
APPLICATION OF CONTEXT KNOWLEDGE IN SUPPORTING CONCEPTUAL DESIGN DECISION MAKING

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Abstract: Conceptual design is the most important phase of the product life cycle as the decisions taken at conceptual design stage affect the downstream phases (manufacture, assembly, use, maintenance, and disposal) in terms of cost, quality and function performed by the product. This research takes a holistic 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 to make an informed decision making 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. Using a case study, this paper shows the proof of the concept by selecting one concept among different design alternatives using design context knowledge thereby proactively supporting conceptual design decision making for an informed and effective decision making.

Keywords: Conceptual Design, Decision Making, Context Knowledge, Product Life Cycle.

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1 Introduction

Conceptual Design is a stage of the design process in which: problems are identified, functions and specifications are laid out and appropriate solutions are generated through the combination of some basic building blocks using some working principles (Navinchandra, 1992; French, 1985). Conceptual Design is commonly seen to be the most important phase of the design process (Roozenburg and Eekels, 1995), because the decisions made here will strongly impact on all subsequent phases of the design process. A weak concept can never be turned into an optimum detailed design. In addition the main functions of the conceptual design stage are to generate and evaluate broad solutions, given the specification, which provides a suitable start up point for embodiment design and detail design.

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 different stages of the product life cycle as well as on the external world which comprises environment of the product in which it operates and users of the product. It is therefore necessary for the designers to be aware of the consequences (Andreasen and Olesen, 1990; Borg and Yan, 1998) 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. A review of existing methods and associated frameworks (Rehman and Yan, 2007) argue that there is a need not only to identify the whole context and all 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 design context knowledge 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. Hence, it is essential to identify, understand the role and utilize design context knowledge in order to support the conceptual design stage where. This research (Rehman, 2006) addresses this problem by proposing, implementing and evaluating a computational framework for supporting decision making at the conceptual design stage. This paper describes about the formalism of the design context knowledge, corresponding computational framework developed to support decision making and a case study in detail to highlight the effectiveness of approach. The second section discusses the importance of conceptual design decision making on later life cycle stages of the product. The third section of the paper explains in detail about the idea of 'Context' in design and the new meaning and formalism of 'Context' proposed by the authors. The fourth section describes the developed model/framework as the core of this research. The fifth section

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explains in detail a case study of design decision making using the proposed model to prove and highlight the effectiveness of the approach. The final section of the paper concludes the paper by commenting on the overall usefulness of developed approach in supporting conceptual design decision making.

2 Decision making at the conceptual design stage

Decision making and design are so intertwined that it has been suggested that the entire decision making can be viewed as design (Simon, 1969). The design concept evaluation and selection undertaken while exploring solution space makes the conceptual design stage a decision intensive process (Mistree and Smith, 1993; Starvey, 1992; Joshi, 1991). Decisions are made on various aspects of the product being designed (Duckworth and Baines, 1998) and typical decisions involve selection of working principles and corresponding concepts and solutions. Furthermore some decisions, which seem appropriate for one life cycle requirement, can pose problems on other life cycle phases (Hubka and Eder, 1988). This implies that the part of a decision taken within one life phase (e.g. product design) affects the type, content, efficiency and progress of activities within other life phases (e.g. assembly, manufacturing and use). For example a decision of using countersink head screws instead of snap fit to assemble two parts will result in different design, manufacture and maintenance approaches and techniques. Therefore designers need to be aware of consequences of their decisions early at the conceptual design stage to undertake an effective and informed life cycle oriented decision making.

2.1 Decisions' consequence awareness

Design decisions are associated with consequences (Andreasen and Olesen, 1990; Duffy and Andreasen, 1993) which can either be intended or unintended and either good or problematic (Borg and Yan, 1998) and have the ability to influence the performance of other life-cycle phases in terms of measures such as cost and time (Hubka and Eder, 1988). Gero (Gero, 1998) argued that the conceptual design process is a sequence of situated acts. He calls this concept *situatedness* i.e. the notion that addresses the role of the context knowledge in engineering design. This implies that conceptual design is a dynamic activity, which should be undertaken in the context of an external world and therefore any decisions made by the designer have implications on the external world, which comprises the product operational environment and users of the product. It is therefore necessary for the designers to be aware of the consequences 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, operational environment, and users of the product.

