A Case Study to Support Conceptual Design Decision Making Using Context Knowledge

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Abstract

Conceptual design is the most important phase of the product life cylce as the decisions taken at conceptual design stage affect the downstreams phases (manufacture, assembly, use, maintenance, disposal) in terms of cost, quality and function performed by the product. This research takes a hoilistic view by incorporating the knowledge related to the whole context (from the viewpoint of product, user, product's life cycle and environment in which the product operates) of a design problem for the consideration of the designer at the conceptual design stage. The design context knowledge comprising knowledge from these different viewpoints is formalised and a new model and corresponding computational framework is proposed to support conceptual design decision making using this formalised context knowledge. This paper presents a case study to show the proof of the concept by selecting one concept among different design alternatives using design context knowledge thereby proactively supporting conceputal design decision making.

Keywords: Conceptual Design, Decision Making, Context Knowledge

1. Introduction

Conceptual design is a dynamic activity, which should be undertaken in the context of external world and therefore any decisions made by the designer have implications on the external world comprising, which comprises environment of the product and users of the product. It is therefore necessary for the designers to be aware of the consequences [1, 2] of their decisions made at the conceptual design stage not only on the later life phases of the product but also on the whole context of the design problem under consideration i.e. the external world, life phases, environment of the product, and users of the product. Therefore there is a need not only to identify the whole context or contextualised information/knowledge of design but also to formalise it in some structured form and present it for designer's consideration early during the synthesis stage of the design, i.e. when the decision making takes place at the conceptual design stage. A good understanding of this design context is essential for successful design and any design support system should investigate as to how the design context knowledge and information can be used to provide effective support [3]. Hence, it is essential to identify, understand the role and utilize design context knowledge in order to support the conceptual design stage. This paper describes about the formalism of the design context knowledge, the framework developed to support decision making and a case study in detail to highlight the effectiveness of the approach.

2. Context in Design

There are many uses for the word 'Context' in design, and information/knowledge described as 'Context' is also used in several ways. One dictionary [5] definition of context is *the set of facts or circumstances that surround a situation or event.* Charlton and Wallace [6] summarised design context interpreted by different researchers as follows:

- *"The life cycle issue(s), goal(s) or requirement (s) being addressed by the current part of the product development process: e.g. safety; usability; assembly.*
- *The function(s) currently being considered as an aspect of the product: e.g. transmitting a torque; acting as a pressure vessel.*
- *The physical surroundings with which a part of the product can interact, including either internal or external aspects of the product's environment; e.g. the components in a hydraulic system; the temperature of the operating environment; the manufacturing environment; aspect of the surrounding landscape reflected in an architectural design".*

To date few researchers have only provided a contextual framework to explore relationships between the design context and design practice giving no consideration to the impact of all context knowledge on decision making at the conceptual design stage. There is not a single work representing the holistic view of *'Context'* in design i.e. from other perspectives apart from these aspects, which is necessary to perform an effective decision making at the conceptual design stage. This research refers *'Context'* as a knowledge having information about surrounding factors and interactions which have an impact on the design and the behaviour of the product and therefore the design decision making process which result in design solutions at a particular moment of time in consideration. Therefore the *Design Context Knowledge* is defined as *the related surrounding knowledge of a design problem at a given moment in time for consideration* [4].

