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A DESIGN PROCESS ROADMAP AS A GENERAL TOOL FOR STRUCTURING AND SUPPORTING DESIGN ACTIVITIES

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ABSTRACT

The contribution of this paper is a new tool for modeling product development processes. Currently there are two types of process models: ones that are so broad that they describe the activities of any designer but provide no assistance, and ones that are so restrictive that they cannot be an accurate description of actual design practice. The challenge is to create a general model from which the designer can structure a specific implementation of the design process. The general model must be flexible to cover all instances of the design process, yet it must contain enough specifics to be useful in guiding the designer.

This apparent contradiction was solved by segmenting the design process into generic activities, with explicit relationships between them, from which the designer can structure a unique design process. Moreover, the activities are specific enough to support the designer in selecting design tools and methods for each activity, to identify clearly decision points, and to create a good information infrastructure for the process.

The paper contains an overview and an analysis of existing design process models, a new proposed tool for modeling product development processes, and detailed descriptions of the activities in this model.

1. INTRODUCTION

An effective product development process, supported by scientifically validated design theories and tools, is becoming an increasingly useful asset in industry for reducing lead-times and costs as well as for improving quality. However, engineers and managers in industry have not been able to integrate theory and practice into their product development processes because they lack a means by which to match their unique problem situations and activities with available design theories and methods—including, for example, Axiomatic Design [29, 30], Pahl and Beitz's method [22, 23], Quality Function Deployment (QFD) [5], Robust Engineering (Taguchi methods) [24], Structured Analysis and Design Technique (SADT) [27, 28], Theory of Inventive Problem Solving (TIPS/TRIZ) [1], Total Design [25, 26], VDI 2221, and the WDK school (Hubka's theory) [2, 15].

As stated by Cross [6 p. 9], "[W]e lack a successful, simplifying paradigm of design thinking. Those simplifying paradigms which have been attempted in the past—such as viewing design simply as problem-solving, or information-processing, or decision-making, or pattern-recognition—have failed to capture the full complexity of design thinking."

Ross defines a model as " M is a model of A if M can be used to answer questions about A" [28]. This paper presents a model of design process activities for the use of either those interested in implementing product development processes, supported by theories and tools, or for those interested in explaining the events and outcomes of these processes. The purpose of this model is to provide answers to questions such as

- What is a design process model which is flexible enough to include all instances of the design process and which is specific enough to enable designers and managers to integrate available design theories and tools into their practice?
- How can an observed phenomenon in a design process be explained?
- How can design theories and tools be used to better support the activities of the design process?
- What is the context of a current research effort?

To answer these questions specific design activities which comprise all design processes were identified so that practitioners can piece them together in an appropriate sequence. This yields a flexible tool for structuring unique design processes for design situations encountered in industry, yet the tool is sufficiently specific to allow mapping of theories and methods to activities. It can also be used in academia to identify new research questions and to place research in a context useful for industry.

2. THE DESIGN PROCESS

The design process is the set of activities by which designers develop and/or select the means to achieve a set of objectives, subject to constraints. The design process may entail the creation of a new solution, the selection of an existing solution, or a combination of the two. A series of activities are performed by which customer perception of a problem is transformed into an output—the design object, which is any satisfactory solution to this problem. The transformation occurs by means of designers working with design tools/methods, with their knowledge of discipline-specific information, and with a set of available resources.

2.1 CHARACTERISTICS OF THE DESIGN PROCESS

All key characteristics of the design process must be included in a model to enable practitioners to make project plans which effectively use all available resources, methods, and tools. These characteristics must be included in the model in the sense that the model must explain, predict, or allow for explanation or prediction based on these characteristics[1]. The characteristics are

1. **Decision making**. The purpose of the design process is to make decisions, specifically to find a solution (in terms of a design object) to some design problem. Thus, clearly defined decision points and decision criteria (and/or rules) must be visible in the process.
2. **Performance measures.** Performance of the design process is evaluated against the quantity of resources (time, costs) used to satisfy the objective (i.e., solve the design problem). An activity is evaluated against the resources expended to produce completely its outputs.
3. **Iteration**. The design process includes iteration. That is, similar activities are performed at different points (historical times) in the design process. (This iteration is distinct from that arising due to re-solving the same design problem multiple times.)
4. **Sequence of activities**. Although the individual activities performed are similar throughout the design process, they may be sequenced in different ways.
5. **Levels of scope and levels of abstraction**. The design process deals with problems at multiple levels: levels of scope (a measure of the amount of impact the problem has on the overall design) and levels of abstraction (a measure of how conceptual or how detailed the problem is).
6. **Information management**. Data about the design object is collected, generated, used to make decisions, and stored. The information gathered varies in certainty, quantity, and relevance for current and future use.

