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13 August 2014
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CE: GG QA: CL
Coll: QC:

Journal of Industrial and Production Engineering, 2014
http://dx.doi.org/10.1080/21681015.2014.951407

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A framework for concept validation in product design using digital prototyping

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(*Received January 2014; accepted July 2014*)

Concept validation plays a critical role in product design especially in the early design phase of market-driven product design. Due to the presence of ambiguous information, arbitrary interpretation of user needs, and so on, design concept validation remains a challenging task. In this work, we aim to involve customers in the conceptual design phase so that understanding about customer needs, expectations, and satisfaction can be better altered through customer–design interaction. A framework for concept validation using digital prototyping is proposed to actively involve customers in three major validation tasks, i.e., specification solicitation, concept selection, and concept refinement. Technical challenges of involving customers in conceptual design using digital prototyping are discussed. Our experimental study based on smartphone dimension design reveals the capabilities of the proposed framework. Experimental results suggest when interacting through digital prototyping, customer satisfaction on design concepts can be enhanced by making alterations to customer needs, expectations, and satisfaction.

Keywords: concept validation; concept communication; concept evaluation; conceptual design; digital prototyping

1. Introduction

Conceptual design is a crucial and critical stage in design process of market-driven products. At this stage of the design process, validation of product concepts for customer expectations and satisfaction of the product play critical roles in increasing the success of the product in the market [33,41,51]. The validation aims to increase customer satisfaction by fulfilling customer needs and expectations [7,20,54]. However, it typically suffers from ambiguous and incomplete understanding about the datum point, which is the needs, expectations, and satisfaction of customers. Thus, alteration to the understanding is of primary importance for reliability of design decisions made upon validation outcomes.

To alter the understanding so that it can better comply with the datum point, customer involvement in conceptual design has been widely studied by researchers [3,10,20,28,36,43,56,57] and adopted by various industry sectors such as car industries [17,19]. They have emphasized that customer involvement can help them enhance product concept(s) by improving their understanding of customer expectations and satisfaction through customer-design/designer interactions and customer evaluations of design [7,10,11,43,56]. However, in practice, customer involvement is generally limited to the very late stage of conceptual design for enhancement of product concept(s) and its last certifications. This can indicate that the concept(s) enhanced and certified is selected from a solution space planned and generated on the basis of ambiguous and incomplete understanding about the datum point. Thus, customer involvement in the late stage may not cause the alteration into the understanding in conceptual design except enhancements around the selected concept(s).

We aim to develop a concept validation framework for incorporation of the alteration to the understanding through involvement of customer in validation tasks at critical stages of conceptual design. The framework can help to alter the understanding about customer expectations and satisfaction through provision of evidence from customer-design/designer interactions and analysis of customer evaluations of designs. Then, it can make the design space focused and aligned with customer expectations and satisfaction during conceptual design, and accordingly can increase the chance to generate and find better concepts during conceptual design. The framework adopts digital prototyping to build the customer-design/designer interactions since it can realize the concepts on a wide range of customizability with low cost and in a short period of time.

The paper is organized as follows. Section 2 reviews the related works. In Section 3, conceptual design is investigated and concept validation is discussed. Section 4 introduces the framework and demonstrates its potentials in involving customers in conceptual design and leading it. Section 4 also discusses technical challenges and blueprints for implementation of the framework. An experimental study on conceptualization of the dimension of a smartphone is given in Section 5. The study is to demonstrate the capabilities of validation through digital prototyping in provision of objective evidence for enhancing customer satisfaction of the resulting concept by making alteration in the understanding. A discussion and our future plan for evaluation of the

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performance of the framework is given in Section 6. Section 7 concludes the paper.

2. Related work

Various studies such as [1,6–8] have tried to involve customers in conceptual design. The results of these studies show that involving customers in conceptual design can increase the chance to generate and find better product concept(s).

Some of the studies have involved customers at late conceptual design for concept refinement [6,8,24,25], and few studies [22] have gone through the process from concept selection stage onwards. These studies could find better concept(s) for customer satisfaction from the space of concepts generated. However, in the space of concepts, better concepts could have been generated (which increases the chance to find a more promising concept) if designers could have clearer and better understanding about customer expectations and satisfaction before concept generation stage as well. In some other studies such as [50,52,55,61], customers were participated before conceptual design to improve designers' understanding of customer needs through prioritization of the needs. However, need prioritization may not well reflect customer expectations and also customer satisfaction of the concepts generated.

Besides, there are several studies that have tried to involve customers during entire conceptual design. They have shown that customer involvement during conceptual design can make design space focused on customer expectations and satisfaction by improving the understanding about the datum point. In these studies, customers were either involved completely in the validation process in laboratories [6,7], or remotely involved [31,35,43]. However, the former suffers from limited number of customers that can be involved and accordingly may cause incorporation of fixation and/or divergence in design. The latter would lack the intuitive and interactive customer-design/designer communication through the current remote communication systems.

Hence, customer involvement is practically limited to the very late stage of conceptual design to further enhance the selected product concept(s) and for the last certifications. Although the late involvement of customer can enhance the concept for customer satisfaction, it may not bring the alteration to the understanding at earlier stages; unless it causes iterations that make designers to review the earlier stages of conceptual design.

We propose a framework that involves customers in concept validation tasks in conceptual design to help designers alter the understanding while the effects of the drawback of customer involvement are reduced. Before introducing the framework, in the next section, we spot critical stages of conceptual design and discuss concept validation process.

3. Concept validation in design

Validation of a product concept is an essential task to suppress uncertainties/ambiguities in the design before moving forward to detail design phase. It reduces the likelihood of changes required in the concepts at detail design phase [41,61] and accordingly reduces time to market and development cost. Validation process would serve several purposes, which are, in the context of this paper, customer expectations and satisfaction. The validation aims to ensure whether a concept complies with customer needs, expectations, and satisfaction.

This section investigates conceptualization process in which the information is mapped sequentially from need statements to product concept. It spots the critical mapping processes for which the validation can play important roles in reduction of ambiguities in design and increasing confidence in decision-making.

3.1. *Conceptualization in early design phase*

Conceptualization maps requirements into concepts, and not only it does happen for customer needs and product concepts, but also it happens whenever a piece of information is mapped from one domain into another domain. According to this statement, we define a concept as a description of WHAT that meets the input and HOW they have been met. Indeed, conceptualization requires ensuring the quality of the WHAT for satisfying its intended uses.

The concept validation process is generally gone through by design groups during conceptual design. Then, the ambiguity in understanding about identified customer needs, expectations, and satisfaction may result in a typically large and unfocused solution space generated at each mapping stage. The large and unfocused solution space can reduce the likelihood that the design group can select the concepts that increase customer satisfaction more than the others do. Accordingly, it can mislead designers in setting the inputs for the subsequent stages.

Setting target specifications and concept generation are two critical stages that deal with a typically huge amount of uncertainty/ambiguity in understanding about the datum point. At setting target specifications, vague and incomplete understanding results in finding several set of product attributes and assigning a typically wide range of values to them. At concept generation stage, the uncertainty in the specifications and the ambiguity would cause to an unfocused space of solutions. Thus, the space may contain inappropriate solutions for customer needs, expectations, and satisfaction of the product. On the other hand, the filtration, modification, and refinement from concept generation onwards select, revise, and refine the concepts on the basis of the understanding about the datum point surrounded by ambiguity. The understanding may mislead the design group about the decisions on the design.

