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SYNERGIES BETWEEN AMERICAN AND EUROPEAN APPROACHES TO DESIGN[1]

Derrick Tate
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA
dtate@mit.edu

Mats Nordlund
Department of Manufacturing Systems
Royal Institute of Technology (KTH)
Stockholm, Sweden
nrdlnd@aol.com

ABSTRACT

Researchers and practitioners worldwide have recognized the importance of structured, scientifically-based, and industrially-tested theories and methods for product (and process) design and development. Recent research has sought similar goals: reduced development time, reduced product costs, and increased value delivered to customers. However, American and European research in engineering design and product development have evolved differently and are distinct in their scope of application. Consequently, little integration and cross-learning have been done.

In this paper we propose a categorization of design research approaches[2] based on evolution and scope. We use this categorization to explain the reasons for lack of integration of design research. We distinguish between the process of creating a knowledgebase of design (the objective of design research in academia) and the process of selecting and implementing such knowledge (the objective of product development in industry). Finally we propose a process for identifying synergies and conflicts in the use of multiple design theories and methods.

1. INTRODUCTION

In recent years, researchers and practitioners from around the world have realized the growing importance of structured, scientifically-based, and industrially-tested theories and methods[3] for conducting product (and process) design and development. Yet, at the same time, leaders in industry are now becoming more skeptical about research being produced in the field of engineering design. In fact, some designers have coined an acronym which describes how they view new presentations from this research area: JAM, an abbreviation of “Just Another Method”.

Is it possible that design theories and methods—which have as a purpose to help designers satisfy their customers—fail to satisfy these designers in industry—their own customers? If this is true, then researchers have failed in the implementation and/or the development of these theories and methods. They have failed to achieve a goal that many of them identify for themselves: customer satisfaction!

Four prominent programs of design research are covered in this paper:

- Suh’s axiomatic design [12],
- total quality development as elaborated by Clausing and others (including house of quality, quality function deployment (QFD), Pugh concept selection, and quality engineering) [3],
- Altshuller’s theory of inventive problem solving (TIPS) [1], and
- the work of Hubka and Eder [5], and Andreasen [A, B]—the Workshop Design Konstruktion (WDK) school.

Each program approaches engineering design from a different perspective. In this paper we assume the reader is familiar with the basic concepts and tools of these design theories and methods, and we discuss the evolution (development) and scope (extent of treatment, activity, or purpose) of these design theories and methods. Our objectives are

- to explain the reasons for lack of integration of design research in academia,
- to illustrate the difference between the creation of theories and methods and the selection of such theories and methods for use in industry, and
- to propose a procedure that can be used in industry to identify synergies and conflicts in the implementation of multiple design theories and methods.

2. DESIGN

Engineering design can be, and has been, interpreted in different ways. Some of the differences will be illustrated in the rest of this paper; however, the purpose of this section is to provide a consistent terminology for the discussion which follows.

Product development is the integration of technology strategy, product strategy, and manufacturing strategy to identify and meet customer needs.

What is the field of engineering design? Design can mean the process which is followed to produce some output. A more formal definition is the following: the design process is a sequence of steps by which the means to satisfy a set of objectives are developed and selected, subject to constraints. Design can also mean an object. Thus, a design object is the product, that is, the output, of

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1. Each author contributed equally to this work.
2. In this paper, we define approach to mean the broad approach researchers take to develop knowledge for their research programs.
3. A method is a tool to help with an activity; methodology is the study of methods.

the above process. So, the design process produces a design object.

Research in engineering design concerns the interplay between the design process and the design object. How does the design process produce a design object? Research which addresses this question produces a descriptive model of design. (The definition of model used is that of Ross [9]: A is a model of B if A may be used to answer questions about B. If instead of a description of how the design is done, research produces a prescriptive model of design, then the model answers questions subsumed under this: how should the design process be performed? In this case specific tools (or methods[4]) may be associated with the design process which have as their purpose to provide guidance or assistance to the designer.

3. EVOLUTION OF RESEARCH METHODS

This section addresses how researchers in the field of engineering design have answered the question: how is knowledge and practice in the field of engineering design advanced? That is, what general approach to studying, systematizing, and transferring engineering design knowledge is to be followed?