[1] The list of key characteristics of the design process was established by performing industrial case studies and by researching published papers [2, 3, 6, 11, 13].

2.2 EXISTING MODELS OF THE DESIGN PROCESS

Other researchers have reviewed models of the design process, and the models have been generalized into different categories. For extensive references in the field of design theory, the reader is referred to references [8, 11, 15, 18, 31] among others. Two prominent reviews of design research have classified models of the design process according to whether they are descriptive, prescriptive, or computer-based [10, 12].

The distinction between prescription and description is said to be the following: "Some...models [of the design process] simply *describe* the sequences of activities that typically occur in designing; other models attempt to *prescribe* a better or more appropriate pattern of activities." [9 p. 19]

As can be seen by understanding the relation between science and underlying reality, as applied to design theory [20], the distinction between prescription and description is determined by the use to which consequences derived from a theorem are put. That is, these statements may be used to explain, to predict, or to test. Thus, particular research results may be descriptive, prescriptive, or theory-building, but the theory underlying them may be applied to any of these three uses.

In this section we will follow the analysis of Evbuomwan [11 pp. 311-312] to discuss the effectiveness of existing design process models in matching reality. In this analysis, design process models may be grouped into two classifications: those which are based on activities and those based on the phases of design object evolution. These two classifications are shown in table 1.

Table 1. Some existing models of the design process [after 11]

Activity-based models	Phase-based models
Archer	Asimow
Cross	Clausing [5]
Harris	French
Jones	Hubka
Krick	Pahl and Beitz
Marples	Pugh [25]
Wilson [34]	Ullman [33]
	VDI 2221
	Watts

Activity-based models (analysis-synthesis-evaluation cycle)

One view, represented in the literature, is that the design process consists of repeated iterations of three activities. The names ascribed to these activities may vary, but are commonly analysis, synthesis, and evaluation. In these models, additional activities observed by Evbuomwan included "optimization, revision, data collection, documentation, communication, selection, decision making, modeling, etc." [11 p. 312], yet the three key activities predominate. They may be defined as the following [16]:

1. Analysis deals with understanding the design problem and generating the requirements and the specifications.
2. Synthesis deals with generating ideas and solutions by exploring the design space.
3. Evaluation deals with the appraisal of design solutions against the requirements, specifications, and "set corporate criteria." [11]

Phase-based models

Phase-base, sequential models of the design process tend to emphasize the progression of the design in terms of the amount known about the details of its implementation—its physical embodiment. The phases may be augmented with more specific activities or steps as in the activity-based models [23, 11].

The model by Pugh describes the sequence of design activities as following a central design core. This core "consists of [activities which produce or identify] market (user need), product design specification, conceptual design, detail design, manufacture and sales." [25 p. 5] Similarly, in the model of Pahl and Beitz, these phases of the design process are described by the following [22 pp. 40-42]:

1. **Planning and clarifying the task** (specification of information in a requirements list): The market, the company, and the economy are accounted to create and select suitable product ideas. Then, requirements and constraints are formed into a requirements list.
2. **Conceptual design** (specification of principle): The objective of this phase is to determine the principle solution. To do this, the essential problems are abstracted; function structures are established; suitable working principles are sought; a working structure is synthesized; and lastly solution concepts are evaluated against technical and economic criteria.
3. **Embodiment design** (specification of layout): In this phase a working principle is elaborated in the form of preliminary layouts which are then evaluated and rejected and/or combined to produce a definitive layout.
4. **Detail design** (specification of production): In this phase all production documents are produced.

These phases must be qualified with two disclaimers. First, a clear border cannot always be drawn between these phases, and second, it is not possible to avoid backtracking [23 p. 65]. The reasons why these are so are explained in the next section.

Comparison with desired characteristics

The two types of models for viewing the design process may be compared against the desired characteristics of a design process model outlined in section 2.1. When such a comparison is done, the strengths and weaknesses of each model type become apparent. See table 2.

The strengths of the activity-centered models are that they acknowledge the primacy of making decisions, within the design process, in order to meet needs. Furthermore, given an understanding of the products of each activity, an evaluation of the performance of each activity may be made in terms of the resources expended to complete the activity. Iteration in design is clearly indicated in some of these models (see [9, 34]); however, the models tend to emphasize repeated evaluations of multiple concepts. Thus, they do not acknowledge the iteration or repetition of activities at multiple levels of the same design. Lastly, the information management consists of producing information such as lists of factors, interaction matrices, partial solutions, and combined solutions.