Figure 1 demonstrates an example of the results of the mapping processes in conceptual design. This example is to illustrate the need for the idea of "concept validation" in conceptual design. It shows the translation of the information, i.e. interpretations and understanding of the needs, expectations, and satisfaction, in each mapping process. As can be seen, the incorrect and incomplete interpretations and understanding at each mapping process can generate a concept (at the end of conceptual design) that may not reflect the specifications and the needs (black arrows indicate the reflections). The idea of "concept validation" is to ensure that the output at the end of each mapping stage complies with the input to increase the chance of generating and finding a concept that better complies with customer needs, expectations, and satisfaction.

Early design phase generally suffers from the incorrect and incomplete understanding of the datum point in the presence of a generally huge amount of uncertainty/ambiguity. The incorrect and incomplete understanding surrounds the design since very first stage of design. Alteration to the understanding is extremely essential at each validation task in conceptualization process especially at earlier stages. However, the current validation activities show that design group with its perspectives on the identified customer needs, expectations, and satisfaction undergoes the process.

3.2. *Concept validation: what it means*

Validation is inherent in conceptualization process [41]. It can be generally defined as a process to ensure whether quality of an output entity complies with intended uses of an input entity. From the current validation activities point of view, this general definition can be rewritten as "the process to ensure whether a concept complies with intended uses of customer requirements".

The definition agrees with the standard bodies' definitions of the term "validation" in different domains, Table 1. Referring to Table 1, it can be said that, validation is the confirmation that requirements of intended uses are fulfilled through provision of objective evidence. However, there is a doubt on the datum point in the confirmation process.

The definitions can reflect the validation intents providing that requirements of an intended use are correct and complete, otherwise validity of the confirmation outcome would be arguable [1,5,46]. In digital models, references are generally clearly defined and well known, whereas, in the second category, the correctness and completeness of references are doubtful. The same argue is applicable on the concept validation activities.

In conceptualization, the incomplete and incorrect understanding significantly challenges the validation process. Two solutions would be proposed for this issue; (1) validating the requirements of intended uses for accurate representation of the intended uses or (2) using the intended uses as the datum point. Indeed, both scenarios require alterations to the designers' understanding of the intended uses.

At late stages of conceptual design, the available validation activities adopt the second solution through involving another party who is "customer." This is a critical and essential task in design before moving forward to detail design phase, and customer involvement would bring higher levels of confidence about decisions made and product concept(s) selected [10,11,43,56]. The confidence comes from the alteration that incorporated into the understanding about the datum point through customer-design/designer interactions. However, the chance to generate and find better concept(s) could be increased if customers were involved earlier at critical stages where the needs are mapped into specifications and product concepts.

3.3. *Concept validation process*

Validation process comprises two steps; provision of objective evidence for a specific purpose(s) and analysis of the evidence [1,5,46]. The former comprises concept communication and concept evaluation with respect to the datum points for the purpose of the validation. Figure 2 graphically illustrates the validation process according to the definition for the concept validation proposed in this paper on the basis of the definitions by the international and national standard bodies summarized in Table 1.

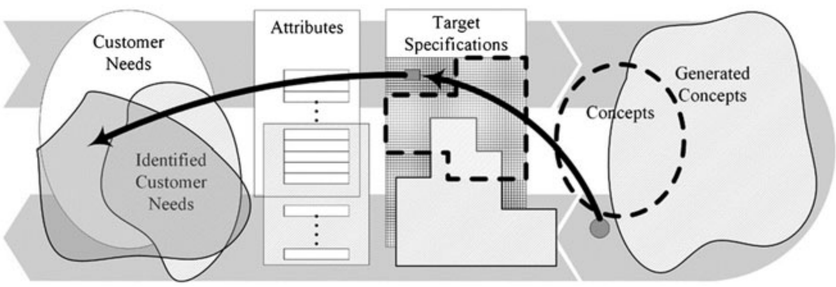

Figure 1. The space of solutions during conceptualization.

Table 1. The definitions of the term validation by national and international standard bodies.

Domain	Standard Body	Definition
Digital models	ASME[a] [4]	The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model
	AIAA[b] [2]	
	DoD[c] [18]	The process of determining the degree to which a model, simulation, or federation of models and simulations, and their associated data are accurate representations of the real world from the perspective of the intended use(s)
	DoN[d] [42]	The process of determining that an M&S (modeling and simulation) implementation and its associated data accurately represent the developer's conceptual description and specifications.
Products Service Systems	ISO[e] 9000 [27]	Confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled
	IEEE[f] Standard [26]	The process of evaluating a system or component during or at the end of the development process to determine whether it satisfies specified requirements

[a]American Society of Mechanical Engineers.
[b]American Institute of Aeronautics and Astronautics.
[c]US Department of Defense.
[d]US Department of Navy.
[e]International Organization for Standardization.
[f]Institute of Electrical and Electronics Engineers.

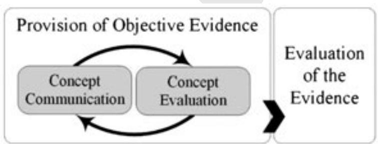

Figure 2. The validation process.

Concept communication is a critical task in which designers' thoughts and design intents are presented for evaluation. Accuracy and completeness of the information presented impact responses in the evaluation process. The interactions with concepts and the evaluations are two of the main sources of objective evidence in validation process. After gathering the evidence for the purpose of validation, the evaluation of the evidence is done to express the validity of the concepts.

Concept validation is generally done by designers with their experiences and understanding of the datum point. Then, the design direction is significantly affected by the level of correctness and completeness of the understanding. Therefore, to alter the understanding, involving customers in validation tasks during conceptual design would be helpful.

4. The framework for validation in conceptual design

This section introduces the framework for concept validation for customer expectations and satisfaction through digital prototyping. The framework aims to increase customer satisfaction by fulfilling customer needs and expectations as correct and complete as possible. The approach is to involve customers in conceptual design to alter the understanding of customer needs, expectations, and satisfaction through the knowledge that can be gained through customer-design/designer interactions and evaluations. The framework engages customers in critical conceptualization processes during conceptual design. It can help to alter the understanding about customer needs, expectations, and satisfaction of product through customer-design/designer interactions. The alteration can make the design space focused and keep it in the right direction for the purpose of the validation. Accordingly, it leads to a better alignment of the design space and customer requirements in conceptual design from setting target specifications to setting the final ones.

4.1. *The framework for validation: why, when, how?*

The conceptualization process and the solution space (Figures 2) demonstrate how the current validation tasks enhance the outcome of conceptualization process during conceptual design. However, vague and incomplete customer need statements and diversity in the interpretations of the needs may result in the understanding that cannot adequately reflect customer needs, expectations, and satisfaction. Then, as it is shown in Figure 2, the design direction may go far from the directions that adequately satisfy customers or the likelihood of that the product concept(s) is one of the promising ones, is decreased. To increase the chance to find the better product concept(s) for customer satisfaction, one of the main factors is to have more improved and altered understanding of the datum point.

Customer participation in conceptual design can help designers to improve their understanding of customer needs, expectations, and satisfaction. Our approach is to provide objective evidence for altering the designers' interpretations and understanding of the datum point through customer-design/designer interactions during critical stages of conceptual design.