By comparing different research programs and examining the literature on engineering design, one realizes that design researchers have evolved their theories in different ways. These differences can be explained by the different ends the research programs are seeking to achieve as well as the approach the researchers have taken to achieve these ends.

In this section categories for classifying the evolution of design research are presented. Several prominent research programs will be mapped onto this categorization in section 5.

Systematic research in engineering design began in Germany in the 1850s. Material presented by Altshuller, Bjärnemo, Pahl & Beitz, Phadke, and Suh [1,2,7,8,12], lists some of the most influential work in the engineering design field.

Very little recent European research builds on material developed in the US and vice versa. One explanation for this is the language barrier. Finger and Dixon write that "even though a large body of research has been published in German, only a small fraction of this (e.g., Hubka and Pahl & Beitz work) has been translated into English" [4]. Going in the reverse direction, even less material has been translated from English into German. However, we also believe that research culture and peer pressure were important factors in isolating the research communities.

When examining how knowledge has been developed by the researchers in this field, two general approaches were found, these are described briefly in sections 3.1. and 3.2 below.

4. The terms tools and methods are used interchangeably in this paper.

3.1 GENERATION OF NEW KNOWLEDGE

Theories and methods developed from some fundamental principles

This is analogous to developing a new design from scratch. Based on the researcher's understanding of the problems with current design practice, a general statement of objectives is created. This approach then leads to the development of prescriptions to meet these stated objectives. The prescriptions take the form of theories or general principles. The principles, as defined, cover a broad range of design problems. Lastly, a process is created to apply these principles to the specific situations encountered by designers working in their particular fields (e.g., mechanical design)

Theories and methods developed based on the study of good design practice

This is analogous to redesign of something which exists. (We like the results we're getting; we'd just like to do things in fewer steps, cheaper, etc.) Existing techniques for creating product X are studied. Prescriptive principles are developed to aid in the design of the next X. Finally these principles are applied to the design of new X.

3.2 SELECTION/USE OF EXISTING KNOWLEDGE

Objectives then selection of tools

This is analogous to selection from among existing designs. The objectives for the particular problem at hand are stated, and design tools which exist are evaluated against a set of selection criteria. Finally, the design tools that best satisfy the objectives are integrated to form a design process.

4. SCOPE[5] AND MOTIVATION

In this section, we look at several specific research programs and match the objectives which the researchers have stated with the methods that they have followed. In particular the research programs which are examined are those put forth by Altshuller [1], Andreasen [A, B], Clausing [3], Hubka and Eder [5], and Suh [12]. These programs were chosen because they represent a cross section of research in design today (and are available in English). Additionally by examining these, we hope to gain an insight into differences between European theories which have drawn upon the early work of German researchers and those which arose independently of German research over the last half century.

We seek to answer two questions in this section with respect to each of the programs examined. In particular these are the following:

5. The definition of scope which we are using is the following: "extent of treatment, activity, or influence" [15 p. 1053].

1. What is the motivation for each program?
2. What is the scope of each program?

The first question deals with the overall goal for the research: why is research in design important? The second deals with how large a problem is addressed: what should be covered by the program, and what are the limits of its applicability?

Altshuller

Altshuller recognized the need for a scientific approach to invention after listening to scientists and inventors speaking of "[design as] sudden enlightenment, the impossibility of controlling the creative process, but also [the impossibility of] understanding what it is and how it comes about." These discussions prompted the following questions: "Why should everything but creativity be open to scrutiny? What kind of process can this be which unlike all others is not subject to control?" The consequences of creativity being an uncontrolled process was clear to Altshuller in that "[m]any inventions have come too late [and that i]nventors make frequent mistakes, dreaming up [unrealistic solutions]." [1 pp. ix-x].

The motivating objective for Altshuller is to make creativity become a controlled process. Creativity may be taken to be the activity of generating new designs. It does not include the selection from among existing designs, rather it is concerned with the statement of problems, an analysis which identifies a key area of conflict, and the application of 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. According to Altshuller, the scope of his method of creative or innovative thinking is general, although it is mainly aimed at engineers. "The principle of controlled thinking in the solution of inventive problems (the principles and not concrete formulae and rules) can be transposed to the organization of creative thinking in any sphere of human activity" [1 p. xi]. Applying this method in 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). Altshuller describes how to go about solving a technical conflict in his algorithm for solving inventive problems.

