academia to industry as well as international academic cooperation.

In industry, new products, manufacturing processes, and planning approaches have been implemented. One company is conducting their new product development process based on the knowledge developed in this thesis. Furthermore, based on this knowledge, a new feature was added to complement a CAD software that is currently being tested. Finally, a new industry network (Swedish Industry Network on Axiomatic Design) has been initiated to promote engineering design methods in Swedish industry and academia.

Axiomatic design has become widely known in Swedish industry, and, as a direct result of this research, Altshuller's Theory of Inventive Problem Solving was quickly introduced to Swedish industry and academia.

8.3 Conclusions

A new information framework for engineering design based on axiomatic design was developed and validated. A new theory was developed to show how to use the information captured in the framework during later stages of the design object's life cycle. This theory shows how such design information can be used to:

- guide a search for problem sources in a design object,
- facilitate field service of the design object,
- enable effective management of engineering change orders, and
- allow design decisions to be traced

In this thesis it is concluded that:

- The proposed framework is useful to designers following the axiomatic design method. There is now evidence supporting the hypothesis that the framework provides an accurate representation of the sources of design information (within the context of axiomatic design). Furthermore, it must be concluded that the framework (at least in special cases) is useful for structuring, searching and managing design information.

  Currently, there is no evidence suggesting that the validity of the proposed framework is limited to the case studies performed as a part of this research. However, the data presented in this thesis are insufficient to allow the conclusion that the framework always is useful for structuring, searching and managing design information.

- It is possible and useful to create a system capable of capturing information developed in the framework, and capable of utilizing the theory developed in section 5. It is also possible to link up information captured in the tree structures with CAD models in order to visualize the design object and facilitate its realization in systems and components. A CAD system with this linking capability built in, could use visual models (rather than text models) to guide the search for problem sources in a design object, or facilitate field service of the design object. This CAD system would also visually show the components affected by an engineering change order.

- At least in special cases of mechanical systems design (where the technical contradiction can be modeled), Altshuller’s inventive principles can be used within the proposed framework to resolve situations where a technical DP fails to meet a technical constraint. It is also suggested that

    - Altshuller’s inventive principles can be used within the proposed framework to resolve a situation where a PV fails to meet a constraint,
    - the collection of effects can help the designer identify possible DPs to satisfy the functional requirements (i.e., designers should search the effects data for DPs as well as the environment, customer domain, and the designer’s own knowledge), and
    - the trends of technology evolution may be applicable during the zigzag decomposition process.

- The framework is valid for designing plans, which is a type non-engineering system. It was also concluded that information captured during planning can be utilized in the same way as information about engineering systems.

  The data set presented in this section is in sufficient to draw the conclusion that the framework is valid for all non-engineering design situations. However, there is currently no evidence to the contrary, therefore it can be assumed that the framework is applicable in design projects in both engineering and non-engineering situations until this assumption is proven to be false.

8.4 Proposed future work based on this thesis

8.4.1 Future research

The area of engineering design is a very new research field. Therefore there is an infinite amount of important design research yet to be conducted on product development and manufacturing. During this research, a number of questions arose that deserve further investigation:

- What software could implement the information framework?
- What sort of databases, and database structures should be developed for the information generated in the framework (such databases would be accessed during analysis for engineering change orders, problem searches, etc.)?
- How effective is Altshuller’s proposed effects [ALTS88 p. 309-314] in generating DPs from FRs?

- How useful are Altshuller's trends of technology evolution in the zigzag decomposition process?
- Can this framework be applied to other areas (besides design of engineering systems and planning)?
- How do noise factors and other variations come into the framework?
- How can the framework be improved to facilitate robust engineering?

8.4.2 Towards the Thinking Design Machine (TDM)

The knowledge developed in this thesis can be used in the effort to develop a thinking design machine (TDM) according to the vision presented by Suh and Sekimoto in [SUH90a]. The TDM is a concept that would automatically generate superior design objects. Suh and Sekimoto write that "through the process of creating the TDM, we may be able to provide a better understanding of human minds." The knowledge developed in this thesis will contribute to the TDM effort in the following ways:

- The information framework will provide knowledge to the TDM developers on what information to use when building up the data bases. For example, it will be useful to create a database (besides those proposed in [SUH90a] of different environments and their possible DPs, PVs and constraints, as well as a data base of the constraints that are introduced from the various sources identified in the framework.

- The information management theory outlines additional functionality to the TDM. It shows how information captured during the TDM's design work also can be used for later engineering change orders and for identifying problems in the design (both during the design process and during field service). It also shows a concept for learning, i.e., <u>feeding back</u> information on the performance of various DPs selected by the TDM.

- The theory on how Altshuller's Theory of Inventive Problem Solving is related to the framework provides the TDM developers with knowledge that relates FRs to DPs, and resolves conflicts when DPs (and potentially PVs) do not meet constraints. Furthermore, the theory provides some rules to consider during the decomposition process.

- Finally, the fact that the framework is applicable to non-engineering problems also indicates that the TDM also may have applications outside traditional engineering applications.

9.

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