We aim to involve customers at the stages that have impacts on the alignment of outcome of conceptualization and customer satisfaction. We spot and highlight three conceptualization stages that significantly impact design direction. The stages are setting target specifications, concept generation, and setting final specifications. These stages are critical since they map information from a domain to a different domain (e.g. in setting the target specifications, customer needs and product attributes are translated into a range of values or set of objects) and the mappings are performed sequentially (i.e. the output of the current stage is the input of the next stage).

The framework is shown in Figure 3(a). It incorporates three validation tasks into conceptual design; namely, specification solicitation, concept selection, and concept refinement. The tasks aim to communicate the design values (i.e. product attributes and their values, and features and their alternatives) with customers and evaluate the values using the evaluations made by customers. Thus, the validation process can alter designers' understanding by involving customers to express their needs, expectations, and satisfaction through their interactions with design and designers and their evaluations of the values. Then, using the framework, designers can be able to make decisions more confidently.

Validation is inherent in conceptual design [41] and the current practices in conceptual design run validation tasks at those stages we identified as well. However, the main difference is in the alteration that is incorporated into the understanding through involving customers in the validation tasks during conceptual design. To make it clear, we interpret conceptual design as a regulator in which the output (product concept(s)) should follow the input (customer requirements). In the current design practices, the feedback loop is typically closed at those critical stages by designers without customer involvement and at the output point with involving customers for last certification of product concept. Then, the last certification may result in time-consuming iterations or a product concept(s) that is obtained from a loosely focused and adjusted conceptualization process (Figure 1).

Figure 3(b) (through an example similar to Figure 1) shows how the idea of "concept validation" embedded in the framework can balance the information after each mapping stage with the input information so that they reflect the input. It demonstrates that the alteration at each stage can increase the likelihood of generating a concept (at the end of conceptual design) that can better reflect the needs. Figure 3(b) illustrates that the datum point is changed to the needs rather than the specifications (Figure 1). In other words, involving customers through the framework emphasizes satisfaction of the needs rather than satisfaction of the specifications that may not reflect the needs correctly and completely.

More specifically, Figure 3(b) shows how our framework may make impacts on the conceptualization process. At each stage, objective evidence is gathered through customer-design/designer interactions and their evaluations of the design values to alter the understanding. The evidence is processed to determine whether the values comply with customer needs, expectations, and satisfaction, and then to alter the understanding about the datum point. Besides, each stage also enhances the outcome of the previous stages using the new knowledge acquired. As the great advantage, the input entities at each stage are filtered by removing unwanted entities or the unwanted values of the entities or including better

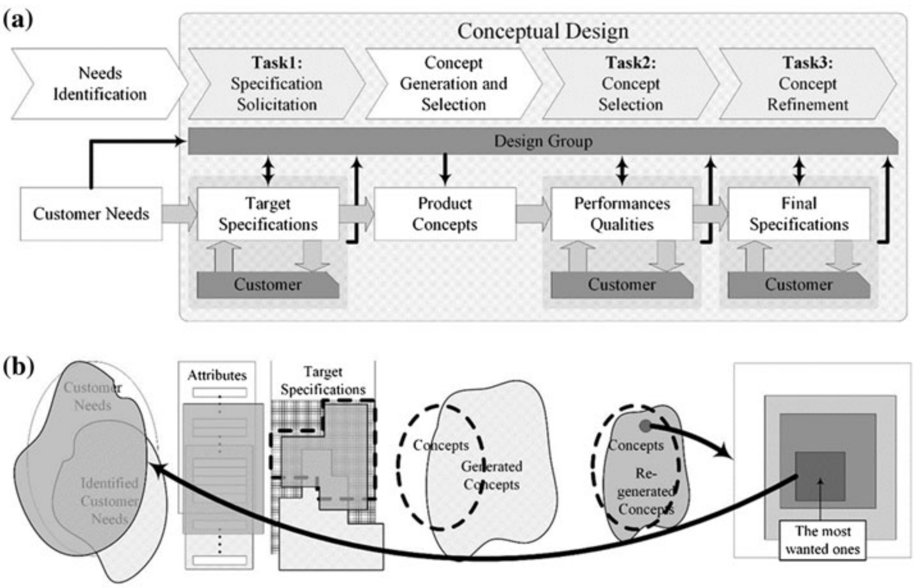

Figure 3. The proposed framework for concept validation in design through digital prototypes.

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values. Thus, the framework can cause to a more focused space of solutions at each mapping output. Customer involvement in conceptual design is discussed and the validation tasks are introduced in the following sections.

4.1.1. *Task 1: specification solicitation*

Specification solicitation (Figure 4) aims to enhance the alignment between target specifications and customer needs, expectations, and satisfaction. It is substantially critical since it provides the basis on which product concepts are generated. To set the specification, specification solicitation deals with vague and incomplete need statements and evidence for customer expectations and satisfaction. Thus, reduction of the ambiguity at this stage is substantially important in conceptual design.

At setting target specifications product attributes and their values are identified. Each attribute would be defined within a range of numbers or using a set of objects. It is important that the attributes and their values are valid for customer needs and expectations and also can lead designers to the concepts that are promising for customer satisfaction. To have better alignment and to increase the chance of finding better concepts, specification solicitation tries to find the attributes and the values that fulfill customer expectations and increase their satisfaction.

Specification solicitation communicates product attributes, the attribute values, and their correlations with customers. Customers evaluate the specifications by ranking them and their correlations. Evaluation of the rankings can give a set of promising specifications and correlations, and then, can help to find out customer expectations and how the values can satisfy customers. This may cause to revisions in the attribute sets and may change the range of their values or put conditions on choosing the values.

The correlation of the attributes indicates that how well the attributes and their values work with each other. It is a very important performance of values that should be evaluated by customers at this stage. Lack of evidence concerning customer expectations and satisfaction of such performances would mislead design directions by missing promising values and emphasizing on less wanted values. In other words, there would be less (more) wanted values that would be more (less) wanted if they work together.

The ranked values can give designers an idea of market segments and also product customization. From one side, customers can be clustered according to their preferences identified through their evaluations of design values. From the other side, the design values can be categorized according to the preferences of the customers at each identified market segment.

Specification solicitation can significantly reduce the ambiguities and alter the understanding. It builds up designers' confidence in making decisions at the very first stage of conceptual design. However, communication of the specifications is problematic as they are in the form of verbal sentences, numerical values, or set of objects and additionally, their correlations have not been put into performances (e.g. the relation between product size and weight). Moreover, customer sampling procedure and sample size at this stage would significantly affect the results. An inadequately defined sample would result in fixation in design and/or wide diversity in design and customization, and accordingly misleading in the design direction.

4.1.2. *Task 2: concept selection and evaluation*

Concept selection and evaluation (Figure 5) is done at late concept generation stage when the space of solution is made by designers. The solution space contains product concepts, their features, and the alternatives of the features and the product attributes, and their values. This task aims to help designers to more confidently reduce the space of solutions to the better concepts and select the concept(s) that better satisfies customers in the space of solutions.

