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**VALUE BASED DESIGN:
AN OBJECTIVE STRUCTURING APPROACH TO DESIGN CONCEPT GENERATION**

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ABSTRACT

Conceptual design is an important early stage activity of engineering design. The decisions made at the conceptual design phase commit up to 70% of the production cost and have significant impact on the downstream design and manufacturing processes. While computer tools have been developed to support design analysis and information management at the later stages of design, generating good design concepts and making smart decisions in conceptual design still largely depend on designers' experience. Our research takes a value-based approach to conceptual design and proposes a set of specific methods and guidelines for designers to identify, structure their design objectives and use the objective structure to guide their concept generation process. This paper describes the proposed objective driven approach to design concept generation and presents a design example to demonstrate the effectiveness of the approach.

Keywords: Conceptual design, methodology, decision-making, objective, value

1 INTRODUCTION

In the field of design research, researchers have realized the growing need for formal structures and methodologies to improve the current practice in the early stages of engineering design and to provide computational support for it. While various computer tools have been developed to support design analysis and optimization at the later stages of design, generating good design concepts and making smart decisions at the early stage of design are still largely experience based.

Conceptual design as an early stage activity of engineering design transforms customer needs into engineering characteristics and yields solution principles of the final

product through generation and selection of the design concepts. The decisions made at the conceptual design phase commit about 70% of the production cost and have significant impact on the downstream design and manufacturing processes [12]. Given a set of design requirements, finding a design concept that satisfies the requirements in the most effective ways is a challenging task. To cope with this difficulty, our research takes a value-based design (VBD) approach to conceptual design and proposes specific methods and guidelines for designers to identify and structure their design objectives and use the objectives to guide their concept generation and selection process.

Following Keeney's Value Focused Thinking [4,5], the basic idea behind our VBD approach is that the design value specifies what is important to the designer; it is, and should be, what the designer cares about; therefore, the design value should be the driving force for both design concept generation and design decision making. In order to make the design value explicit at the early stage of design, we further define design value as a set of structured design objectives and propose a design objective driven approach to supporting design concept generation. We believe that focusing on design objectives provides a clearly defined *value space* for designers, which can lead them to generating more and better design concepts.

In the existing body of design research, several different design methods have been proposed to support design concept generation. Systematic Design method [9] is based on the idea that the design process should be carefully planned and systematically executed. In this method, the design process is divided into 4 main phases: product planning & task clarification, conceptual design, embodiment design and detailed design. During the conceptual design phase, function structures are developed and a morphology chart based method

is applied to generate multiple variants of the design concept. Although many principles and guidelines are provided for embodiment design in the systematic design approach, few are available for conceptual design. Furthermore, the evaluation of generated design concepts (variants) is carried out in an *ad hoc* fashion. Axiomatic Design [10, 11] proposes a zigzag design process across four design domains, i.e., customer domain, function domain, physical domain and process domain. Two important axioms—i.e., independence axiom and information axiom—are introduced for designers to choose among alternatives during the zigzag design process. One important feature of axiomatic design is that most decisions are made during the decomposition process of, and the mapping process between, FRs (i.e., functional requirements) and DPs (i.e., design parameters) so that at the end there is only one design concept resulting from the zigzag process. While the axioms help designers choose among alternative decompositions, generating the decomposition ideas is still experience based. Furthermore, the evaluation of the final design concept is rather implicit and embedded in the axiom-based selections of FRs and DPs. QFD (quality function deployment) [2] is another well-known design method, which uses matrices to transform information of the customer needs drawn from market research and benchmarking data to product characteristics and design variables and so on. The strength of QFD is that it clearly captures dependencies between the concepts generated at different stages of design so that the impact of any design change at the later stage can be traced back to the requirements and customer needs set at the early stage of design. Again, QFD provides little guidance for idea generation and the evaluation of design concepts are mostly *ad hoc*. In comparison with the above-mentioned methods, TRIZ [1] method focuses more on providing principles for solution generation. However, how to evaluate the solutions is less a concern. Our previous research on VBD [6, 7, 8] illustrated the significance of developing design objective structures in guiding the conceptual design function space exploration. It suggested that developing design objective structures stimulates designers to think systematically about what is important for them in the design process, before diving into searching for design function combinations, which could lead to sub-optimal design solutions.

To summarize, the existing conceptual design methods provide clear processes but relative little guidance for designers to generate design concepts. Furthermore, the evaluation of the generated concepts is mostly *ad hoc*. Our key research question is: *How can we develop a design framework that provides both a systematic design process for design space exploration (i.e., design concept generation) and a rigorous evaluation scheme for choosing design concepts?* Our long term goal is to develop a systematic method to guide value-based design concept generation and evaluation. As the first step toward this goal, in this paper, we focus on objective driven function decomposition. In the following, we first introduce our

proposed framework, methods and guidelines, and then present a case example to demonstrate the proposed VBD approach.

2 A FRAMEWORK OF VALUE BASED DESIGN

Conceptual design is difficult because both the design problem and the design space are to be defined. A designer must address three fundamental issues: 1) what do I want to achieve (i.e., problem framing and value definition); 2) how can what I want be achieved (i.e., alternative generation); and 3) how good is a chosen design concept (i.e., alternative evaluation). Traditional methods deal with these three issues by explicating customer needs, product functions and solution principles. The designer's experience plays a key role in determining the extent of both the "value space" (i.e., the extent of "what I want") and the "design space" (i.e., the extent of "how can I achieve what I want"). In our research, we emphasize "what I want" (i.e., the design value) and attempt to provide means for designers to explore the value space and design space simultaneously. In order to clarify the concepts and their relations involved in conceptual design so that the design methods and guidelines can be developed, we introduce the definitions and nomenclatures in terms of the set theory.