Clausing

The driving force behind Clausing's work has been a very broad one—to improve industrial performance. Our interpretation is that Clausing is trying to use 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".

The scope of design as viewed by Clausing is very broad: "*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" [3 p. 3].

Suh

Suh's primary motivation for developing axiomatic design is education; he wants designers to learn how to make good design decisions. Suh's goal is to establish an "academic [discipline] for design and manufacturing" [12 pp. 21-22]. The reason is found in the following: "[i]n order to obtain better performance, both engineering and management structures require fundamental, correct principles and [methods] to guide *decision making in design;* otherwise, the ad hoc nature of design can not be improved" [12 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" [12 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" [3 p. 5]. This is a more restricted view than Clausing, but encompasses more than Andreasen or Hubka. In contrast to Clausing, Suh does not describe how to connect design activities to the company's general activities; Suh's theories and methods are focused on decision making in the design process.

In his book [12] Suh considers designs primarily in three fields: manufacturing process design, product design, and organizational design. Although the bulk of his personal experience in applying 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. (See [6] for a description of these applications.)

The WDK School

Hubka and Eder are working to enable systematic work in designing, and "independent auditing" in order to improve the efficiency of the designer [5 p. iii]. The motivation for this is given as follows: "to make [design] more efficient by scientifically reducing or eliminating waste of labor, time, or materials" [5 p. 45].

Andreasen observes that European schools of design in general have the utilization of the theories and methods in practice as the declared aim of their research. Andreasen considers the aim of design methodology to be "to structure design procedures and to model them, and also to give support to each step through models and methods with the aim of increasing efficiency and of making the area easy to learn and transparent" [A p. 1].

Our interpretation is that although some literature on this school suggests that different groups perform their tasks in an integrated manner, that these groups are separate entities: product planning, engineering design, etc. Furthermore, these groups are not using the same fundamental process (that is, the design process) for performing their activities. The design process is restricted to the certain stages of the product development process: after specification of needs, but before manufacturing.

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 [5 p. 49]. Clearly though, they do not feel that this is *necessarily* within the scope of design. An engineering design team begins its design task when it receives a set of requirements (either from a customer or another sponsor). "This document is the start of the design sequence, the engineering design team accepts the assignment of the problem" [5 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) is considered the aim of an engineering design process, its *output*" [5 p. 46].

4.2 DISCUSSION

European schools of design tend to separate out a portion of product development activity and address this primarily. There is no specific word in English for this activity, but Clausing has a term for it: "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" [3 p. 5]. This term is unsatisfactory, however, because it unfairly misleads. The activity is not partial in the sense that it is incomplete; rather it only covers a small, well-defined fraction of design. We propose to use the Germanic word "konstruktion" for this narrow, detailed activity.

5. EVOLUTION

In this section, we will describe, in more detail, how the theories and methods covered can be categorized among the evolution approaches described in sections 3.1 and 3.2.

5.1 GENERATION OF NEW KNOWLEDGE

Theories and methods developed from some fundamental principles

Altshuller:

Altshuller identified "a need for new methods for managing the creative process capable of radically reducing the number of 'empty' trials" [1 p.3] during a trial-and-error approach. Also needed was a new organization of the creative process that would permit the effective application of new methods. All this required a scientifically based theory for the solution of inventive tasks that is capable of being implemented in practice [1 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" [1 p. 35].

Altshuller begun work on an algorithm[6] for the solution of inventive problems [1 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 (that is what 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[7] contained in the problem presented, and bad if the technical contradiction was not revealed and eliminated" [1 p. 40].

Suh:

Suh started the development of his program by asking: "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?" [11]

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 [12]. Based on such a set of axioms, many

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6. Altshuller defines an algorithm as any sufficiently clear program of action [1 p. 36].

7. 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" [1 p. 28].

specific methods for analysis and problem solving could be developed [12 p. 171]. Out of this exercise evolved twelve hypothetical axioms which later have been reduced into two and a set of corollaries and theorems [12 p. 20].

Suh had started his search for design axioms by observing that that there are good design solutions and unacceptable design solutions. Because these can be distinguished, this indicated that there exist features or attributes that distinguish these. The first axiom defines an acceptable design as one where design parameters and the functional requirements are related in such a way 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 (highest probability of success) [12 p 47-8].