The solution space in concept generation stage is typically large and customer involvement would be time-consuming and costly. Then, before directly involving

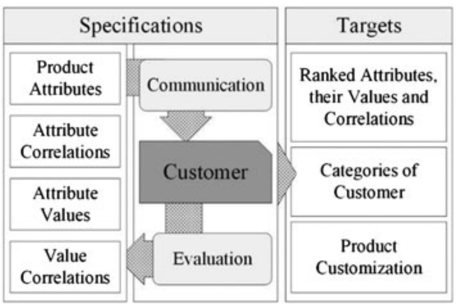

Figure 4. Task 1: specification solicitation.

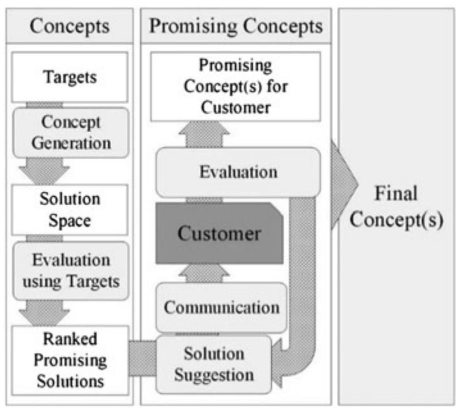

Figure 5. Task 2: concept selection.

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customers in this task, the space of solution is initially filtered by designers and with the evaluations and the rankings obtained in specification solicitation. After that, customers are involved to explore the reduced design space and find the solutions that better satisfies them.

This task requires that customers interact with the concepts, and explore and evaluate different aspects of them. Concept modification in this task means changing alternatives of features and attribute values. Several possible modifications should be considered by designers and incorporated in the concept communication process for customer exploration of design space.

The solution space by considering the possible modifications would be large and customers would get tired of the exploration or get confused. Then, this task helps customer to easily explore the space by making suggestions using his/her evaluations and the evaluations obtained from specification solicitation to include other customer preferences. The process continues until the customer finds a design(s) that best fulfills his/her expectations and satisfies him/her among the designs he/she explored.

Concept communication and evaluation task can provide designers with concepts each of which obtained by a customer. After that, it can help designers to find the promising concept(s) with the promising features, alternatives, and attribute values among the concepts selected by customers. It is done with respect to the evaluations obtained in this task and the previous one.

This task can help designers to find the promising concept(s) based on customer evaluations and selections. It can be more robust to the effects of customer sampling process than specification solicitation. The evaluations from specification solicitation can help to prevent incorporating bias in the results of this task.

4.1.3. *Task 3: concept refinement*

Concept refinement task (Figure 6) is performed at late conceptual design. Customers are typically involved at late conceptual design in the current design practices for the last certification of product concept(s). The task is executed to determine whether the concept complies with customer needs and whether it satisfies customers. Concept refinement task, in the context of our framework, aims to increase customer satisfaction of the product concept(s) selected. This task focuses more on the specifications and their final values rather than certifying the concept itself. It looks for the values that increase satisfaction of customers through customer-design/designer interactions.

To perform the task, possible refinements that the design considerations, e.g. cost and technology, allow, should become available for communication of the concept. The range of refinements would be reduced using the rankings obtained in specification solicitation. Customers rank the values through interaction with the design. The rankings are analyzed to find an optimized concept in the solution space of the selected product concept.

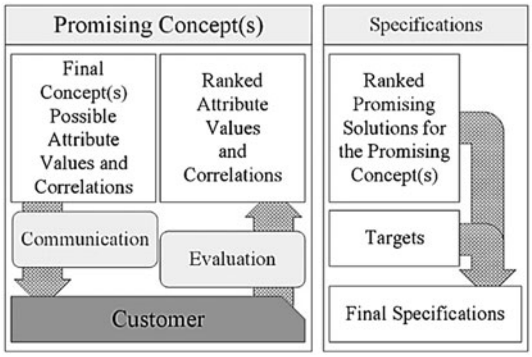

Figure 6. Task 3: concept refinement.

4.2. *Technical challenges in concept validation by involving customers*

Provision of objective evidence and evaluation of the evidence for specific purposes are the main steps of validation process. Concept communication with customers and evaluations of concepts by customers are two of the main sources for providing the evidence in concept validation process. Then, they should be done carefully to prevent misleading in design directions.

4.2.1. *Concept communication with customers*

Concept communication is the first step to validate a concept. The process is performed by presenting the concepts (source) to customers (receivers) through a transmitter (e.g. sketches, storyboards, and prototypes) in an environment.

The communication process aims that customers understand the space of solutions as correct and complete as possible. The degree to which a customer understands about the concepts significantly impacts the reliability of the evidence provided for the validation. To improve customer understanding of the space of solutions, concept communication process should possess the characteristics that are discussed below.

First, we emphasis that, there is no matter on the technique by which a concept is communicated, but it is of primary importance that customers can understand the concepts and the space of solutions as correct and complete as possible. We propose the term “fidelity” to express the degree to which customers can truly and completely understand the design values through the communication process.

Fidelity, in the literature, is defined as the degree to which a transmitter looks and works like the real realization of a concept. Sauer et al. [49] and Virzi et al. [59] proposed physical similarities, depth of function, breadth of functions, and similarity of interaction as four dimensions for determining the level of fidelity. Several studies such as [13,47,48] reported that low level of fidelity is widespread in industries since they are low cost and available in a short period of time. Additionally, majority of them emphasized that reduced fidelity provides equivalent results to the real realization of a concept. From other side, in some cases, a different object, which possesses the same value with the product for some attributes, can be used in communication process [16,32,37]. These reports imply that fidelity means that no matter how the value is presented, it should be truly received and perceived by customers [37,58].

Our definition changes the indication of fidelity from physical similarity between the transmitter and the realization of a concept to similarity in the understanding of the values. Anyway, there is no doubt that communication through a transmitter that looks or works as the real realization of a concept can increase the likelihood that customers receive truer and more complete design values, and accordingly it can improve customer understanding of concepts.

Second, interaction with design helps customers explore different aspects of the design and accordingly can enhance their understanding of the design. The way that customer can interact with the design and the possible interactions impact the exploration process. Work-like interactions and considering possible interactions in the communication process can enhance the design exploration process and improve customer understanding of the concept. We define the term "Interactivity" that indicates how conveniently customers can explore different aspects of a design in the environment. For example, manipulation of a prototype in space gives customer a freedom to move and rotate it to understand design's form in different views. In this case, the degree to which the user can conveniently manipulate the design to understand the form is one of the factors for evaluating the interactivity of the communication process. Interactivity is different from the similarity of physical interactions defined by literature as a dimension in measuring the fidelity. Interactivity, as it is clear in the definition, is the ability to do the interactions rather than the similarity between the interactions.

Third, concept communication in conceptual design demands presenting typically wide ranges of concepts and their possible modifications [3,10,20,43,56]. Flexibility represents the degree to which the communication process can be adapted to cover the possible space of solutions. Concept validation is in demand for the high level of flexibility in order that variations in design can be explored, compared, and evaluated [31,63]. Moreover, the possibility to apply modifications and communicate several modifications simultaneously can enhance the outcome of the evaluation by customers.

The level of fidelity, interactivity, and flexibility indicates the degree to which a communication system can communicate the space of solutions in order that customer can understand it truly and completely. The higher level would increase the cost and the lower levels would mislead customer cognition and understanding of the source.