2.1 Design value and design objectives

A designer's design value in general specifies what is important to the designer. It is used to guide alternative generation and evaluate the consequences of specific alternatives. Generally speaking, design values can be expressed as general principles, such as *minimizing use of materials*. For a given design problem, however, design values can be made explicit by identifying design objectives within that design context. A design objective is a statement of some aspect of the design product that the designer desires to achieve. Designers often have to consider multiple, and sometimes competing, design objectives. Using the concept of objective, a designer's design value can be manifested by a set of design objectives. In order to define the concept of design objective, we first introduce the following definitions.

Definition 1: Purpose

A design *purpose*, denoted by $p \in P$, is an area of concern in a given design situation. For a specific design domain, P represents a complete set of all areas of concern. ■

For example, in the vehicle design domain, 'passenger comfort', 'manufacturing cost' and '0-60mph acceleration time' are typical areas of concern.

Definition 2: Entity

An entity, denoted by $e \in E$, is a physical object or a feature of a physical object that can be considered in a design domain. $E = E_p \cup E_f$, where E_p and E_f are physical entity set and feature entity set, respectively. ■

A motor can be a physical entity, while the weight and size of a motor can be feature entities.

Definition 3: Action

An action, denoted by $a \in \mathbf{A}$, is an active behavior that can be performed by one physical entity upon another one or more physical entities. For a given design domain, \mathbf{A} is a complete set of all actions that can be considered in the domain. ■

Definition 4: Function

A function, denoted by $f \in \mathbf{F}$, is generally defined as

$$f = \{a, e\}, \quad \text{where } a \in \mathbf{A}, e \in \mathbf{E}_p \quad (1)$$

that indicates the situation where an entity e is acted upon by an action a of a unspecified physical entity. Since the goal of action is often to change features of a physical entity, we have a *specific* form of function:

$$f = \{a; e_f, e_p\}, \quad \text{where } a \in \mathbf{A}, e_f \in \mathbf{E}_f, e_p \in \mathbf{E}_p \quad (2)$$

that indicates the situation where the feature e_f of entity e_p is modified or changed by action a . ■

For example, ‘clean teeth’ is a general form of function, and ‘clean surface of teeth’ a specific form of function.

Definition 5: Context

A design context, denoted by $c \in \mathbf{C}$, is defined as

$$c = \{e_p, \text{design-related-action}\}, \quad \text{where } e_p \in \mathbf{E}_p \quad (3)$$

that indicates the situation where the physical entity e_p has been identified by the designer as a product or a component of the product to be designed. ■

For example, ‘vehicle design’ is a broad context. Its sub-contexts may include ‘engine design’, ‘body design’, ‘body-structure analysis’, and ‘suspension design’ etc.

Given the above concepts, we can now define design objective as follows.

Definition 6: Design Objective

A design objective, denoted by $do \in \mathbf{DO}$, is defined by

$$do = \{d, p, c; T, u\} \quad (4)$$

where

$d \in \{\text{maximize, minimize}\}$, the direction of the objective,

$p \in \mathbf{P}$, the purpose of the objective

$c \in \mathbf{C}$, the context of the objective.

$T = \{t_1, t_2, \dots\} \subseteq \mathbf{E}_f$, the attributes of the objective for measuring the degree to which an alternative achieves the design objective. For a given design objective, there can be one or more attributes. Each attribute must be associated with a measurable unit. For example, the *purpose* ‘maximize passenger comfort’ can be measured

by *attributes* ‘noise level (db)’, ‘vibration level (Hz)’, and ‘leg room (inch)’.

u , value function; contains the value function that maps the measured attributes into a single scalar number indicating the relative desirability of the achievement of the objective and can be used to derive preferences for design alternatives. ■

Based on the above definitions (4) and (3), the *value space* for a given design domain can be defined by

$$\begin{aligned} \mathbf{DO} &= \{\text{maximize, minimize}\} \times \mathbf{P} \times \mathbf{C} \\ &= \{\text{maximize, minimize}\} \times \mathbf{P} \times \mathbf{E}_p \end{aligned} \quad (5)$$

In this paper, we adopt an easy-to-understand form for describing objectives:

$$\langle \text{max/min} \rangle \langle \text{purpose} \rangle \text{IN} \langle \text{context} \rangle \text{MB}(\text{measured-by}) \langle \text{attributes} \rangle \text{EB}(\text{evaluated-by}) \langle \text{value-function} \rangle.$$

For example,

$$\begin{aligned} &\langle \text{max} \rangle \langle \text{passenger-comfort} \rangle \text{IN} \langle \text{car-design} \rangle \text{MB} \langle \text{noise-level (db), vibration-level (Hz), leg-room (inch)} \rangle \text{EB} \\ &\langle u(\text{noise-level, vibration-level, leg-room}) \rangle. \end{aligned}$$

In practice, it is often the case that the definition of a specific design objective is initially incomplete. In these cases, a design objective can take short forms, e.g.,

$$\langle \text{dir} \rangle \langle \text{purpose} \rangle \text{IN} \langle \text{context} \rangle, \quad \text{if } T \text{ is not available; or}$$

$$\langle \text{purpose} \rangle \text{IN} \langle \text{context} \rangle, \quad \text{if } \text{dir} \text{ is also explicitly known; or}$$

$$\langle \text{purpose} \rangle, \quad \text{if } \text{context} \text{ is also explicitly known.}$$