Phase-based models emphasize two things concerning the information produced about design objects: first its progression from abstract to detailed, and second its increasing quantity. Understanding of the design problem is weighted to the front end of the process, and the solution of this problem may become divorced from the production of solution details. The documents that are produced tend to evolve as the design progresses; thus, since they lack a clear endpoint, it is difficult to measure the resources expended to perform each task. Furthermore while repetition, or revisiting, of a phase is undesirable because it tends to change design details produced, it is acknowledged to occur in practice frequently.

Table 2. Strengths and weaknesses of design process models

(key: ✓=strength, ⊕=passable, ×=weakness)

Characteristic	Activity	Phase
1. Decision making	✓	×
2. Performance measures	⊕	⊕
3. Iteration	⊕	×
4. Sequencing of activities	×	×
5. Levels of scope & abstraction	×	✓
6. Information management	⊕	✓

The discussion above explains why often neither approach may be used to trace the progression of a design in an effective manner. This result occurs because the progress of the design process does not match its description in the model. Thus these models function as ideal cases only and are not useful for describing what was actually done.

Looking at typical models of the design process, Bucciarelli has concluded that "[t]o anyone interested in process, these diagrams shed very little light on how design acts are actually carried out or who is responsible for each of the tasks within the various boxes. Nor is it apparent what these participants need know, what resources they must bring to their task, and, most important, how they must work with others." [4 pp. 112-113]

The conclusion of this section is that a new model of the design process is needed which accurately describes the sequence of activities performed and which may be used to guide designers more effectively .

3. PROPOSED MODEL OF THE DESIGN PROCESS

The design process model presented in this section is an abstraction and generalization of several design processes that were studied in European and US industries [21, 32]. In the model, terminology from axiomatic design [29, 30] has been used in order to identify consistently the information developed during and transferred between the activities.

3.1 PROPERTIES OF THE DESIGN PROCESS MODEL

The design process model consists of a collection of distinct activities with clear starting and end points. Each activity is the transformation of inputs to outputs. These activities can be sequenced in many ways. The activities are to be fit together into a project-specific design process. Each project will have its unique sequence, depending on its status, scope, and goals.

Figure 1, shows all activities and the possible links between them in a design process roadmap. This model should enable the explanation of the decisions regarding the sequence of activities of any design process. The design process model consists of a set of activities: project control and decomposition, analysis of an existing solution, problem formulation, decoupling, concept generation and analysis, trade-off, and implementation.

The start of a design process (i.e., project) is at the left side of figure 1. Here, customer needs and constraints imposed by the customer and the environment are the input. At the end of the design process, at the right of figure 1, a solution is specified in terms of product and implementation (i.e., manufacturing) details.

3.2 DESCRIPTION OF GENERIC ACTIVITIES OF THE DESIGN PROCESS MODEL, AND THEIR PROBLEM SITUATIONS

This section contains a detailed description of each activity in the design process model in figure 1. Each description explains the activity's purpose, inputs, outputs, and typical questions encountered in the activity.

3.2.1 PROJECT CONTROL AND DECOMPOSITION

Project control and decomposition is the activity in which the scope of and controls on the design project are established. In a design project, this activity will be revisited multiple times. This activity will be performed when it is necessary either to plan 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 decided. Typical questions of 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 subproblems?

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 in an ongoing design project, the inputs will be descriptions of the design object at the current level of abstraction and a description of problems which have occurred, if any.

Outputs of this activity are project goals, constraints, and instructions on for conducting the design project through performing a sequence of activities.