4.2.2. *Concept evaluation by customers*

Customer evaluation of design concept is another main source of evidence for concept validation. Customer evaluation process must be designed in order to lead customers to express their expectations and satisfaction of design.

The space of design concept is typically large in conceptual design and customers may not be able to evaluate the whole space. Then, suggesting the customer the concepts from the space by using his/her evaluations would reduce the time. In this case, customer can evaluate the concepts by focusing on the concepts that may have more compliance with his/her expectations and satisfaction.

On the other hand, quantification of customer evaluations is one of the challenges in involving customers in design evaluation process. The quantification results must reflect the customer evaluations as much as possible. Otherwise, customer involvement may mislead the design direction.

Besides, verification of the evaluations by customer himself/herself is an important process for certification of the evaluation before analysis of the evidence for the validation task. Additionally, diversity in the concepts and their modifications can confuse customers in the evaluation process, and then, they would wish to review their previous evaluations. Therefore, the results should be representatively demonstrated to customers so that they can review their own evaluations and verify them.

4.2.3. *Evaluation of the evidence for validation*

Evaluation of the evidence analyzes the evidence gathered during customer interactions with design/designer and evaluations of concepts by customers. The analysis outcome impacts on designers' decisions and accordingly design direction by finding the design values that align with customer expectations and satisfaction in the space of concepts. Thus, from one side, optimization of the results for the purpose of the task and from other side, suppressing the effects of fixation and/or divergence in results are challenging in this task.

Moreover, as we discussed before, the space of concepts is typically large and communication of the whole space with customers would be confusing and time-consuming. Then, suggestion of concepts to customers during their interactions with the space is another challenge in this task. Making suggestions requires prediction of customer expectations through his/her interactions with concepts and his/her evaluations of concepts.

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However, fixation in the suggestions would be expectable from the very first customer–design interactions. Moreover, the fixation conflicts with the necessity of the exploration of the space by customers as discussed before.

The evaluation of the evidence would face prediction issues during customer exploration of the space, and at the end of each validation task, it is required to suppress the fixation and/or divergence in the results and optimize the solution space for better fulfillment of customer expectations and better satisfaction of customers.

4.2.4. *Discussion on customer involvement in conceptual design*

Customer involvement would lengthen the time-to-market and increase the development cost. Thus, it is useful as long as the resultant outcome is worth the extra time and cost added to the development process. Therefore, customer involvement in validation at conceptual design should be done systematically and carefully.

Customer interactions with the designs/ designers and their evaluations of the designs are the main sources of objective evidence for the validation tasks. The communication process should be done in a way that customer can understand the concepts as correct and complete as possible. However, the space of concepts is typically large during conceptual design and the communication process would be costly and time-consuming. Additionally, customers may get confused during comparison and evaluation of the concepts in the space.

From other side, involving customers brings up sampling process considerations: selecting procedure, and size. Sampling has significant impacts on design direction. A well-defined sample can lead the design process into better directions while a badly defined one can incorporate fixation and/or divergence in the space of selected concepts. Fixation may result in a biased exploration of possible concepts in concept generation stage or selecting promising concepts from the space of concepts by biased definitions for the term “promising.” In other words, fixation reduces the likelihood to find the truly promising concepts. Divergence in design solution would be another drawback of customer involvement in conceptual design. It causes to diversity in design solutions and a wide range of possible solutions that confuse designers and put them in trouble in decision-making process. Moreover, the size of a well-defined sample affects the time to market and development cost.

According to the all above-mentioned reasons, customer involvement in the current design activities is generally limited to the very late stage of conceptual design for last certification of the product concept. However, the benefits of customer involvement can outweigh the drawbacks providing that customers are involved systematically and carefully. Customer involvement can help designers to alter their understanding of customer needs, expectations, and satisfaction during conceptual design. Thus, importantly, it can help them to define the term “promising.” The alteration leads to have a space focused on customer expectations and satisfaction. Thus, the chance to find the promising concept(s) from the space would be increased.

4.3. *Technical blueprints*

This section contributes towards proposing the techniques and the methods for implementation of the framework. It expresses the technical blueprints for concept communications, concept evaluations, and evaluations of the evidence in the validation tasks of the framework.

4.3.1. *Concept communication*

Prototyping as a means of communication had come to the designers’ interests in the last decades and has been widely used in conceptual design. Advances in prototyping technologies have shown great promises in fulfilling the communication process requirements in contrast to the other techniques and methods such as storyboarding and sketching.

Prototyping can be categorized into physical, digital, and mixed prototyping. Physical prototypes can offer higher levels of fidelity and interactivity but lower flexibility in comparison to other two groups. Additionally, they are costly and time-consuming, and accordingly their applications are generally limited to the last stage of conceptual design for the last anticipation and certification of product concept(s).

Rapid prototyping has been widely used in conceptual design. It would be less costly and time-consuming than typical physical prototyping. Rapid prototyping suffers from low level of flexibility and moreover, it currently covers a narrow range of product attributes such as form and dimension.

Digital and mixed prototyping have shown promises to be employed in earlier stage of conceptual design and are potential choices for the framework. They enable designers to simulate the behavior of concepts and test their functionality and ergonomic aspects through communication of digital prototypes [12,13,31,34,39]. This gives design groups a great opportunity of visualization and anticipation of several aspects of their ideas and concepts before physical realization of concepts [13,14].

Digital and mixed prototyping are low cost and available in a short period of time and generally possess high level of flexibility. Their level of fidelity and interactivity are lower than physical prototyping, but nowadays, by advances in technologies of digital prototyping, they can be built within the high range of fidelity and interactivity.

Digital prototyping supports collaborative design (designer–designer and designer–customer) in digital environment [40,44,45], especially through the internet [15,21,29,30,43,53]. Several internet-based concept communication systems have been developed so far such as [14,31,35,58,62].

A digital prototype or in some literature "digital mock-up" digitally realizes a concept to look and work like its physical realization [3]. Generally, it is desired that, the digitally realized concept possesses almost the same quality as its physical realization possesses [63]. The quality of a concept can be communicated quantitatively through simulation systems and qualitatively through communication systems such as virtual/augmented reality and haptic devices [9].

Virtual reality and haptic devices are the potential choices of digital prototyping systems for conceptual design. They have been extensively used in illustration and exemplification of a wide-range physical attributes in conceptual design through virtual objects and environments. Communication through virtual reality lacks physical interactions and haptic systems are incorporated to add sensation of touch and physical interactions to the process.

Mixed prototyping mixes physical and virtual objects and environments and gets the benefits of the virtual world in the physical world. In mixed prototyping, virtual objects are projected in physical environment, physical objects are augmented in virtual environments, or virtual scenes are projected on physical environment, objects, and in some cases on physical prototypes [38]. Mixed prototyping use the beneficial features of virtual and physical prototypes to offer less expensive and more interactive prototypes in a mixed environment.

Specification solicitation and concept selection tasks aim to investigate the space of product attributes, their values, and correlations and the space of product concepts, their features, and alternatives. Digital prototyping can cover a wide range of values with low cost and the prototypes are available in a short time and with high level of flexibility. Besides, augmented reality with the real objects as the environment would be another potential choice in these tasks. It helps customers to make comparisons between the design values and the reality.