2.2 Functional objectives and product objectives

The design objective definition described above provides a means to represent designers’ values. To assist designers identify their design objectives and develop design concepts, we differentiate between function objectives and product objectives by separating purposes into the *function* and *product* categories. We have,

$$\mathbf{P} = \mathbf{P}_{fun} \cup \mathbf{P}_{prd} \quad (6)$$

$$\begin{aligned} \mathbf{DO}_{fun} &= \{\text{maximize or minimize}\} \times \mathbf{P}_{fun} \times \mathbf{C} \\ \mathbf{DO}_{prd} &= \{\text{maximize or minimize}\} \times \mathbf{P}_{prd} \times \mathbf{C} \end{aligned} \quad (7)$$

The *function purposes* and *function objectives* are always associated with *functions* and indicate the concern of the result of the corresponding actions. For example, from function $\langle \text{clean} \rangle \langle \text{teeth} \rangle$, we can derive the function purpose of $\langle \text{cleanness} \rangle \langle \text{of} \rangle \langle \text{teeth} \rangle$ and hence the function objective of $\langle \text{maximize} \rangle \langle \text{cleanness} \rangle \langle \text{of} \rangle \langle \text{teeth} \rangle$. As will be discussed below, clarifying function objectives provides a wide design space for generating design alternatives.

On the other hand, product objectives define desired properties of the overall product. We further divide product

objectives into *physical*, *lifecycle*, and *economic* categories, again based on different types of purposes. We have:

$$DO_{prd} = DO_{phy} \cup DO_{lfc} \cup DO_{eco} \quad (8)$$

Physical objectives (DO_{phy}) represent expectations on the physical and embodiment features of a design outcome. For example, $\langle \text{min} \rangle \langle \text{curb-weight} \rangle \text{IN} \langle \text{car-design} \rangle$ is a physical objective. *Lifecycle objectives* (DO_{lfc}) are composed of *ergonomic* or *operational objectives*, *maintenance objectives* and *environmental objectives*. Finally, *economic objectives* (DO_{eco}) are the ones that define a designer's expected profit or cost of the design consequence. For example, $\langle \text{minimize} \rangle \langle \text{cost} \rangle \text{IN} \langle \text{vehicle manufacturing} \rangle$ is an economic design objective.

The design objective categories identified above are intended to help designers capture all possible design objectives. While having design objectives from each of the above categories in a design process is not necessary, the categories do provide directions for designers to look for their design objectives and it is always desirable to make all relevant design objectives explicit throughout the design process. Designers should treat the elicitation of design objectives a major part of their design work.

Unlike later stages of design where the major task is to decide on the details (e.g., parameter values) of known design concepts, a designer doing conceptual design must *generate* as many as possible solution concepts and then *select* good ones for further design. It is worth mentioning that in VBD the functional objectives provide a space for designers to generate design concepts and the product objectives serves as the criteria for selecting the good ones.

2.3 Value based design process

In our proposed VBD approach, the design value, i.e., the design objectives, is at the center of the design process. Figure 1 highlights our proposed design process. Details of the process will be discussed in the following sections.

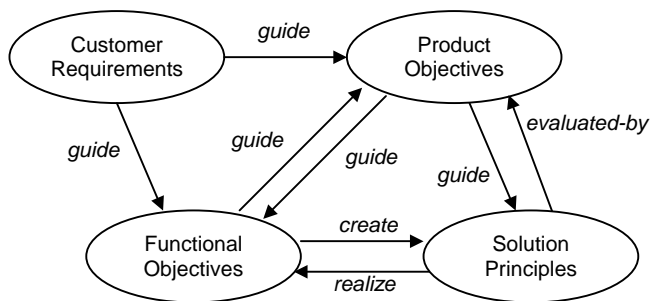


Figure 1: A Value based design process

As shown in Figure 1, the VBD design process starts from collecting customer requirements. Based on the customer requirements and the designer's own preference, both the functional objectives and product objectives are developed and

structured. The functional objectives must be realized by solution principles, and the functional objective structure itself constitutes a large space for identifying such solution principles. At the same time, not all designs are good designs. The product objectives are developed and structured to evaluate and select the superior design concepts. The design objective categories described above allow designers to examine each aspect of the product and identify their preferred product objectives.

There are two challenging questions for realizing the above VBD process: 1) *how can we help designers identify and structure their functional and product objectives*, and 2) *how can the objective structures help designers generate more and better solution principles?* We address the first question by introducing a set of objective structuring methods and guidelines. The second question has two components involved. One is generating function structures, and the other is to generate solution principles to fulfill the functions. The former will be discussed in Section 4 through a case example. The solution principle generation issue will be addressed in our future publications.

3 DESIGN OBJECTIVE STRUCTURING

The first step in design objective structuring is to convert the given customer requirements into a number of high-level design objectives. The initial major functional objectives can be derived from the initial major functions. For example, in designing a device to sample lake water at a given depth [9], the top-level function and major functions can be developed as shown in Figure 2. By transforming the 'actions' of the functions into 'actional (or functional) purposes', we can have three top-level function objectives shown in Figure 2(b).