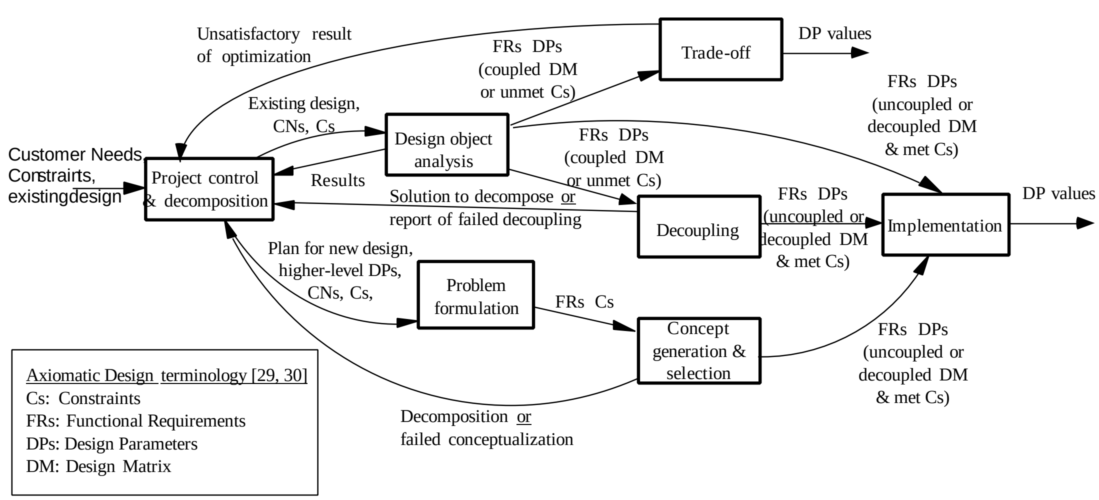

Figure 1. The design process roadmap

3.2.2 *ANALYSIS OF AN EXISTING SOLUTION*

Analysis of an existing solution (design object analysis) presupposes an existing design object about which there are questions regarding functionality or feasibility. The analysis may follow a specific approach, for example, axiomatic design [29], functional analysis (value engineering) [19], or TRIZ [1]. It is often a central activity in feasibility studies where the results of this activity can be fed back to the project control 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 of this activity include the following:

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

In design object analysis, there are two inputs: an understanding of the customer needs, and an existing design to analyze. The output of this process is a description of the design in terms of its functions, constraints, physical implementation, and functional independence (or dependence).

3.2.3 *PROBLEM FORMULATION*

The activity of problem formulation is performed when the objective of the designers is to create a new or innovative solution to a design problem. This is done when the project resources allow the flexibility to select a new or an innovative solution. This could be sought because of a new, previously unsolved, design problem. Or, it could be sought because customer needs have changed and an analysis of the existing solution has shown that the current solution is 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 on an acceptable solution (imposed by the customer or by the company)?

Problem formulation involves translating information from the customer—in terms of customer needs and constraints—into a necessary and sufficient functional description of a design object which will meet these needs. If the current design problem is at an intermediate level of the design hierarchy, then during problem formulation, the functional description is produced, given the decisions made at previous levels about the physical embodiment of the design object.

The inputs for problem formulation are customer needs and constraints at the current level of the design hierarchy and, if applicable, decisions about the physical embodiment of the design from previous levels of the hierarchy. The outputs of problem formulation are a set of FRs and Cs which are then the input for the conceptualization activity.

3.2.4 *DECOUPLING*

Decoupling (conflict resolution) is one possible follow-up activity after design object analysis in the case where the result of the analysis shows that the existing design object does not satisfy Suh's independence axiom (see [29]). (The other alternative in this case is the trade-off activity, described below.) The desired output of the decoupling activity is an uncoupled or decoupled design and is sought by applying problem-solving strategies for conceptual design (e.g., Altshuller's principles [1], su-field analysis [1], Suh's theorems [29], etc.).

Often, decoupling is performed when the designer must improve the design's performance, but the designer does not have the freedom to make major changes to the design. Typical questions that this activity is intended to answer include these:

- What modifications to the design object would ensure functionality?
- How can the conceptual solutions be implemented better to meet the constraints?

The input to this activity is a description: either of a design or concept that is coupled or of a design object that does not satisfy its constraints. In the first case, the design object does not perform its functions satisfactorily, in the second case, the design object performs its intended functions, but the physical solution is unacceptable for another reason (e.g., it is too big, or too heavy, or it does not meet some legal requirement, etc.).

The preferred output of this activity is a description of a design object, or concept, that is functionally uncoupled and which meets all its constraints. With this result, the designer decomposes the design further into subprojects (in project control and decomposition), or the designer progresses to implementation.

In cases which produce an unsatisfactory (coupled) design, a report of the activity's failure is the input then for a repetition of the project control.

3.2.5 *CONCEPT GENERATION AND SELECTION*

Concept generation and selection (conceptualization) always follows problem formulation. The objectives of the conceptualization activity are

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

Hence, this activity is supported by concept generating (synthesis) tools and by concept selection (analysis) tools. Typical questions addressed during this activity include the following:

- Given a set of functions, what are possible solutions?
- What are different ways can this problem be solved?
- Will this concept work?
- Which concept should be chosen, and why?

- How can conceptual solutions be physically integrated while achieving their functions?