Concept refinement task deals with a rather smaller space of concepts than its two previous tasks. At this task, the core of the product concept(s) is selected and refinements are typically performed on the attribute values to increase customer satisfaction. Mixed prototyping would be a better choice than digital prototyping since the touch realism and physical interactions are more realistic in mixed prototyping. However, it would be more costly than pure digital prototyping.

Concept communication demands high level of fidelity, interactivity, and flexibility to transmit truer and more complete design values to customers and to cover the space of concepts [3]. Digital and mixed prototyping as a means of communication are the potential choice for our proposed framework. Exemplification and illustration of the design values through digital and mixed prototyping improve customer understanding of design intents and values and also the wide ranges of values covered would cause improvement in designers' understanding of customer expectations and satisfaction.

4.3.2. *Concept evaluation*

Ranking of design values is a simple system for customers to understand and they can review their rankings at a glance. Moreover, by ranking, quantification of the customer evaluations is done by themselves. In this case, the quantified results would better comply with customer evaluations and better reflect customer expectations and satisfaction.

The ranking process we are proposing for the framework has two steps. First, customers rank the values from different perspectives as set by designers. Then, they specify how the most and the least wanted values fulfill their expectations and satisfy them. This is done by evaluating these values for each perspective through assigning scores to them. Next, the rankings are mapped on the scale of the least and the most scores.

Different perspectives would impact on customer satisfaction differently. To better capture customer expectations and satisfaction, customers rank the perspectives and assign a weight to each of them. Their evaluations of the perspectives can demonstrate their expectations and specify their impacts on their satisfaction.

4.3.3. *Evaluation of the evidence in the validation tasks*

In specification solicitation, stochastic analysis of the evaluations is one of the best choices at this stage. Each customer is interpreted as random variable whose values are his/her evaluations of the solutions. Then, using formal stochastic analysis methods and techniques, we can extract the concepts that are better wanted by customers and have a ranked table of the concepts and their evaluation results. Clustering the customers (random variables) according to their preferences identified (values of the random variable vector) can give designers an idea about market segments. From the other side, the ranked table can be divided into different levels of satisfaction and the higher levels can be categorized according to the similarity in their design values. This gives designers an idea of the correlations among the design values.

In concept selection, genetic algorithm is one of the best candidates for evaluation of the evidence at this task. On the one hand, we aim to adopt it for the concept suggestion process and on the other hand, it is employed to regenerate the better concepts from the concepts that better satisfy each customer.

Genetic algorithm is well developed for producing new better generations from old generations of gens (concepts). Customer evaluations of the concepts and the ranking table from task one are the criteria for evolution in selection and mutation process. Incorporation of other customer evaluations, obtained in task 1, can help reducing the effects of fixation in concept regeneration.

We emphasize that customers can modify the concept values within the ranges defined by designers and considered in the communication process. Moreover, the concept regeneration process also suggests a concept from the considered space.

In concept refinement, neural network is one of the best candidates to analyze customer evaluations and optimizing the concepts. Additionally, it can fit to our framework. The promising concept(s) selected in the last stage of conceptual design and their selected modifications make the set of satisfactory concepts. Customer evaluations at this stage and the ranked tables from tasks one and two are used as the evaluation knowledge and evaluation indicators, respectively. Consideration of the customer evaluations from the previous stages and this stage suppress the effects of fixation and the drawbacks of limitations in exploration of the solution space. Next section contributes to discuss some possible impacts of customer involvement through communication by digital prototyping on the alteration of the understanding for increasing the satisfaction.

5. An experimental study: dimension of a smartphone

In this section, through an experimental study of the conceptualization of the dimensions of a smartphone, we show how customer involvement through building communication by means of digital prototyping can alter the understanding about the datum point to enhance the satisfaction of the concept. In this regard, first, we validated our digital prototyping system for communication of the true values of the dimensions. Second, we employed the validated system for building the customer-design/designer communication and the design evaluation. Third, we show how the evidence provided through the communication by digital prototyping and the evaluations can alter the understanding for generating more satisfactory concepts than communication by physical prototyping.

5.1. *Material*

A box was physically and digitally prototyped, and then, the prototypes were presented to the customers. The dimensions of the box were $60 \times 130 \times 8$ mm^3 (width × height × depth).

Before starting the communication process, a study on the customer understanding of the dimensions through the digital prototyping system was conducted to validate the system for presenting the true values to the customers. The study is briefly reported below.

5.1.1. *The study design for the validation of the digital prototype*

The study was done in a mixed environment (Figure 7). The digital prototype was projected with scale 1 for the dimension in a physical environment. The subjects could rotate and move the box in the real environment they were locating. The zoom and perspective features were automatically adjusted to present the true value of the dimensions with respect to the position of the box in the environment. In the study, the scenes were projected on a two-dimensional screen. Two tasks were performed for the provision of objective evidence for the validation as described below.

Figure 7. The environment and user–design interaction.

Task 1: The subjects were asked to interact with the prototype, draw it on a millimeter paper, and compare it with the prototype. This task was done in three rounds, and in each round, they had 30 s for interacting with the prototype. They were given up to 1 min for drawing the box and the comparison. The rounds were started immediately after finishing the previous one, and the sketches were drawn on the same paper.

Task 2: Virtual prototypes of the box with two different dimensions were shown separately. The subjects were asked to compare the boxes and draw them on the paper used in the first task. They were given up to 30 s for completing this task.

The prototype was evaluated for customers' true understanding. We assigned $5 \times 6 \times 2$ mm (width × height × depth) as the acceptable magnitude of error (E) for the true understanding (criterion F); 180 s as the acceptable time (T) for achieving the true understanding (criterion I); and 30 s as the acceptable handling time (H) for distinguishing the scales of three dimensions in the acceptable error range (R) of 10% (criterion X). Four levels were assigned to each criterion. Table 2 illustrates the conditions for scoring each criteria and specifying their levels.

Unpaired two-sample Student's t-test was used to check whether the mean of the results (levels) in each two successive rounds are the same, with $p < 0.05$. One-tail t-test was performed to check the inequality. Thus, the null hypothesis was set as "the mean of the results obtained from study are equal for the two successive rounds, and the alternative hypothesis stands for the inequality. Therefore, if the means of the results are found different for a criterion, we can assume that there is evidence against the null hypothesis and the next round possesses higher mean level in comparison to the current one for a criterion. Otherwise, we fail to reject the null hypothesis and the rounds may possess the same level. AQ1

Table 2. The levels of the criteria.

		Levels & Specifications			
		Very Low	Low	Medium	High
Criteria	F*	|E| > ψ1	ψ2 < |E| < ψ1	ψ3 < |E| < ψ2	|E| < ψ3
	I	T > 180	135 < T < 180, |E| < ψ2	90 < T < 135, |E| < ψ2	T < 90, |E| < ψ2
	X	H > 30	25 < H < 30, |R| < 10	15 < H < 25, |R| < 10	H < 15, |R| < 10
Criterion score		0	1	2	3
Range		0	(0, 1)	[1, 2)	[2, 3]

Six subjects participated in the study. They were within the age range of 26–31 with mean value of 28.

5.1.2. *The experimental results for the validation of the digital prototype*

Table 3 illustrates the data recorded during the experiments and their values for each subject. The errors given in Table 3 are the absolute errors. The symbols '✓' and '×' show whether the value is acceptable or unacceptable, respectively, by referring to Table 2.