3 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 (Oxford, 1998) definition of context is *the set of facts or circumstances that surround a situation or event*.

To date some researchers have only provided a contextual framework to explore relationships between the design context and design practice, giving no systematic consideration to the implications of all context knowledge on decision making at the conceptual design stage. For example Maffin (Maffin, 1998) has presented a contextual framework to explore the relationships between the design context and design practice. Design context is captured in terms of a company's unique internal and external attributes (i.e. its organization, markets, products, production process, suppliers, local and global environment), its strategic policies and the key features of the specific projects. Hales (Hales, 1993) has presented a contextual model, which incorporates environmental influences at the macroeconomic, microeconomic, and corporate and project levels by using pre-developed checklists to allow the designer to assess the impact of these influences on the design project. Dorst (Dorst and Hendriks, 2001) investigated the role and importance of design context in practical designing by studying the interactions and influences of various stake holders which they referred 'context parties' such as design team, design project managers, clients, suppliers and design agency on the practical designing of the product. Sudrasan (Sudrasan et al., 2005) developed a product information modelling framework for product life cycle management (PLM). The framework used a core product model to capture the design context in the form of product and design rationale, assembly and tolerance information at different life cycle stages of the product. Shahare (Shahare and Gurumoorthy, 2007) argued that context is the frame of mind defined by an individual designers' Meta knowledge and beliefs that are active at that particular instance, invoked to characterise an entity. Kim (Kim et al., 2007) presented an approach to improve design reuse through actively delivering the information that a designer will need for subsequent tasks in different contexts so that he or she is aware of available information. Charlton (Charlton and Wallace, 2000) summarised design context interpreted by some 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".*

These examples clearly indicate that the use of 'Context' in engineering design is limited to the consideration of only some aspects such as socio-economic pressures on designer, environmental influences and company's policies. There is not a single piece of work representing the holistic view of design 'Context' to support 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 behavior 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* can be defined as *the related surrounding knowledge of a design problem at a given moment in time for consideration* (Rehman and Yan, 2004).

3.1 Design context knowledge formalism

The review of existing methods and frameworks (Rehman and Yan, 2007) 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 (Zhang, 1998) (that is partial solution information 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 (Rehman and Yan, 2004). 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 (Yan, et al., 2002; Borg and MacCallum, 1997; Borg et al., 1999). The work (Yan, et al., 2002; Borg and MacCallum, 1997; Borg et al., 1999) 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 briefly summarised below. -

3.1.1 User requirements/preferences

This category of context knowledge deals with the users of the product and is defined as *the knowledge about the requirements/preferences of the users of the product*. This type of knowledge is important to understand the intended users of the product and their preferences about the product. Reasoning using product user requirements can help the designer to gain an insight into the user preferences in the selection of a particular solution, which would be considered as more suitable for the users. An example could be a requirement of a smaller size of handle bar of an iron or a kettle for the female user group.

3.1.2 *Product/Components' material properties*

This category of context knowledge is defined as *information related to product's material properties* and includes general material specifications of the components like type of material, specification, strength, durability, allowable stress and hardness etc. Providing timely information to the designer using background reasoning about material properties would help the designer in selecting those solutions, which are structurally feasible.

3.1.3 *Quality of means/solution during use*

It is defined as *the measure/degree of fulfilling the intended function by a solution in different working environment/conditions*. This also implies how much a selected solution deviates from desired behaviour due to the quality of the solution and the influence of working environment. This knowledge could be the suitability of the selected solution to different working conditions like high temperature environment, increased vibration, and shock/impact load application. An example of this type of knowledge is a lack of consideration of the impact of high temperature on the slack in a friction belt, which will be significantly high as compared to one at the ambient temperature environment.