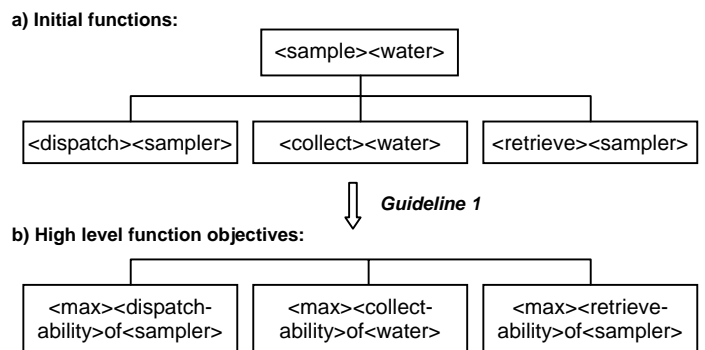


Figure 2: Derived top level functional objectives from initial functions

It is important to note that functional objectives are different from functions in that the former can have attributes to measure its achievement. For example, 'dispatch-ability' can be measured by 'speed', 'accuracy of location' etc., while 'dispatch' cannot be measured.

Guideline 1: Derive function objectives from functions

For a given function $\langle \text{action} \rangle \langle \text{entity} \rangle$, its functional objective can be described as $\langle \text{maximize} \rangle \langle \text{action} \rangle$

ability>of<entity>, where <action-ability>of<entity> is a functional purpose. ■

Guideline 2: Use specific form of functions

For a given function <action><physical-entity> (e.g., <test><specimen>), if possible, try to make it into a specific form of <action> <feature-entity> of <physical-entity> (e.g., <test><deformation>of<specimen>). ■

To generate initial product objectives, a designer can examine each category and generate ones that are considered important. For the lake water sampler example, Figure 3 illustrates examples of possible initial product objectives.

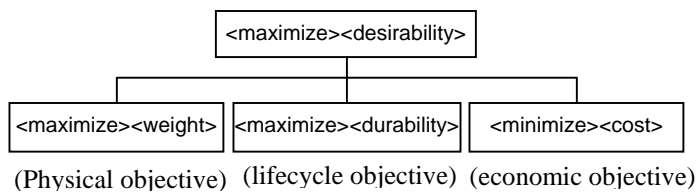


Figure 3: Generate product objectives from categories

Guideline 3: Use product objective categories

To generate initial set of product objectives, try to generate at least one objective in these categories: *physical objectives*, *lifecycle objectives* (including ergonomic operational, maintenance & environmental), and *economic objectives*. ■

3.1 Elaborate high-level design objectives

To introduce general elaboration methods, assume a higher-level object *obj* is to be elaborated. The *obj* can be a function, action, purpose, context, physical entity, or feature entity. Our general elaboration methods are the following:

Method 1: Decomposition

For a given object *obj*, if $obj = \{obj_1, obj_2 \dots\}$ then $obj \xrightarrow{decompose} \{obj_1, obj_2, \dots\}$ ■

Method 2: Requirement

For a given object *obj*, if *obj* requires $\{obj_1, obj_2 \dots\}$ to co-exist, then $obj \xrightarrow{require} \{obj, obj_1, obj_2, \dots\}$ ■

Method 3: Refinement

For a given object *obj* and $obj = \{obj_1, obj_2 \dots\}$, if the concern over *obj* is really the concern over *obj₂*, then $obj \xrightarrow{refine} obj_2$. ■

When elaborating a specific *function*, *action*, *purpose*, *context*, or *entity*, the above three general methods may be applied in combination and repeatedly at different level of the elaboration hierarchy. A designer can apply the above general

methods to design objective elaboration based on the following guidelines and steps.

Guideline 4: Elaborate objective components

For a given design objective <obj> = <dir><purpose>IN <context>, elaboration of its components <purpose> or <context> leads to elaboration of the objective <obj>. ■

Guideline 5: Ask questions

To apply the general methods to elaborating a specific <purpose> or <context>, the designer should ask following questions: How to measure the <purpose>? What is important to measure the <purpose>? Does this <purpose> or <context> “require” any other <purpose> or <context> to co-exist? Is the concern over the <purpose> or <context> actually the concern of a specific part of it? ■

3.2 Functional objectives and function decomposition

The methods and guidelines mentioned above are general and apply to developing both functional and product objective structures. Given the close relationship between the functional objectives and the function structure, our next question is “how can the functional objective structure development help function structure development and vice versa?”

As shown in Figure 1, functional objectives are especially important because they are directly related to the generation of design concepts. Following Pahl and Beitz [9], in our research we consider a two-stage design concept generation process. The first stage is functional design in which a top-level abstract function is elaborated hierarchically into lower level implementable sub-functions. During the second stage of design concept generation, specific design solutions or principles are identified to fulfil the sub-functions and finally combined into design concepts. In axiomatic design [10], function decomposition is guided by the decisions made in the design parameter (i.e., solution principle) domain. The decision on how to implement or realize a higher-level function provides useful information for how to decompose the function.

In our VBD approach to design concept generation, we propose that function decomposition should be guided by functional objectives. That is, in order to decompose a higher-level function F, we must know exactly *what do we want to achieve* for this function. This functional objective information together with its measurable attributes provides a rich context for designers to think about possible sub-functions. For example, to decompose <dispatch><sampler>, a designer should look into the functional objective <maximize><dispatchability>of<sampler>. The examination of the attributes of this functional objective should lead to the development of sub-functions.

Guideline 6: Generate sub-functions based on attributes

For a given functional objective <maximize><action-ability>of<entity> (see Guideline 1 and Guideline 2), identify

all possible attributes for measuring the achievement of the functional objective. For each attribute, ask the question: “what needs to be done in order to achieve this attribute?” The answers to this question provide insights for generating possible sub-functions. ■

Based on the above Guidelines and Methods, we can describe the steps for function objective structuring and function structure development as follows (see Figure 4).