2.1 Design Context Knowledge Formalism

The review of existing methods and frameworks indicated that the lack of the consideration of design context knowledge and its implications during the decision making is due to the lack of understanding and non-availability of a proper formalism of the design context knowledge. Based on the adopted definition, this research has proposed and implemented a classification in order to structure the design context knowledge for a systematic use. The research formalizes design context knowledge in six different groups. These groups are Life Cycle Group, User Related Group, General Product Related Group, Legislations & Standards Group, Company Policies and Current Working Knowledge [7] (that is partial solution generated up till current stage of the design process for a given problem). Design context knowledge formalised in first five groups is of static nature and it can be further classified into different categories of knowledge depending upon the nature of design problem and design domain under consideration so that it is easy to use this knowledge in decision making. However as first three groups are generic in mechanical design domain and can be used in any design organisation, therefore this research has classified these three groups in ten different categories of context knowledge [4]. This identification stems from the work done by the authors and other researchers in the areas of design synthesis for multi-X as well as product life cycle modelling [8, 9, 10]. The work [8, 9, 10] done earlier by authors illustrate the significance of generation of life cycle consequences on different life cycle phases (design, manufacturing, assembly, dispose) of product in the form of positive and negative implications due to the selection of a particular design solution. The work reported in this paper built further on previous work by not only considering consequences related to different life cycle phases but also consequences related to the user of product and the environment in which the product works/operates. Therefore a more holistic and wider view of design problem is considered by formalising design context knowledge into different categories and using them in supporting decision making at the conceptual design stage. It is noted that these categories of context knowledge are by no means exhaustive. There could be even more knowledge groups/categories that should be considered depending upon the nature of a design problem under consideration, however in metal component design particularly in sheet metal component design, these categories can be used to explore fully the knowledge important for consideration at the conceptual design stage. These categories are:-

User requirements/preferences	Post production requirement
Product/Component material properties	Production equipment requirement
Quality of means/solution during use	Quantity of product required
Pre production requirement	Achievable production rate
Production requirement	Degree of available quality assurance techniques

The detail of these categories is out of the scope of this paper. These ten categories of context knowledge can be used for reasoning to provide decisions' consequences awareness to the designer at the conceptual design stage.

3. Function to Means Mapping Model

The conceptual design process is often modelled as the transformation between three different information states [11] as function, behaviour and form of solution means framework explaining the interactions between these three elements, therefore this research proposes a new function to means mapping model, which used these ten categories of design context knowledge to support conceptual design decision making. Conceptual design process involves deriving implementable functions by decomposing them into finer resolutions, identifying means to realise them and evaluating those means by reasoning using existing and new knowledge/information against evaluation criteria.

Observing the product from the constructional point of view [12] gives a product break down structure (product, assembly, subassembly, component, and feature) each of which requires be designing and therefore calling as Product Design Elements (PDEs) [13]. A PDE at component building level is a reusable design information unit (element) representing a potential solution means for a function requirement. Of relevance to this definition and looking from the viewpoint of component construction, a more commonly used term *feature* is considered to be an information element defining a region of interest within a product.

3.1 Design Context Knowledge Based Function to PDE Mapping Model

In order to support decision making at the conceptual design stage, a new generic function to PDE mapping process model is proposed here in this research [14], which uses design context knowledge to support decision making as shown in Figure 1.

The model consists of three groups of information or activities. The first group (i.e. the left hand column of the shaded rectangular box) is called the *Design Context Knowledge Based Solution Storage* and models a solution space in which the new decision made from an earlier design stage becomes the output to support the subsequent stage of the function to PDE mapping process. The second group (i.e. the right hand column of multiple square blocks) is called *Design Resources* and consists of resources to support the decision-making. These include a database, a library of functions, a function means association dictionary, a design context knowledge base, Analytic Hierarchy Process (AHP) [15] rules and designer preferences through which knowledge/information is input to different stages of the function to PDE mapping process. The third group (i.e. the central column of the oval shaped blocks) is called the *Design Context Knowledge Based Mapping Process* and describes the four stages of function to PDE mapping process, which is detailed below.

At every stage during the mapping process, the designer uses the inputs from the solution space and the design resources and generates new potential solution(s) thereby evolving the design solution. During the first stage, the designer takes the *Functional Requirements* and a *Dictionary of Proven Function-PDEs association* as inputs which result in *Initial Generated PDEs as output.* At the second stage, the designer takes these *Initial Generated PDEs* and searches for suitable models from the *Multi Perspective Product Current Working Model* library. This *Current Working Model* and the *Design Context Knowledge Base* are used to identify the exact context of the design problem i.e. functional requirements and solution information in different contexts. The design context knowledge base also facilitates the designer to reduce the initial set of PDEs into a reduced sub-set of

PDEs, which don't comply with the desired physical properties as defined in the functional requirements. During the third stage, the designer takes this reduced set of PDEs as inputs and performs function and PDEs reasoning simultaneously using the design context knowledge to generate *Context Knowledge Consequences* as the output of this stage. More information can be found in [3] and [4].