3.1.4 *Pre-production requirement*

This category of context knowledge is defined as the information required to prepare the material (i.e. cut material to correct size, straightening the stock, cut edges and so forth) before a component is manufactured or bought in if any required. This type of context knowledge is normally referred as Life cycle more specifically context knowledge in the form of life phase system's constraints. Reasoning using pre-production requirements involves evaluating and comparing time and cost required incurred on pre-production processes and bought in components for different solutions. This is an important source of knowledge about the constraints that manufacture/assembly systems impose on design decisions of a solution product. Designers are often unaware of these limitations and as design decisions become more related to other factors, it is very difficult, if possible, for designers to foresee these potential decision consequences. Through the use of these Life Cycle Consequences (LCCs), it is possible to remind designers proactively the potential consequences of their decisions. An example is the requirement for the use of shielding flux as well as the preparation of edges before welding two sheet metal plates.

3.1.5 *Production requirement*

Production requirement is defined as *the knowledge about actual manufacturing/production requirements for a solution*. For example a sheet metal base slot-fit solution requires a rectangular slot on female part and a double 90° bend on male part. This type of knowledge is important for designer not only to analyse the ease of manufacturing of a specific feature on the component but also to compare the cost incurred in manufacturing each of these features, thus giving support to the designer in selecting solutions that involve less manufacturing time and low manufacturing cost.

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3.1.6 Post-production requirement

Post-production requirement is described as *a special process that is needed after manufacturing/inscribing a solution on the component*. An example of such a requirement could be retightening of a specifically designed nut in case of *Hole-fastener* as solution to an 'Assembly' function between two products during service/use. Reasoning using this type of context knowledge generates consequences about life phase systems (Maintenance/Service) and helps designer in avoiding unintended problematic/costly consequences. The consequence in this example could be the time and cost of equipment incurred in retightening of nuts. Therefore it is necessary to compare the time required and the cost of equipment that would occur during use, maintenance and service phase of a product among all the potential solutions in order to select the low cost and short lead-time solution.

3.1.7 Production equipment requirement

The knowledge related to Production Equipment Requirement comes under the category of life cycle context knowledge and deals with *knowledge of Tooling/Machines required to manufacture a particular solution on a component*. Timely prompting designer about the type and cost of machine/tooling that would require manufacture/realize a selected solution will help in making a cost effective decision as more costly and increased number of machines will increase the overall lead-time and product cost. An example could be the use of fine blanking dies for high surface finish in punching/blanking operation of sheet metal components instead of ordinary dies which are less costly, but requires a secondary (trimming) operation to get high surface finish of products.

3.1.8 Quantity of product required

Quantity of product/component required is an important factor in selecting a particular manufacturing solution to realize a certain function. The quantity of product directly affects the selection of production method because an expensive production method can result in high quality better selling mass manufactured product. Therefore higher equipment cost can be justified if return from the profit of mass produced components is sufficiently high. Therefore the information about quantity of product is necessary at conceptual design stage to select a suitable manufacturing solution, which can be cost effective.

3.1.9 Achievable production rate

Time required and level of difficulty to manufacture different features varies considerably. Therefore it is necessary to consider the achievable production rate of each solution using the selected production equipment before making a final decision to go ahead with the selected design solution. Higher achievable production rate will not only reduce the lead-time of the product, but also reduces the production overhead costs thus reducing the overall product cost. It is clear that the achievable production rate should be used to help evaluate design solutions, which affect the lead-time and production cost.

3.1.10 Degree of available quality assurance techniques

A selection of a solution with high degree of available quality assurance techniques helps in avoiding accidents or breakdowns due to performance of solution during use. This

results into low maintenance cost as well reduced time in maintenance/repair work. An example of this type of information is the availability of non-destructive testing methods such as X-Ray and ultrasound techniques to determine the strength of a metal joint during its operation/use phase.