Step 1: Derive function objectives from functions

The functional objectives can be derived from the functions by following Guideline 1.

Step 2: Identify attributes of function objectives

A function objective usually can be measured by a number of attributes. Therefore, the designer should identify a set of attributes for the functional objective using Guideline 5 and possibly Methods 1 through 3.

Step 3: Generate sub-functions based on attributes

Generate sub-functions based on the attributes by following Guideline 6. The identified attributes of the functional objectives can help designer generate sub-functions. Each attribute associated with a functional objective provides insights on the important aspects of the design process and can guide sub-function generation.

Step 4: Derive lower functional objective from sub-function

The lower level functional objectives can be derived from a set of generated sub-functions in the same way as step 1.

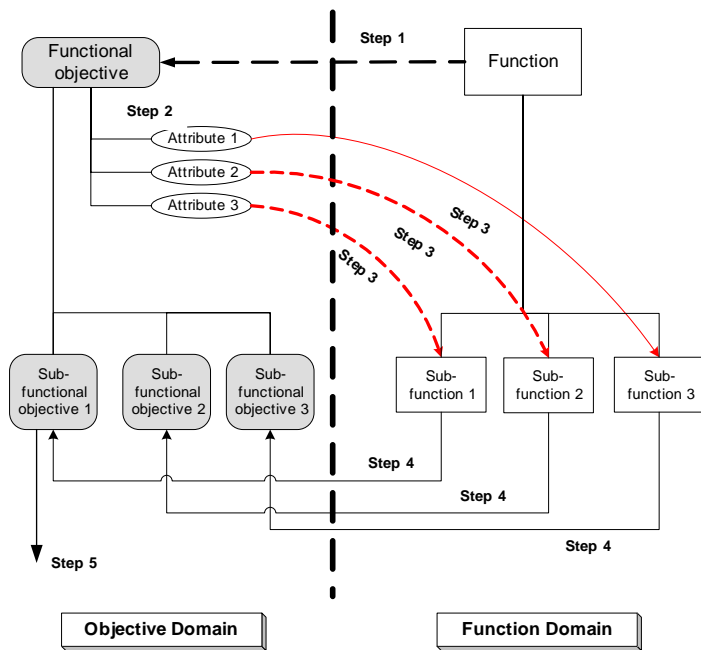


Figure 4: The steps for elaboration from function to functional objective

Step 5: Make a decision for further elaboration

At this step, the designer examines the possibility of further decomposition for sub-objectives. If the lower level functional objectives are detailed enough for identifying solution principles, the designer should identify the attributes of the lower level functional objectives by following Step 2 and start to explore design alternatives. On the other hand, if the designer decides to further decompose the functional objectives, the elaboration process from step 2 to 5 is carried out again.

Figure 4 illustrates specific steps to elaborate high-level functional objective.

4. A CASE EXAMPLE: LAKE WATER SAMPLER

In this section we present a case study to illustrate the proposed VBD approach to conceptual engineering design. We describe how the design objectives can be structured and how the objective structure can help the designer generate sub-functions. We use the Lake Water Sampler (LWS) design problem adopted from [9] for this case study. According to [9], the LWS design problem is stated as follows:

The water sampler must be able to be used from a rowing boat by a research worker who wishes to collect samples of water from fresh-water lakes at known depths down to a maximum 500 meters. After release, the device must not be attached to the boat and must decent to within 10 meters of an easily adjustable predetermined depth. It must return to the surface with a 0.5 liter sample water from that depth and then float on the surface until picked up [9].

From this design problem statement, we can derive that the top-level function of the device to be designed is <sample><water>. After the initial top-level function is obtained, the next step is to develop the first level decomposition of the top-level function. Following Guideline 1, the top-level functional objective derived from the top-level function, <sample><water>, can be stated as <maximize><sample-ability>of<sampler>. To decompose this top-level functional objective, the examination of the attributes of this functional objective should be conducted. Following Guideline 5 and step 2, the required attributes to measure the purpose of this functional objective, <sample-ability>, are “time” of sampling, “volume” of sample, “range” of sampling, and “quality” of sample. Identifying and clarifying the essential attributes of functional objectives shed light on the entire scope of design problem and stimulate the designer to develop sub-functions by following step 3. As the result of Step 3, three sub-functions, “dispatch”, “collect”, and “retrieve” are generated. As we stated earlier, in order to develop a good design concept, a designer needs to identify his or her design objectives. Following Guideline 1, these sub-functions can be transformed into functional objectives as below:

1. <maximize><dispatch-ability>of <sampler>

2. <maximize><collect-ability>of <watersampler>
3. <maximize><retrieve-ability>of <sampler>

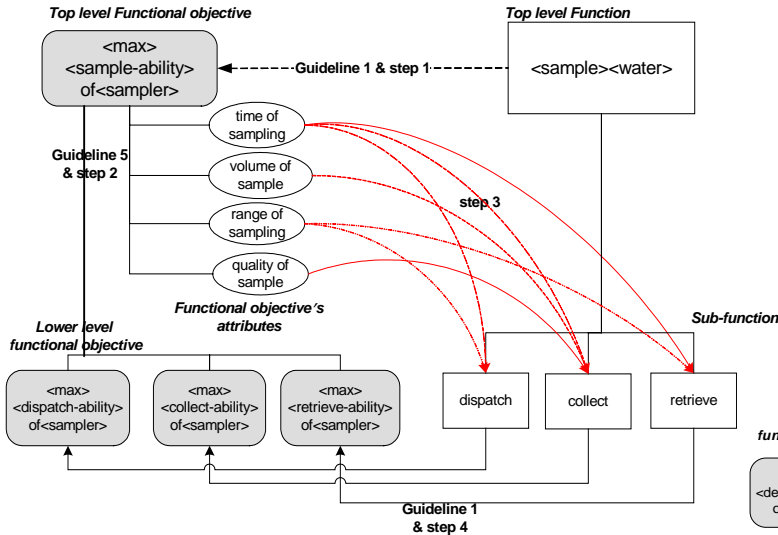


Figure 5: The first level decomposition process for the top-level function

Figure 5 shows the first level decomposition of the top-level function and how the guidelines and steps can be applied in the elaboration process.