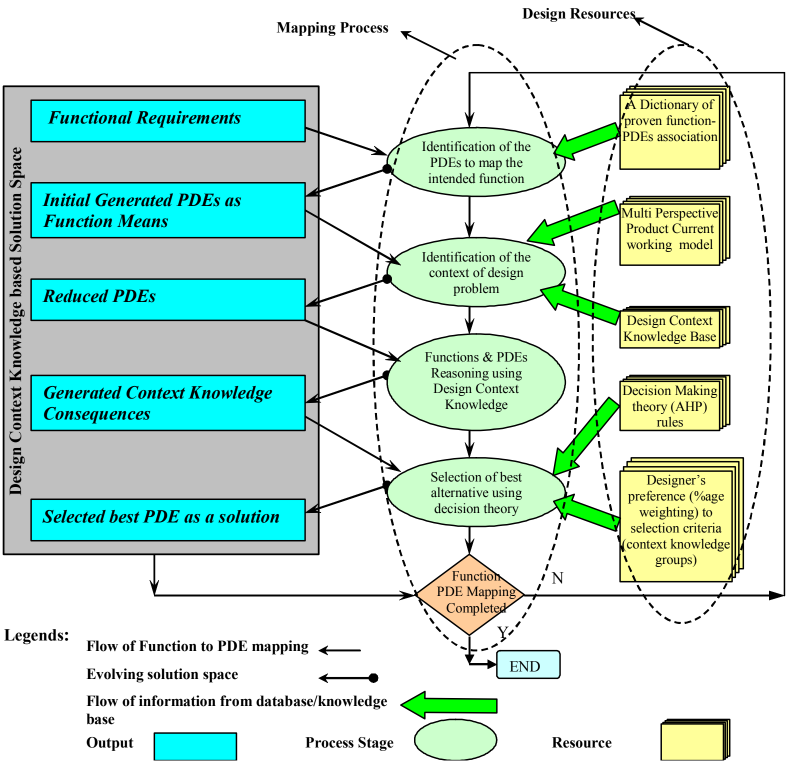

Figure 1. Function to PDE mapping model

At the final stage of the model, the designer uses the *Generated Context Knowledge Consequences, AHP rules* and the *Designer's Preference* as the reasoning engine and performs *decision making* by selecting the *best solution,* which not only fulfils the functional requirements, but also caters for the whole context of the design problem under consideration. This life cycle awareness is performed, by timely prompting the designer about these consequences, thereby providing proactive decision-making support to the designer.

This whole process of function to PDE mapping spanning these four stages, should be iterated for all functions in a given design problem, until all functions are realized by selecting the best solutions as described above. At this stage, function to PDE mapping is completed for a design problem.

4. Case Study

A case study of supporting conceptual design of a structural component using design context knowledge background reasoning is presented in this section. The case study is about to identify suitable PDEs/solutions to a functional requirement and then evaluate and select the best solution using context knowledge reasoning using different functionalities of the system.

Functional Requirement

The functional requirement is to *"Support Uniformly Distributed Load Along Length of Beam"*.

Conceptual Solutions

Based on the functional requirements following five conceptual solutions are generated/proposed (Figure 2).

These are different types of beams and with different cross sectional shapes and manufactured through different processes. A brief description of these solutions is

- *Rolled I-Beam* is manufactured through rolling process and a stock/ingot of material is fed through consecutive rolling mills to achieve the required shape.
- *Fabricated I-Beam* is manufactured by welding two flange plates with web plate using either continuous or intermittent fillet welding.
- *Fabricated Hollow Girder* is manufactured by welding two flange plates with two web plates using welding.
- *Staggered Web Beam* is manufactured by cutting the web plate in a staggered fashion and then welding the opposite edges of web plate to increase the depth of web plate and subsequently welding it with flange plates.
- *Rolled Channel Beam* is manufacture through rolling process and has Channel C cross sectional shape.