These ten categories of context knowledge can be used for reasoning to provide decisions' consequence awareness to the designer at the conceptual design stage. The conceptual design process is modelled as the transformation between three different information states (Welch and Dixon, 1992) which are function, behaviour and form of means/solution alternatives. This implies that conceptual design can be interpreted as function to means mapping process during which decision making takes place regarding the selection and evaluation of different design alternatives. Since a framework explaining the interactions of these three important elements (function, behaviour and form of solutions/means), therefore this research proposes a new function to means mapping model, which uses these ten categories of design context knowledge to support conceptual design decision making.

4 Function to Means Mapping Model

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 (Andreasen and Hansen, 1996) 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) (Borg et al., 1999). 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 manufacturing *feature* is considered to be an information element defining a region of interest within a product.

4.1 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 (Rehman and Yan, 2003), 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) (Saaty, 1990) rules which a decision is making method and designer preferences through which knowledge/information is input to different stages of the

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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.

4.2 Working of the Model

The function to means mapping process takes place in four stages. At every stage during the function to means 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 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 as shown in Figure 2.

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.

Analytic Hierarch Process is selected as the chosen decision making methods because of its following merits:

- AHP can be used for both quantitative and qualitative subjective information analysis.
- Since the desired problem of decision making in this research requires pair-wise comparison, (i.e. the chosen PDE selection problem, requires pair-wise comparison of each PDE alternative against other PDEs), the use of AHP method seems appropriate.
- This method provides comparison of different design alternatives against design criteria but also provides for comparison of different design criteria against designer's preferences.
- By virtue of adopting the AHP as decision making method, it is possible to take into account criteria with different levels of description i.e. hierarchical ranking of a criterion from the top to the bottom level is possible.

This whole process of function to PDE/means 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.

5 Case Study of Structural Component Selection

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 3).

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.

5.1 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 4a and figure 4b in ten different categories. 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:

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Absolutely High=5; Very High=4; High=3; Low=2; Very Low=1; Not suitable=0.

5.2 Relative Weighting and Numerical Rating

The relative weighting among ten-design knowledge criterion (preference of one criterion over other) can be done by giving percentage weighting out of 100 for each category. In this case study the relative weightings as designer's preference is shown 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. These scales are shown in figure 5. The ratings of alternatives using these scales for each context knowledge category are shown in figures 6a and 6b.

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.

5.3 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 2 below. Therefore *Rolled I-Beam* is the best solution out of all five alternatives.

The case study illustrated realisation of only one solution for a selected functional requirement. In order to realized all functional requirements all 4 stages of the model should be iterated again for each desired functional requirement, until all functions are realized by chosen/selected solutions. However the impact on the mapping of the considered function to those solutions, which have already been mapped still needs to be investigated as a future research direction of this research.

6 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. The developed function to means mapping model guides a designer not only in choosing the best solution to a given functional requirement but also informs an individual designer about the consequences of selecting a particular solution thus

supporting in making an informed decision making. Proper formalising and structuring of design context knowledge in different categories can help a designer to use this vast amount of information and knowledge in making an effective decision making during design concept selection at conceptual design stage. By exploring the design context knowledge as shown in the presented case study, a designer can gain insights into understanding of the design problem and the solutions generated with an increasing emphasis on the product life cycle performance for a selected functional requirement. Reasoning using context knowledge can further assist individual 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.