In the next step, we will move forward with the elaboration of the first level functional objectives shown in Figure 5. The first design objective is <maximize><dispatch-ability> of <sampler>. To elaborate this functional objective, the purpose of functional objective, “dispatch-ability”, is considered. The attributes identified for measuring “dispatch-ability” are dispatching “velocity”, “accuracy of location” and “range” of dispatch, following Guideline 5 and Step 2. Following step 3, considering how to maximize these attributes of the functional objective should stimulate the designer’s thinking in developing sub-functions. In this case, the designer introduces three sub-functions, i.e., “descend”, “locate”, and “control.” As the decomposition process progresses, by following Guideline1 and Step1 the function objectives for these three sub-functions can be obtained below:

1. <maximize><descend-ability>of <sampler>
2. <maximize><locate-ability>of <sampler>
3. <maximize><controllability>of <sampler>

Figure 6 shows how the guidelines and steps described above can be applied in elaborating higher level functions and functional objectives.

The second design objective in Figure 5 is <maximize><collect-ability>of<water>. In the same way, the purpose of the second functional objective is “collect-ability”, and “collect-ability” can be measured by “collecting time”, “accuracy of volume”, and “collected sample quality”. These attributes provide the guidance for the designer to generate sub-

functions. To answer the question in Step 3, sub-functions such as “obtain” and “secure” are included. Therefore, the second functional objective can be decomposed into the following lower level objectives as shown in Figure 7.

1. <maximize><obtain-ability>of <water>
2. <maximize><securement>of <water>

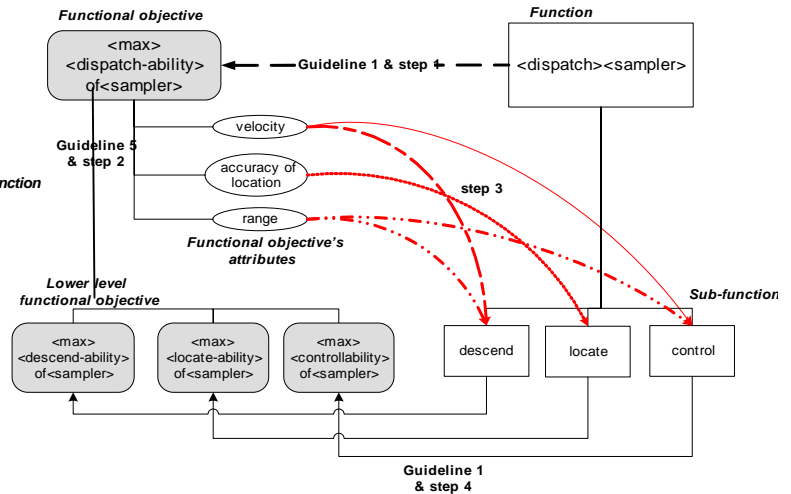


Figure 6: The elaboration process for functional objective, <maximize><dispatch-ability>of<sampler>

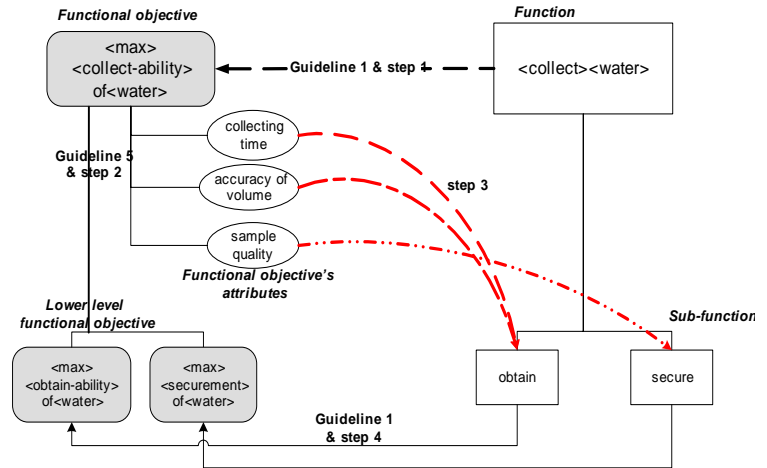


Figure 7: The elaboration process for functional objective, <maximize><collect-ability>of<water>

The last functional objective at first level of Figure 5 is <maximize><retrieve-ability>of<sampler>. To elaborate this functional objective, the purpose of the functional objective, “retrieve-ability”, is considered. The attributes to measure “retrieve-ability” can be “velocity”, “securement of sample”, “restoration of sample”. Figure 8 illustrates the decomposition process and the decomposed lower level functional objectives are:

1. <maximize><ascend-ability>of<sampler>

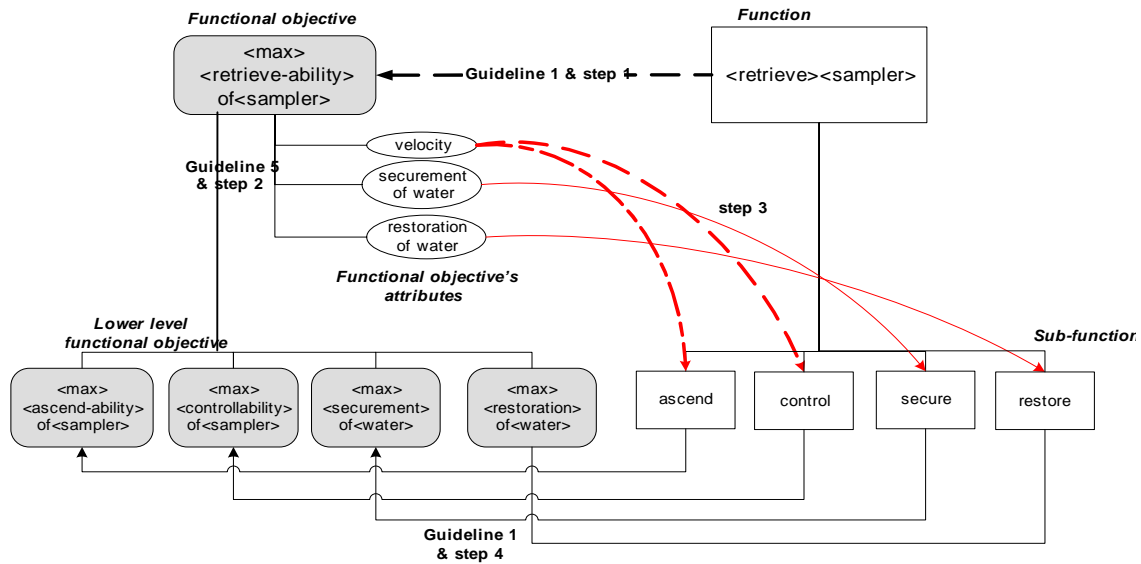


Figure 8: The elaboration process for functional objective, <maximize><retrieve-ability>of<water>

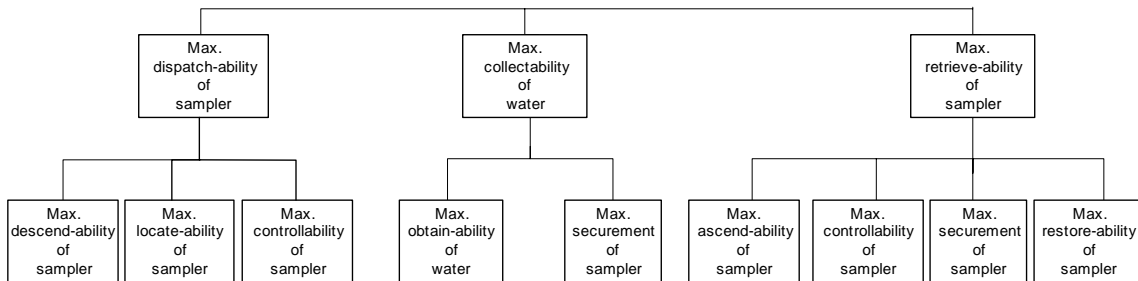


Figure 9: Second level of functional objective decomposition

2. <maximize><controllability>of<sampler>
3. <maximize><securement>of<water>
3. <maximize><restore-ability>of<water>

As a result of the high-level functional objectives elaboration, 9 sub-functional objectives are generated, as shown in Figure 9. At this point, the designer has to decide whether further decomposition is needed or not. In this example, the second level functional objective <maximize><obtain-ability>of<water> can be broken down into sub-functional objectives. As shown in Figure 10, to measure the purpose of this functional objective, <obtain-ability>, the required attributes are “time”, “accuracy of volume” and “capacity of volume”. Fulfilling these attributes leads to the generation of sub-functions, “monitor” and “store”. Finally, the transformed lower functional objectives are:

1. <maximize><monitor-ability>of<volume>
2. <maximize><store-ability>of<water>

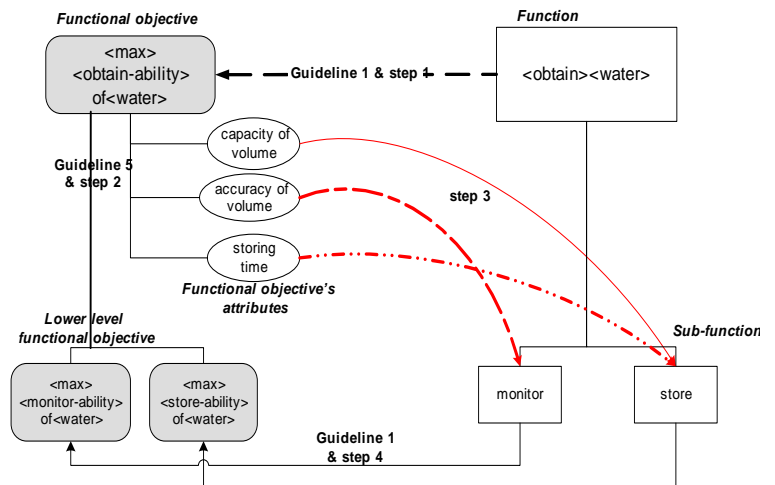


Figure 10: The decomposition process for lower level functional objective, <maximize><obtain-ability>of<water>

Figure 11 illustrates the application of our VBD method to the lake water sampler design problem. While traditional methods provide little guidance for idea generation, our VBD framework is developed to assist designers to systematically understand the design problem and generate solutions by moving between the value space (e.g., functional objectives) and the solution space (e.g., functions). The suggested guidelines are used for thinking about required co-existing objects and looking into each component of the objectives. During this process, the designer can express his or her design values in formal ways and use them to consider more specific

directions for solving the design problem. The VBD approach attempts to help designers get “what they really want”.