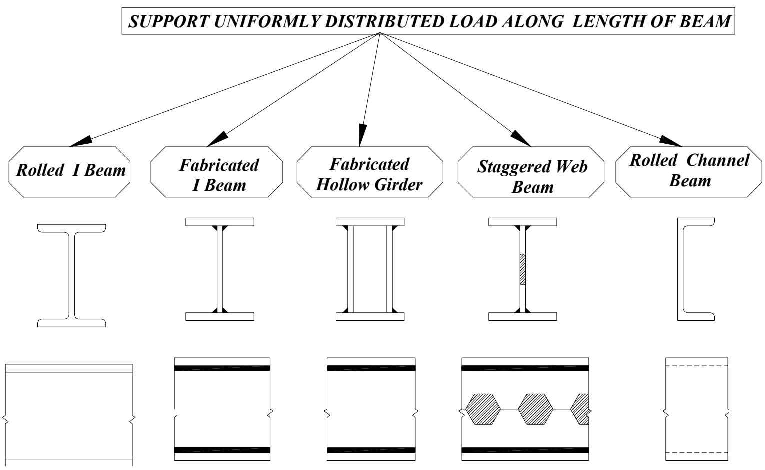

Figure 2. Functional requirement and corresponding generated solutions

4.1 Generated Context Knowledge and Reasoning

Context knowledge for the design problem under consideration is generated for each of the ten categories of context knowledge. As soon as these five means/solutions selected, context consequence knowledge/information is generated regarding each one of these means/solutions in each one of the ten categories of context knowledge. The context knowledge generated in this case study is taken from different sources of beam/structural design references.The information generated in each context knowledge category is analysed and reasoned to assign degrees of suitability from 0 to 5 as shown in figure 3 in first five different categories and the other five categories can be similarly derived and is omtted due to space constraint, but the results can be seen in Table 1. The higher the degree the more suitable is solution regarding the category under consideration. The degrees of suitability are assigned based on this study. The fewer the problematic consequences, the higher the degree of suitability. The scale and range of degrees of suitability are set as shown below:
Absolutely High=5; Very High=4; High=3; Low=2; Very Low=1; Not suitable=0.

4.2 Relative Weighting and Numerical Rating

The relative weighting among ten-design knowledge criterion (preference of one criteria over other) can be done by giving percentage weighting out of 100 for each categories. In this case study the relative weightings as designer’s preference is shown in the left hadn of table 1.

The assignment of numerical rating to each of design alternatives under each context knowledge criterion category is done by converting degree of suitability of each alternative described in previous section into weighting factor. This is done by using the comparison scales defined in decision making theory Analytic Hierarchy Process The Analytic Hierarchy Process (AHP) is a method that arranges all decisions factors in hierarchical structure, which descends from an overall goal to criteria, sub-criteria and finally to the alternatives, in successive levels. The decision maker is required to create matrices for the pair-wise comparisons for the alternatives’ performances using conversion scales against each criterion.

The values in each cell of matrices are then normalized and added to determine percentage numerical rating of each alternative against a particular context knowledge criterion to determine its suitability amongst all alternatives.

4.3 Selection of Best PDE/Design Solution

After determining relative weighting of each criteria and numerical rating of alternatives, the final task in this case study is to find the best design solution/alternative out of these five alternatives *(Rolled I-Beam, Fabricated I-Beam, Fabricated Hollow Girder, Staggered Web Beam, Rolled Channel Beam,).* The highest added normalized value is *3089* for *Rolled I-Beam* as shown in the table 1 below. Therefore Rolled I-Beam is the best solution out of all five alternatives.

1- *USER REQUIREMENT*

- Support Uniformly distribute load of 200 kg/M
- Length should be 10 M

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rolled I Beam	*Can be used for all types of loading*	5
Fabricated I Beam	*Can be used for all types of loading*	5
Fabricated Hollow Girder	*Can be used for all types of loading*	5
Staggered Web Beam	*Can be used for all types of loading*	5
Rolled Channel Beam	*Can be used for all types of loading*	5