References

- Andreasen, M.M. and J. Olesen (1990) 'The Concept of Dispositions', *Journal of Engineering Design*, Vol. 1, No. 1, pp. 17-36.
- Andreasen, M.M. and Hansen, C.T. (1996), 'The Structuring of Products and Product Programmes', *Proceedings of 2nd WDK Workshop on Product Structuring*, Delft University, The Netherlands, pp. 14-53.
- Borg, C. J., and MacCallum, K.J. (1997) 'A Life-Cycle Consequences Model Approach To The Design For Multi-X of Components', *Proceedings of the 11th International Conference on Engineering Design (ICED97)*, Tampere, Finland, pp. 647-652.
- Borg, C. J., Yan, X. T., Juster, N. (1999) 'Guiding component form design using decision consequence knowledge support', *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 13, pp. 387-403.
- Borg, J. C. and Yan, X.T. (1998) 'Design Decision Consequences: Key to 'Design For Multi-X' Support', *Proceedings of 2nd International Symposium 'Tools and Methods for Concurrent Engineering*, Manchester, UK, pp. 169-184.
- Charlton, C. and Wallace, K. (2000) 'Reminding and context in design', *Proceedings of Artificial Intelligence in Design 2000*, Massachusetts, USA, pp. 596-588.
- Dorst, K. and Hendriks, D. (2001), 'The Role of the Design Context: In Practice and in Design Methodology', Virtual Symposium on Designing in Context, Delft University, Delft University of Technology, The Netherlands, 18-20 December 2001.
- Duckworth, A.P. and Baines, R.W. (1998) 'An Eco-Design Framework for Small and Medium Sized Manufacturing Enterprises', *Proceedings of 2nd International Symposium 'Tools and Methods For Concurrent Engineering*', Manchester, UK, pp. 132-141.
- Duffy, A.H.B. and M.M. Andreasen (1993) 'Design Co-ordination for Concurrent Engineering', *Journal of Engineering Design*, Vol. 4, No. 4, pp. 251-265.
- Gero, J.S. (1998) 'Conceptual designing as a sequence of situated acts', *Artificial Intelligence in Structural Engineering* Ed I. Smith, Springer, Berlin, pp. 165-177.
- Hales, C. (1993) *Managing Engineering Design*. John Wiley & Sons, New York.
- Hubka, V. and W.E. Eder (1988) *Theory of Technical Systems: a Total Concept Theory of for Engineering Design*, Springer Verlag, Berlin.
- Joshi, S.P. (1991) 'Decision making in Preliminary Engineering Design', *Artificial Intelligence in Engineering Design and Manufacture*, Vol. 5, No. 1, pp. 21-30.
- Kim, S., Bracewell, R.H., Wallace, K.M. (2007), 'Improving Design Reuse Using Context', *Proceedings of International Conference on Engineering Design, ICED07*, pp. 177-178.
- Maffin, D. (1998) 'Engineering Design Models: context, theory and practice', *Journal of Engineering Design*, Vol. 9, No. 4, pp. 315-327.

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- Mistree, F. and Smith, W. (1993) 'A decision-based approach to concurrent design', *Concurrent Engineering-Contemporary Issues and Modern Design Tools* eds H.R. Parsaei and W.G. Sullivan, London, Chapman & Hall, pp. 127-158.
- Oxford (1998) *The New Oxford Dictionary of English*. Oxford University Press, UK.
- Rehman F. (2006) 'A Framework for Conceptual Design Decision Support', PhD Thesis, CAD centre, Dept. of DMEM, University of Strathclyde, Glasgow, UK.
- Rehman, F. and Yan, X.T. (2003) 'Product design elements as means to realize functions in mechanical conceptual design', *Proceedings of 14th International Conference on Engineering Design ICED 03*, Stockholm, Sweden, pp. 213.
- Rehman, F. and Yan, X.T. (2004) 'Conceptual Design Decision Making Using Design Context Knowledge', *CD-ROM Proceedings of 5th Integrated Design & Manufacture in Mechanical Engineering Conference*, Bath, UK.
- Rehman, F., Yan, X.T. (2007), "Supporting Early Design Decision Making Using Design Context Knowledge", *Journal of Design Research*, Vol. 6, Nos. 1-2, 2007, pp. 169-189.
- Roozenburg, N.F.M. and J. Eekels (1995) *Product Design: Fundamentals and Methods*, John Wiley & Sons: West Sussex, England.
- Saaty, T.L. (1990) 'How to Make a Decision: The Analytic Hierarchy Process', *European Journal of Operational Research*, Vol. 48, pp. 9-26.
- Shahare, M. Gurumoorthy, B. (2007), 'Towards Defining Context', *Proceedings of International Conference on Engineering Design, ICED07*, pp. 175-176.
- Simon, H.A. (1969) *The Sciences of the Artificial*. Massachusetts Institute of Technology Press, Cambridge, USA.
- Starvey, C.V. (1992) *Engineering Design Decisions*, Edward Arnold, London.
- Sudarsan, R., Fennes, S.J., Sriram, R.D., Wang, F. (2005), 'A product information modeling framework for product lifecycle management', *Computer Aided Design*, Vol. 37, pp. 1399-1411.
- Welch R V and Dixon J R. (1992) Representing function, behaviour and structure during conceptual design. *Proceedings of ASME Design Theory and Methodology Conference*, Scottsdale, USA, pp.11-18.
- Yan, X.T., Rehman, F., Borg, J.C. (2002) 'FORESEEing design solution consequences using design context information' *Proceedings of the Fifth IFP Workshop in Knowledge-Intensive Computer-Aided Design*, Malta, pp.18-33.
- Zhang, Y. (1998) *Computer-based modelling and management for current working knowledge evolution*, PhD Thesis, Strathclyde University, UK.