Explicitly capturing functional objectives and their associated attributes helps designers develop ideas for elaborating functions. The attributes linked to each functional objective indicate real concerns about the functional objective and provide clues for designers to think about sub-functions. Ultimately, identifying these attributes can help designers generate alternatives and evaluate them using the value functions associated with the objectives.

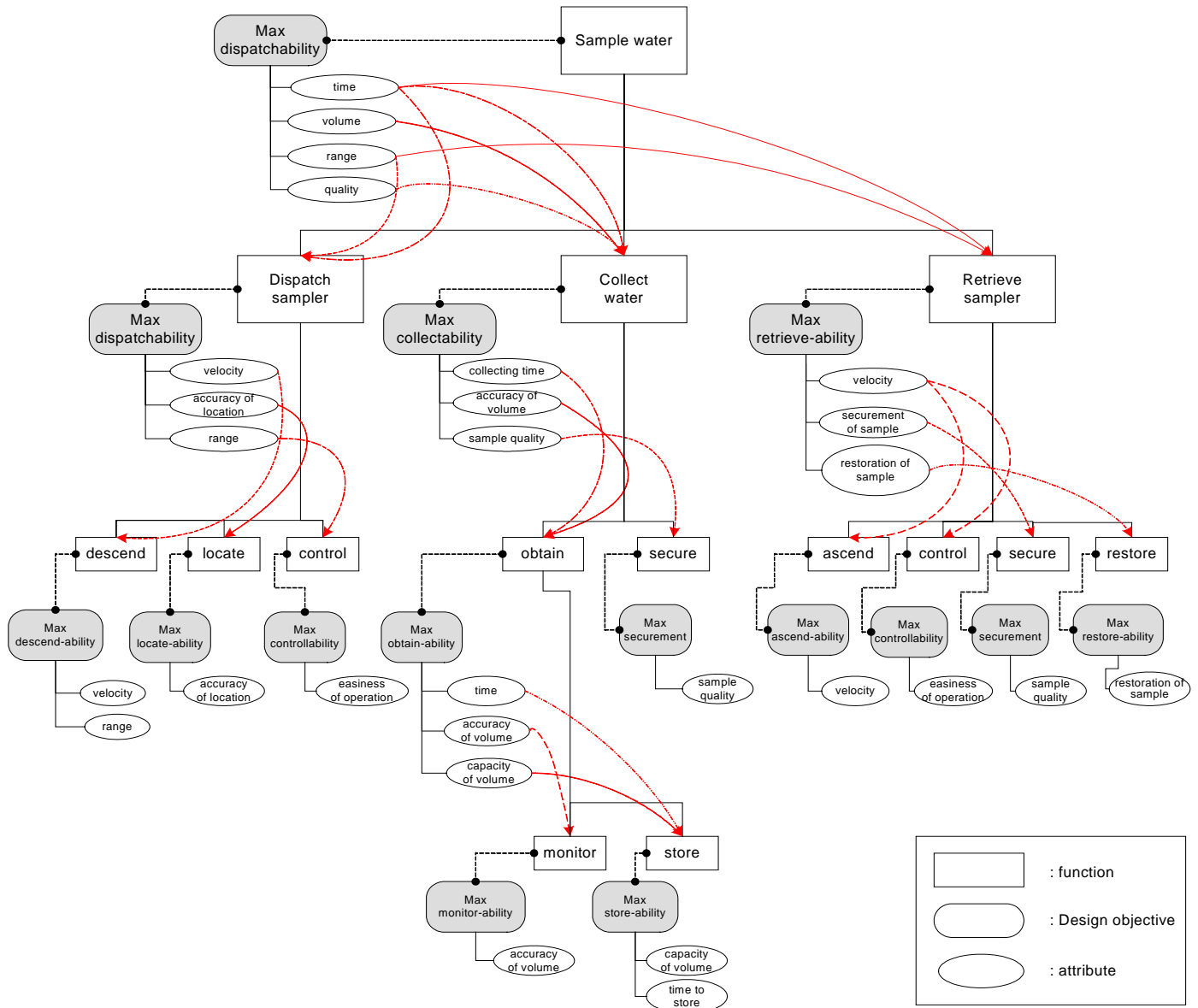


Figure 11 Design objective structuring for lake water sampler

5. CONCLUDING REMARKS

In this paper, we presented a value-based approach to support conceptual design. We defined design value as a set of design objectives and proposed a number of methods and guidelines for design objective structuring.

In the early stage of design process, a designer's task is to explore his or her value space and design space and generate good design concepts based on the exploration. In this situation, providing guidance for designers to clarify what they want and generate solution principles to achieve what they want is a major challenge for the design research community. Our value-based design approach emphasizes that focusing on design objectives provides designers with better means to explore their value space and the design space. The definition of the design objective and the methods and guidelines of design objective structuring are the major components of this approach. The Lake Water Sampler design case example has shown how the methods and guidelines can be followed to develop and structure design objectives and to generate sub-functions for creating design concepts.

Generating sub-functions through *functional objective* identification and structuring is only the first step of design concept generation. The next step is to identify solution principles. Our ongoing research is focused on how the *product objective* structuring can help designers generate solution principles and select design concepts.

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