The criteria *F*, *I*, and *X* were evaluated by the scores assigned to them according to Tables 2 and 3. The scores and the evaluation results are tabulated in Table 4. Referring to Table 4, the scores for *F* and *I* are more between 2 and 3 in the second and third rounds. This indicates that the subjects understood the true dimensions through the interactions with the prototype. Additionally, a comparison between the mean values shows that the true understanding was improved after each round. The results of the *t*-test show that there is strong evidence against the null hypothesis and the understanding improves after each round. Therefore, the subjects can understand the true values if they interact with the prototype in an appropriate amount of time; in this study, the worst case was 132 s (2 rounds).

On the other hand, handling different dimensions was not adequate through the system (score = 0.67). However, further experiment demonstrated when the prototypes showed simultaneously, the score of *X* rose to 2.67. This may indicate that the subjects can compare the values correctly if they interact with them simultaneously. Overall, the system is valid if the subjects have enough time to interact with the concepts and can compare them when they can see them simultaneously.

Table 3. The experimental data.

		S1	S2	S3	S4	S5	S6
E	R1	4,5,2	3,4,1	1,3,1.5	3,5,0	5,6,1.5	2,0,2
	R2	3,3,1	1.5,3,.5	1,1.5,0	1,2,.5	2,1,.5	2.5,1,.5
	R3	2,2,1	1.5,2,.5	1,1.5,0	1,1.5,1	1.5,1,.5	1,.5,0
T	R1	×	86	37	×	×	×
	R2	97	×	×	104	132	121
	R3	✓	✓	✓	✓	✓	✓
R		1	3	✓	2	4	✓
H		20	28	26	12	10	17

R1: round1, R2: round 2, R3: round 3.

5.2. *Experimental study design*

The experiment was done in two stages; stages *P* and *V*. In stage *P*, first, the physical prototype of the box was given to the subjects, and then, they were asked about their opinion about the dimensions. After that, the concept was refined on the basis of the opinions and concept *P* was generated. In stage *V*, the subjects interacted with the digital prototype according to the requirements mentioned in Section 5.1.2. The subjects could ask for changing the dimensions and see the results simultaneously. After gathering the feedback, the concept was refined according to the evidence gathered during the interactions and concept *V* was generated. Finally, the subjects were asked to evaluate the physical realization of the generated concepts, *P* and *V*, and their width, height, and depth on the Likert scale of 5. In this study, six subjects participated in the study. They were within the age range of 26–31 with mean value of 28.

5.3. *Method*

The concepts were compared by using the mean values of the evaluations. Unpaired two-sample Student's *t*-test was used to check whether the mean of the evaluations are the same for the concepts, with $p < 0.05$. One-tail *t*-test was performed to check the inequality. Thus, the null hypothesis was set as "the mean of the evaluation are equal for the concepts," and the alternative hypothesis stands for the inequality. Therefore, if the means are found different, we can assume that there is evidence against the null hypothesis and the concept generated in stage *V* possesses higher mean values in comparison to the one generated in stage *P*. Otherwise, we fail to reject the null hypothesis and the concepts may scores the same mean value.

5.4. *Experimental results and discussion*

The concepts P and V generated had the dimensions 58 × 135 × 5 mm and 63 × 132 × 7 mm. The evaluations

Table 4. The evaluations of the *F*, *I*, and *X*.

		Mean	SD[a]		*t*-stat	*P*	*t*-crit
F	R1	1.33	0.47	}}	−3.80−2.24	0.00170.0378	1.812.02
	R2	2.5	0.5				
	R3	3	0				
I	R1	1	1.41	}	−2	0.0462	1.94
	R2	2.33	0.47				
	R3	2.33	0.47	–	–	–	–
X		0.67	0.94	–	–	–	–

[a]Standard deviation.

of the concepts are tabulated in Table 5. In Table 5, the highest score is 5.

Referring to Table 5, the mean values of the scores given by the subjects to the width, height, and depth of concept *V* were higher than those given to concept P. This difference was significant for the width (3.5/2.33 = 1.50 times) and depth (4.33/2.67 = 1.62 times), whereas, for the height, it was small (4/3.83 = 0.04 times). According to the results of the *t*-test, strong evidence could be found against the similarity of the mean values of the evaluations of the concepts *P* and *V*. Overall, the results show that concept *V* satisfied the subjects better than concept *P*.

The higher satisfaction level gained by concept *V* can be attributed to the alteration to the designers' understanding of the customer expectations and satisfaction. The alterations were done by providing the evidence from the communication and evaluation. These alterations were brought into the conceptualization process by means of digital prototyping. Importantly, the subjective terms that caused arbitrary interpretations in stage P were made clearer for the designers in stage V. More importantly, the subjects could see whether they want what they think. For example, when a subject asked for a smaller width, he/she could see the designers' understanding of the term "smaller" and could feedback on it. Additionally, he/she could see the smaller width and could think whether he wants the smaller one. Overall, these statements can indicate that involving customers in conceptual design through digital prototyping can help to alter the designers' understanding of customer needs, expectations, and satisfaction.

6. Discussion and future plan

The framework aims to alter designers' understanding of customer needs, expectations, and satisfaction by involving customers in validation tasks through digital prototyping rather than simple evaluation and selection of concepts by customers. The tasks under the framework were designed to alter the understanding by using the evidence that can be gathered during customer interactions with the digital prototypes of the concepts. In the framework, designers design the interactions for reducing their uncertain interpretations and understanding of the datum point. The experimental study in this paper can make it clear that customers are not involved to design or simply select and evaluate the design. They are involved so that the designers can alter their understanding of customer needs, expectations, and satisfaction through the interactions and evaluations.

In this section, we also discuss our future plan for evaluation of the performance of the framework. We express the expected performance of the framework according to the initial results obtained in this study on the dimension of a smartphone and our expectations. First, we will evaluate specification solicitation for finding the promising values of the attributes. For example, Figure 8(a) shows the front face of a smartphone, and its nine possible solutions generated in setting target specification. Referring to task 1, customers will be asked to rank the solutions for different adjectives, e.g. "hot" and "luxurious." The solutions will be ranked on a scale of 5 scores and weighting are assigned to each adjective by customers. We expect that the mean and variance of the scores can indicate the degree to which a solution is wanted for each adjective (Figure 8(b)). The expectation

Table 5. The evaluations by the subjects and the results of the *t*-test.

	Concepts		*t*-test		
	Concept P	Concept V	*t*-stat	P	*tt*-crit
Width	2.33 ± 0.47[a]	3.5 ± 0.5	−3.80	0.0017	1.81
Height	3.83 ± 0.69	4 ± 0.58	−0.42	0.3434	1.81
Depth	2.67 ± 0.75	4.33 ± 0.75	−3.54	0.0027	1.81
Overall	3 ± 0.58	3.67 ± 0.47	−2.00	0.0367	1.81

[a]Mean ± SD.

can be confirmed if the generated concept at the end of conceptual design has the scores close to the mean and variance of the similar solutions to the generated concept.