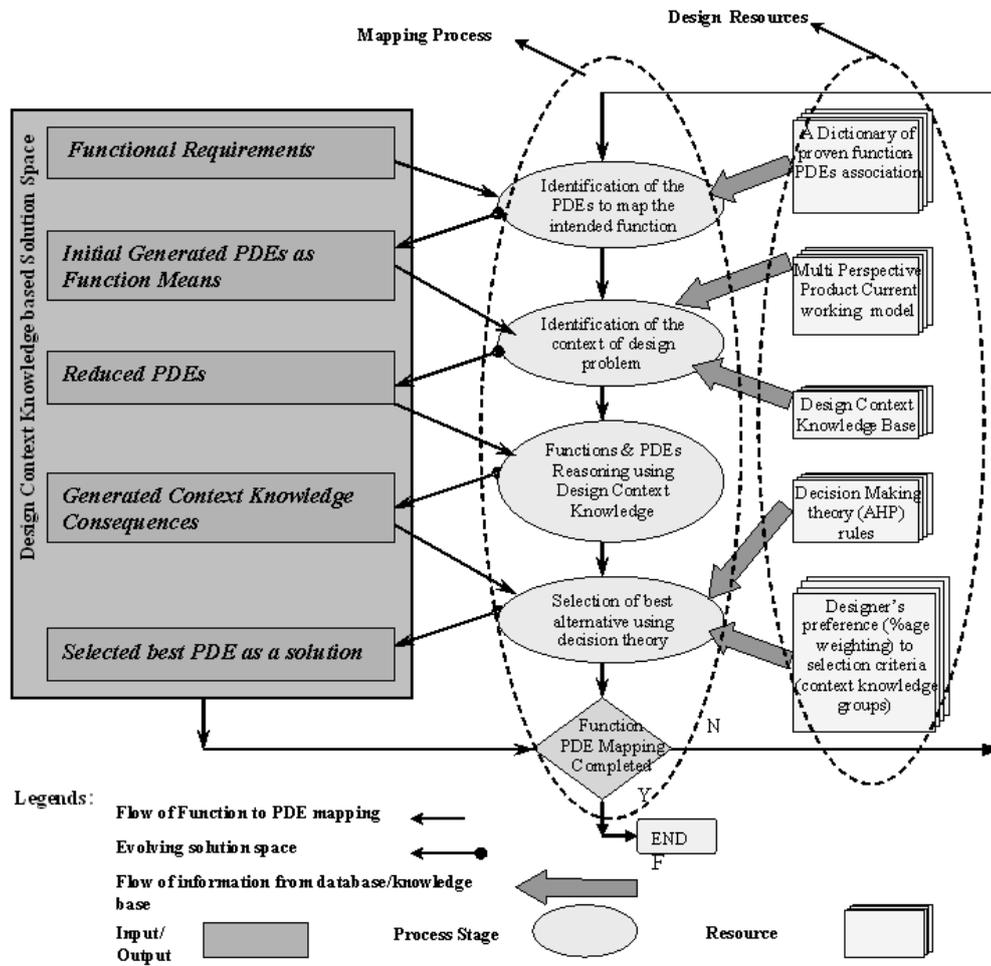


Figure 1: Function to PDE mapping model

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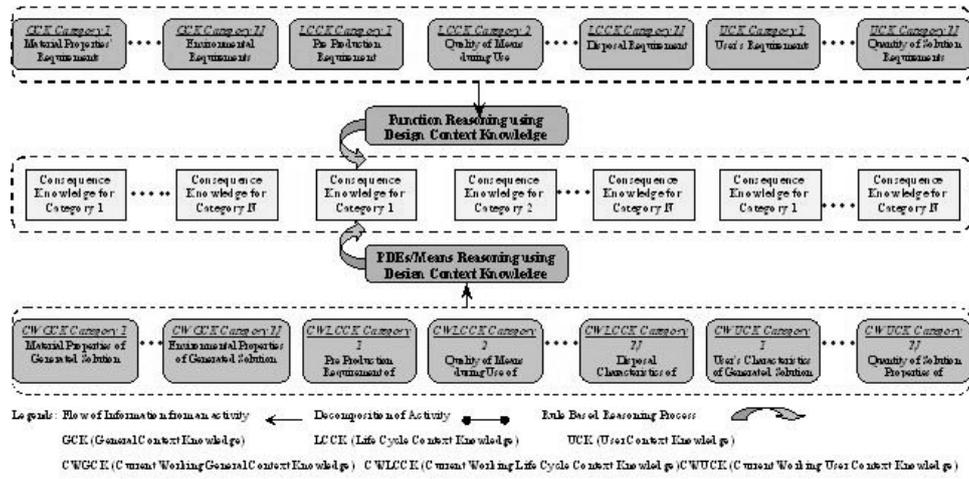