Concept generation tools include brainstorming, databases, etc., while analysis tools include the design axioms [29], group decision making, Pugh concept selection [25, 26], and other design rules. Suh illustrates this activity as a feedback control loop (see figure 2) and emphasizes the complementary nature of synthesis and analysis: "If we cannot analyze a design solution, then we cannot rapidly generate the 'best' design since we cannot distinguish a good design from a bad design." [29 p. 7]

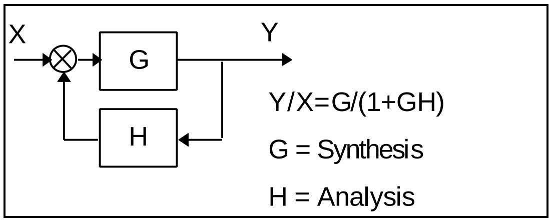

Figure 2 Feedback control loop depicting synthesis and analysis during conceptualization, from [29 p 7]

Inputs to this activity are a set of functional requirements (FRs) and constraints. Outputs are a set of FRs, constraints, design parameters (DPs), and design matrices (DMs) which show the functional dependencies within the design object.

3.2.6 TRADE-OFF

The objective of the trade-off activity is to get the best possible performance out of a design which does not satisfy Suh's independence axiom (see [29]). (The implementation activity concerns determining parameter values for designs which do satisfy the independence axiom and is described below.)

The trade-off activity becomes necessary when an existing design has been found to have inherent problems, but no changes to the concept may be made other than small changes to some DP values. In this situation, the trade-off activity entails setting the design parameters to values that, as closely as possible, provide the desired functionality. 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 that can be achieved with this design?

The input to this activity is a unacceptable design (not independent or not meeting its constraints) described in terms of functional requirements, constraints, design parameters, and design matrices. Outputs of this activity are functional requirements, constraints, design matrices, and design parameters that are set at their optimal values given that they are a part of a design which does not satisfy the independence axiom.

3.2.7 IMPLEMENTATION

The implementation activity is the desired final activity for any design project. The key difference between implementation and trade-off is that when implementation is performed, the analyses during the design process have shown that all functional requirements can be achieved because the design satisfies Suh's independence axiom. A typical question for this activity is

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

Inputs to tuning are functional requirements, constraints, design parameters, and uncoupled or decoupled design matrices. Outputs for this activity are functional requirements, constraints, design matrices, and design parameters that are tuned to provide optimal functionality for this design object.

3.3 CONNECTING THE ACTIVITIES

The design process roadmap described in this paper consists of a set of activities as described in the previous sections. These activities are project control and decomposition, analysis of an existing solution, problem formulation, decoupling, concept generation and analysis, trade-off, and implementation.

A design process (project) begins with the project control activity at the left side of figure 1. Here, customer needs, constraints imposed by the customer or the environment, and any existing solutions are the inputs. At the end of the design process, the final activity is either trade-off or the implementation activity in which a solution is specified in terms of a design object and its implementation (drawings, models, and manufacturing) details. If no solution—at all—can be found, a decision is made during an instance of the project control activity to terminate the project.

The specific path which is followed between the starting and the end points is the responsibility of the design team. The preferred outcome of the project is to reach the end of the implementation activity—and thus be done with the whole project—as quickly as possible.

Each time an activity is completed, a decision is made about the progress of the design. By understanding the desired outcomes of the various activities as described in the model (FRs, DPs, uncoupled/decoupled DM, etc.) and by comparing these with the actual outcomes, decisions can be made as needed and can be based firmly on concepts of independence and minimum information (maximum probability of success) [29].

Often the choice to perform one activity over another if performed successfully will allow the design team to reach its goal in less time with better results. For example, the choice to decouple a design, as opposed to performing a trade-off, will—if successfully done—allow a design to be implemented which satisfies the independence axiom. Trade-off, on the other hand, is a much more involved and iterative process which is not guaranteed to yield a desirable result.

4. CONCLUSIONS

Existing design process models have shortcomings in that they either cannot be adjusted to reflect an actual design process or do not provide sufficient specificity to support the practitioners in this design process. Thus, a new tool for structuring and explaining the product development process has been introduced. It consists of a roadmap of specific design activities that can be assembled to describe any unique design process.

The tool is possible to implement in software. This will enable designers to create a instance of the design process by selecting activities from the roadmap. The model generated in the software will support managing and implementing the design process and the information generated within it. At any time, the designer will be able to identify the stage at which the project is and can be supported by software based on design theories and tools appropriate for the stage. At MIT, a software based on axiomatic design that will support the conceptualization, problem formulation, design object analysis, and decoupling activities is currently being developed [14].

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