The most wanted solutions can be found through summation of scores with their weightings and thresholds. For example, the solutions with values more than 6 and 12 for hot and luxurious are considered the most wanted solutions, respectively. Referring to task 1, we expect that customers can be categorized based on their evaluations of the most wanted solutions. This also can give an idea of product customization. For instance, four categories are shown in Figure 8(c). Two categories have assigned lower scores to the solutions. If we assign "yes" or "no" to the regions, one category finds the solutions luxurious but no hot and the other finds them neither hot nor luxurious. This can give designers an opportunity to investigate these customers' expectations in the solution space and build a trade-off between their preferences and the other customers placed in the most wanted region. This expectation can be confirmed if the space of concepts that will be generated according to the information are ranked by the customers in a category similar to the ranking of the solutions in the category.

Specification solicitation gives the ranked solutions through the evaluations performed and quantified by customers. Then, designers can have better understanding of customer expectations and preferences in the target specifications. Specification solicitation is expected to lead to a better space of solutions in concept generation stage by focusing on the better specifications and their values.

In concept generation, designers may focus on the categories of customers and move the design process forward in several directions. We want to check whether filtering the space of concepts by using the results of task 1 can result in a space that contains better concepts than the space of removed concepts (Figure 9(a)). To check this expectation, the ranked space by the customers will be compared with the ranked space by the outcome of specification solicitation.

In concept selection, each customer evaluates the promising solutions for each category of customers (e.g. Figure 9(b)). The distance of customer from each category of customer is obtained and the better solutions in those categories in addition to the close solutions to him/her in the most wanted region are suggested to him/her for evaluations (e.g. Figure 9(c)). The process continues until no new solutions can be suggested or the customer stops further exploration. In this task, we will check whether the promising solution(s) can be found by designers from customers' most wanted solutions by using rankings from specification solicitation and customer evaluations. Besides, we aim to compare the performance of this task with performance of a typical concept selection process. We also expect that possible customizations can be also found for the solutions selected as promising.

In concept refinement, the core of the product concept is obtained and it is gone through the last certifications and refinements for further enhancement of customer satisfaction. Customer interacts with the concept(s) and the possible refinements in the space of attribute values and rank them for his/her satisfaction (for instance, Figure 10(a) and (b)). We expect that by analysis of the evaluations we can find an optimized concept for customer satisfaction from the solution space in concept refinement task.

We are planning to evaluate the performance of our concept validation framework in helping designers to alter their understanding of customer needs, expectations, and satisfaction. Overall, the framework can be evaluated if the expectations are confirmed and the resultant concept satisfies customers as it is expected through the whole process.

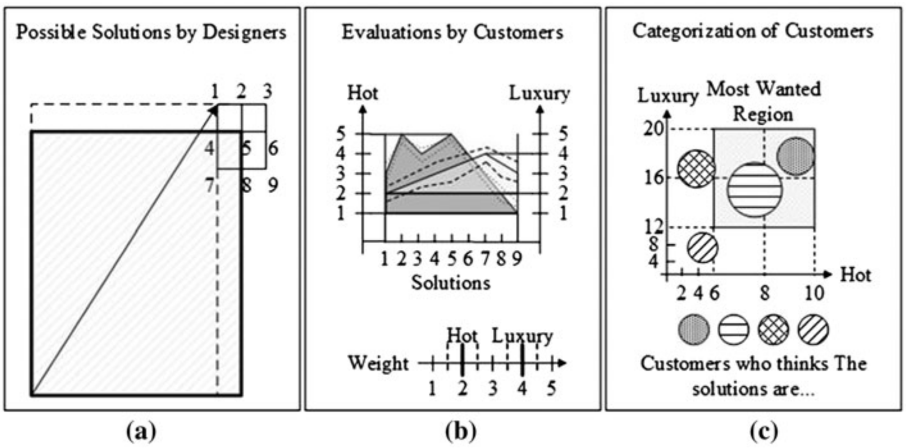

Figure 8. Task 1: the example.

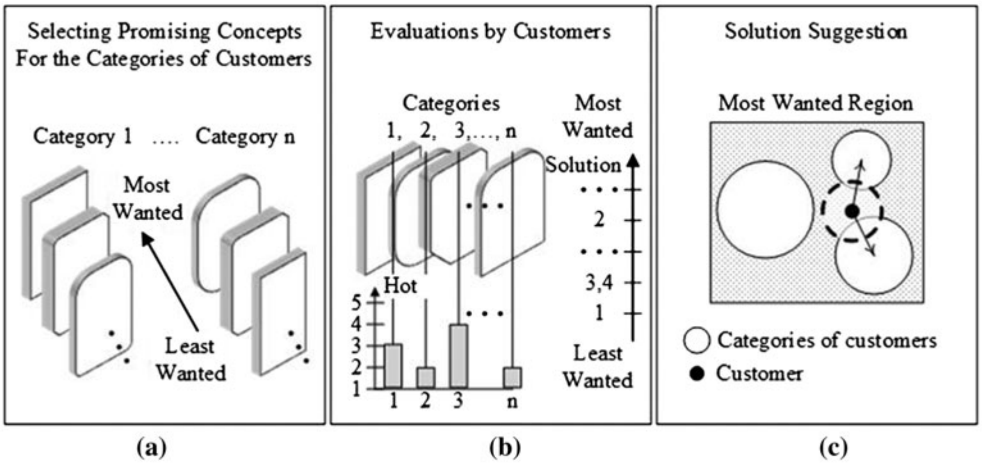

Figure 9. Task 2: the example.

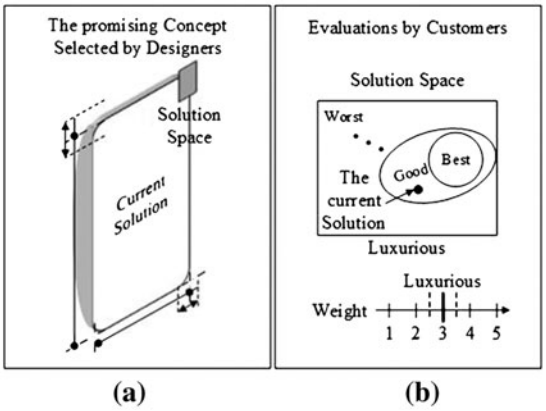

Figure 10. Task 3: the example.

7. Conclusions

A framework for design concept validation using digital prototyping is proposed to address several critical issues in concept validation. We intend to engage customers during the entire conceptual design to help alter the understanding about customer needs, expectations, and satisfaction through customer–design interactions and customer evaluations of design. The framework actively involves customers in conceptual design and adjusts the space of concepts at critical stages of conceptual design to the needs, expectations, and satisfaction. It leverages the space of concepts to a space generated based on the improved understanding of designers about customer needs, expectations, and satisfaction. Furthermore, with more inputs harvested from customer–design interaction, it helps to uncover hidden customer needs that increase the likelihood of identifying concepts for better customer satisfaction. We have discussed how the proposed framework can be systematically implemented, its primary technical challenges, and its implementation blueprints. The detailed account of the proposed framework is accompanied by an experimental study of the conceptualization of the dimension of a smartphone. The study demonstrated the capabilities for provision of evidence for concept validation that exist in the interactions with concepts through digital prototyping. The experimental results showed the impacts of the interactions through digital prototyping on enhancing the customer satisfaction of the concepts by making the alteration to the understanding, which is the main intention of building the framework for concept validation. Our future plan for evaluation of the performance of the framework is also discussed.

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