Figure 2: Consequences generation through reasoning process

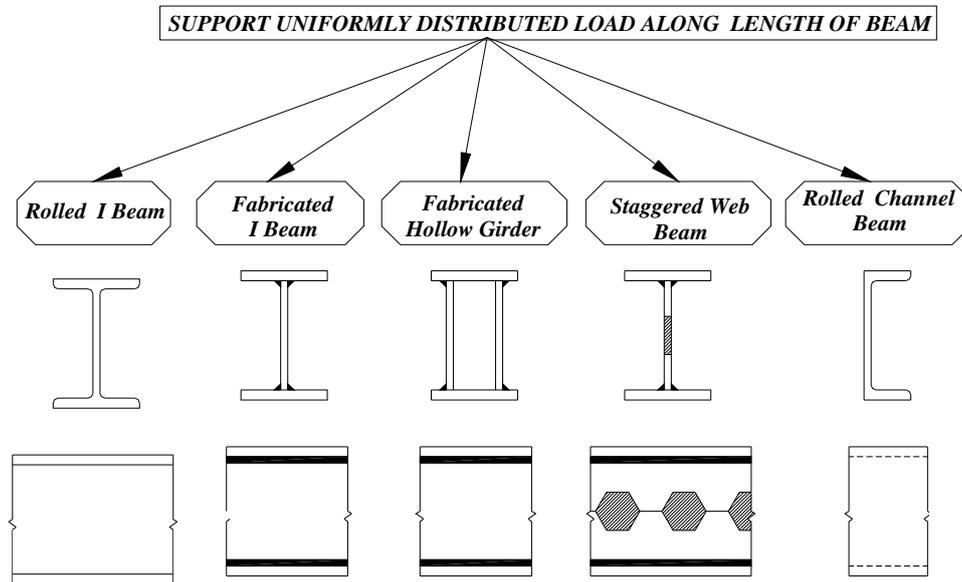


Figure 3: Functional requirement and corresponding generated solutions