2- *COMPONENT MATERIAL PROPERTIES/CONSUMPTION*

- ASTM A-36 Structural Steel as material of Beam

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rolled I Beam	*Can be used for all types of materials, Low material consmuption*	5
Fabricated I Beam	*Can be used for all types of materials, High material consumption*	4
Fabricated Hollow Girder	*Can be used for all types of materials, Very high material consumption*	3
Staggered Web Beam	*Can be used for all types of materials, low material consumption*	5
Rolled Channel Beam	*Can be used for all types of materials, low material consumption*	5

3- *QUALITY OF MEANS DURING USE (DEGREE OF FULLFILLING INTENDED FUNCTION IN DIFFERENT CONDITIONS)*

- Capable of withstanding/abosrbing shock load due to earthquake
- Capable of withstanding/absorbing lateral wind load
- Capable of withstanding load in high temperature conditions

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rolled I Beam	*Medium shock load resistant, high temperature resistant*	4
Fabricated I Beam	*Medium shock load resistant, low temperature resistant*	3
Fabricated Hollow Girder	*Very High shock load resistant, low temperature resistant*	4
Staggered Web Beam	*Very High shock load resistant, low temperature resistant*	4
Rolled Channel Beam	*Low shock load resistant, high temperature resistant*	3

4- *PRE-PRODUCTION REQUIREMENT {PREPARATION OF MATERIAL (S)}*

- Cost/Ease of preparing components (Less time to prepare)

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rolled I Beam	*No preparation is required*	5
Fabricated I Beam	*Edge preparation of sheets is required*	4
Fabricated Hollow Girder	*Edge preparation of sheets is required*	4
Staggered Web Beam	*Edge preparation as well as cutting of sheets is required*	2
Rolled Channel Beam	*No preparation is required*	5

5- *PRODUCTION REQUIREMENT (ADDITIONAL ITEMS/COMPONENTS)*

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rolled I Beam	*No additional item required*	5
Fabricated I Beam	*Low quantity of welding rods and filler material is required*	4
Fabricated Hollow Girder	*High quantity of welding rods and filler material is required*	3
Staggered Web Beam	*Very high quantity of welding rods and filler material is required*	2
Rolled Channel Beam	*No additional item required*	5

Figure 3. Partial list of degree of Suitability of a solution to a particular context knowledge category

Table 1 Evaluation and selection of alternatives according to Analytic Hierarchy Process

CRITERIA	WEIGHTING (%)	RATING OF SUITABILITIY OF ALTERNATIVES				
		ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
User Requirement	15	20.0	20.0	20.0	20.0	20.0
Component Material Properties/Consumption	10	28.1	10.8	5.1	28.1	28.1
Quality of Means During Use (Degree of Fullfilling Intended Function in Different Conditions)	10	27.3	9.1	27.3	27.3	9.1
Pre-Production Requirement {Preparation of Component(s)}	20	34.5	13.6	13.6	3.8	34.5
Production Requirement (Additional Items/Components)	15	36.0	16.2	7.9	4.0	36.0
PostProduction Requirement {Special Process(s) Required}	10	35.2	13.3	17.1	5.6	28.9
Production Equipment Requirement/Cost (Tooling/Machine Cost Required)	10	33.3	11.1	11.1	11.1	33.3
Quantity of Product Required	2.5	36.0	16.2	7.9	4.0	36.0
Achievable Production Rate of Selected Means	5	36.0	16.2	7.9	4.0	36.0
Degree of Available Quality Assurance Techniques	2.5	20.0	20.0	20.0	20.0	20.0
Consolidated Rating of Each Alternative	**100**	***3089***	**1430**	**1406**	**1237**	**2844**

5. Conclusions

Design context knowledge is an important source of product background knowledge and it can and should influence design decision making, which result in design consequences. Adequately relating this knowledge and using it as a guide can lead to design solutions, which are most relevant and optimised for a given product application context. By exploring the design context knowledge as shown in the presented case study, designers can gain insights into understanding of the design problem and the solutions generated with an increasing emphasis on the product life cycle performance. Reasoning using context knowledge can further assist designers to concentrate on exploring design alternatives and generate more innovative design solutions thus reducing/eliminating the chances of redesign by considering manufacturing implications and increased costs earlier at conceptual design stage due to the selection of a particular solution.

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