Theories and methods developed based on the study of good design practice

The WDK School:

In contrast with the other programs discussed here, this school, as presented by Hubka and Eder, has its primary focus to develop descriptive models—of both technical systems and the design process [5 pp. 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]” [5 p. 116].

Based on this general procedural model of the design process, a procedural plan for a specific situation can be “derived and adapted from the ideal model” [5 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, as “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[8] must be based on a theory of the design process and a theory of mechanical systems [A 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” [A p. 10].

8. Theory here is defined as a system of concepts, rules, axioms and models.

5.2 SELECTION/USE OF EXISTING KNOWLEDGE

Clausing:

As was described in section 4, 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 then integrating the best components he has found into a holistic approach to design [3 p. xix].

This approach of developing a design method is different in that it is totally goal oriented - 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) analyzing pragmatically 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. By its evolutionary nature, this program will continually change and improve as Clausing continues to search for new components that complements or improves his approach.

5.3 DISCUSSION

Both Altshuller and Suh’s 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 virtually the same definition 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.

One of the complementary properties of these two methods is that while Suh’s analysis method points out when interdependencies are harmful and can easily visualize interdependencies between *several* variables, Altshuller’s method lacks this property. However, once the conflicting interdependencies are identified, Altshuller provides a set of tools to resolve it—something Suh’s method lacks. It has been proposed to use these methods in a complementary fashion, making use of their respective strengths, to further enhance these principled approaches to design [6].

The approach that Hubka and Eder followed to develop 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, that is, it will provide a scientific description of what the designers do—but no statement on 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 define what constitutes a good design—something that is central to both Altshuller and Suh. Instead, Hubka and Eder use the ISO 9000 definition of quality, "the totality of those properties and characteristics of a product or an activity that relate to its suitability to fulfill the stated requirements" [5 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 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. We believe that Clausing uses an unique approach in this research field in applying a concept selection method, combining useful features from several different methods to create a holistic method, then using benchmarking to ensure that the new method indeed is superior.

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....." [13 p. 801]. Even if Clausing's approach by some would be called unscientific, it is nevertheless effective.

This differences in approaching the development of knowledge in this field is captured in the following statement where Sohlenius expands on a 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, analyses the results of the creation" [10].

6. PROCESS FOR SELECTION OF DESIGN TOOLS BY INDUSTRY

In this section we discuss the difference in perspective concerning design methods held by design researchers and by practitioners. Furthermore, we propose a process by which practitioners can identify methods which meet their needs. Such a process would imply that design researchers need to provide information more accessibly to industry to facilitate the selection of appropriate methods.

The perspective of researchers in academia must necessarily be different from that of practitioners in industry. In particular academia asks the question: how can knowledge be generated, or collected, to expand the body of work which constitutes engineering design? That is, design theories and methods are the product of design research, and researchers seek to <u>create, refine, and expand</u> these by adopting a means to evolve their work. In contrast, in industry design theories and methods are a means to achieve the end of product development. Thus, rather than create a new knowledgebase of engineering design, the strategy is to <u>select</u> from among existing design research those tools which will meet the objectives of the firms designers. This distinction is illustrated in figure ??.

The procedure to be followed in selecting methods for use by industry is as follows: understand the design process used currently, formulate specific objectives (improvements) to be met in performing the design process, identify design tools/methods (products of design research) which could potentially meet these objectives, analyze the situation to identify conflicts (coupling) and synergies in the proposed process, and choose the best proposal.

This is the same process which is followed when design is not performed from a blank slate, but rather selection between existing design objects is performed. Here the important consideration is not the synthesis of new methods, but rather the selection of methods which realize specific objectives that have been formulated and which are compatible with each other.

6.1 EXAMPLE

Clausing describes ten cash drains which "plague traditional product development" [3 p. 19] These cash drains were formulated based on product design, the area of Clausing's background. Analogies can likely be found between these problems and problems encountered during other types of design.

In this short case study, two of these cash drains will be used as objectives, to illustrate how design research can be evaluated and selected in the context of industrial practice. The two cash drains are known as disregard for the voice of the customer and pretend design. [3]

We will assume as a prototypical design process the model presented by Wilson [14] (see figure 1). By comparing the descriptions of the above two cash drains with Wilson's model, we can identify the design process steps which have not been performed satisfactorily when the cash drains are found to occur.

When cash drain two (disregard for the voice of the customer) occurs, this is the result of not formulating the problem correctly (the first box in Wilson's model). The solution, therefore, is to perform problem formulation correctly. This is one objective which must be met by the company's design process. When cash drain number four (pretend design) occurs, this is the result of problems with analysis (again see Wilson's model). The objective which may be stated for the company's design process is to perform analysis to ensure that the desired product functionality is met. (Problems with functionality could be the result of two causes: the product design or the process used to produce the product.)

Now that specific objectives for the company's design process have been identified, design research from academia can be evaluated and selected. (In reality, of course, many more objectives than two would need to be identified and tailored to the specific industry or company.)

Table 1 lists the tools provided by each of the research programs discussed in this paper to deal with the two cash drains described above. As can be seen the tools range from principles to organizational/communication aids to collections of knowledge.

7. CONCLUSIONS

Like other types of creation, there are different ways that knowledge can be generated/selected. These can be classified according to their method of evolution as follows:

- Generation of new knowledge, and
- Selection/use of existing knowledge.

We believe that no single theory or method today covers all aspects of the product development activities. However, we have demonstrated that the way to evaluate and select design research for use in a corporate setting is to identify the objectives which need to be satisfied for the company and then to select from among theories which have been developed in academia.

In order to make this possible two things are neccessary: 1) That the company articulates its objectives for product development, and 2) that the design theories and methods are presented in such a way that the company can match its needs with the respective capabilities of each theory and method. This requires advanced, systematised understanding of the design process within the company as well as a more informative label attached to the design theories and methods provided by academia.

8. ACKNOWLEDGMENTS

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Table 1 Tools vs. cash drains

	Cash Drain 2: disregard for the voice of the customer objective: perform problem formulation correctly	**Cash Drain 4: pretend design** objective: perform analysis to ensure desired functionality
Clausing	customer voice deployed to factory floor and to piece parts using QFD and EQFD	competitive benchmarking
Suh	problem formulated in solution neutral language no specific tools to generate requirements	independence axiom ensures basic functionality information axiom selects from available designs the one with the highest probability of meeting functionality
Altshuller	not addressed	tools to avoid psychological inertia technological evolution
WDK school	not addressed	morphological approach generates alternative designs, but no analysis tools for concept selection

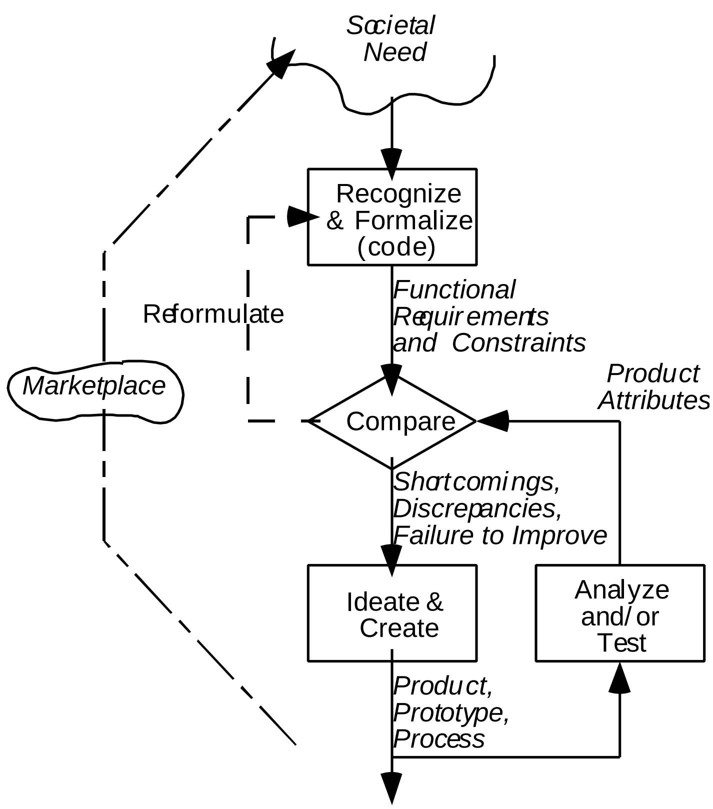

Figure 1 Design Process according to Wilson [14]