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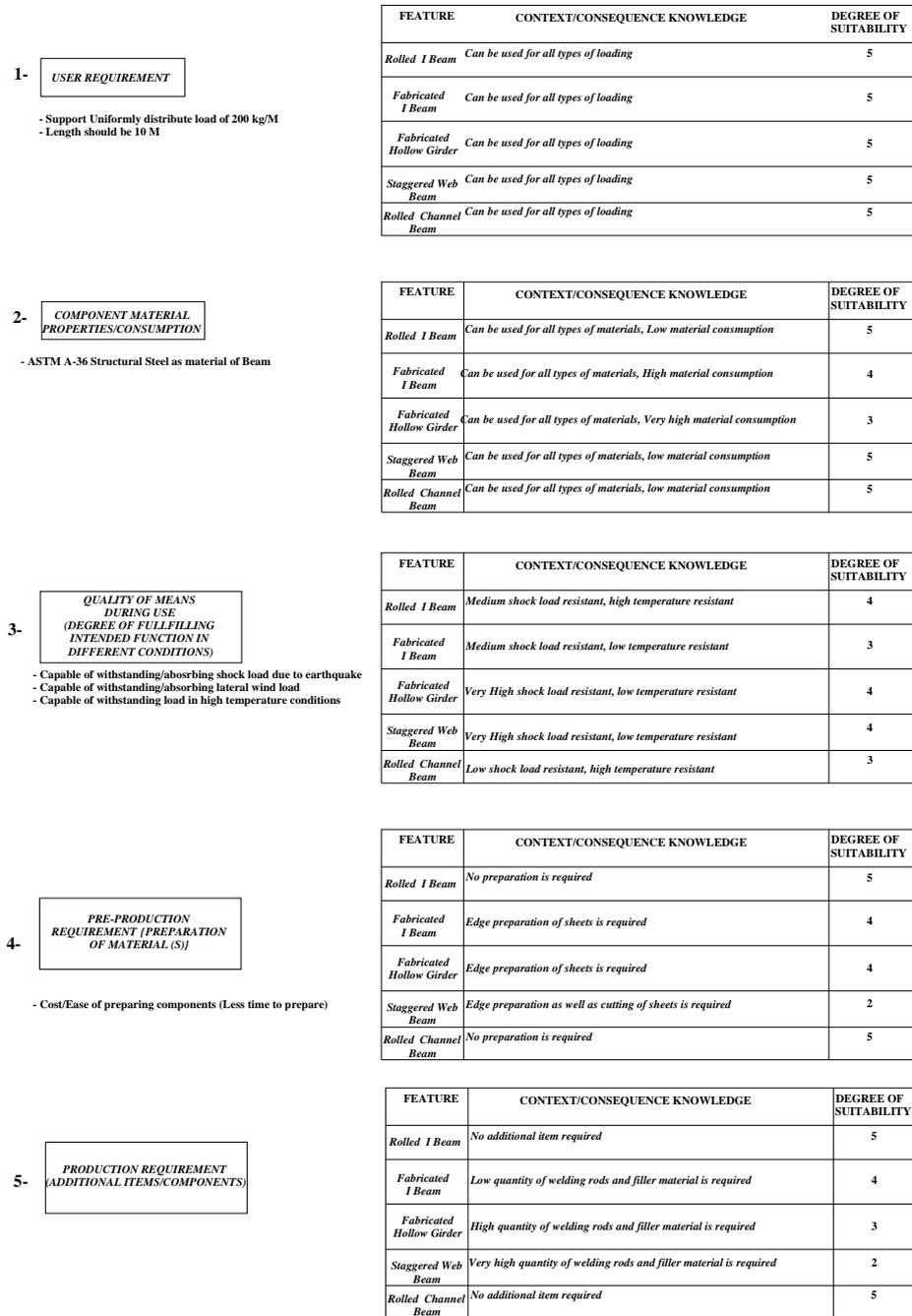


Figure 4a: Degree of Suitability of a solution to a particular context knowledge category for 1st 5 categories

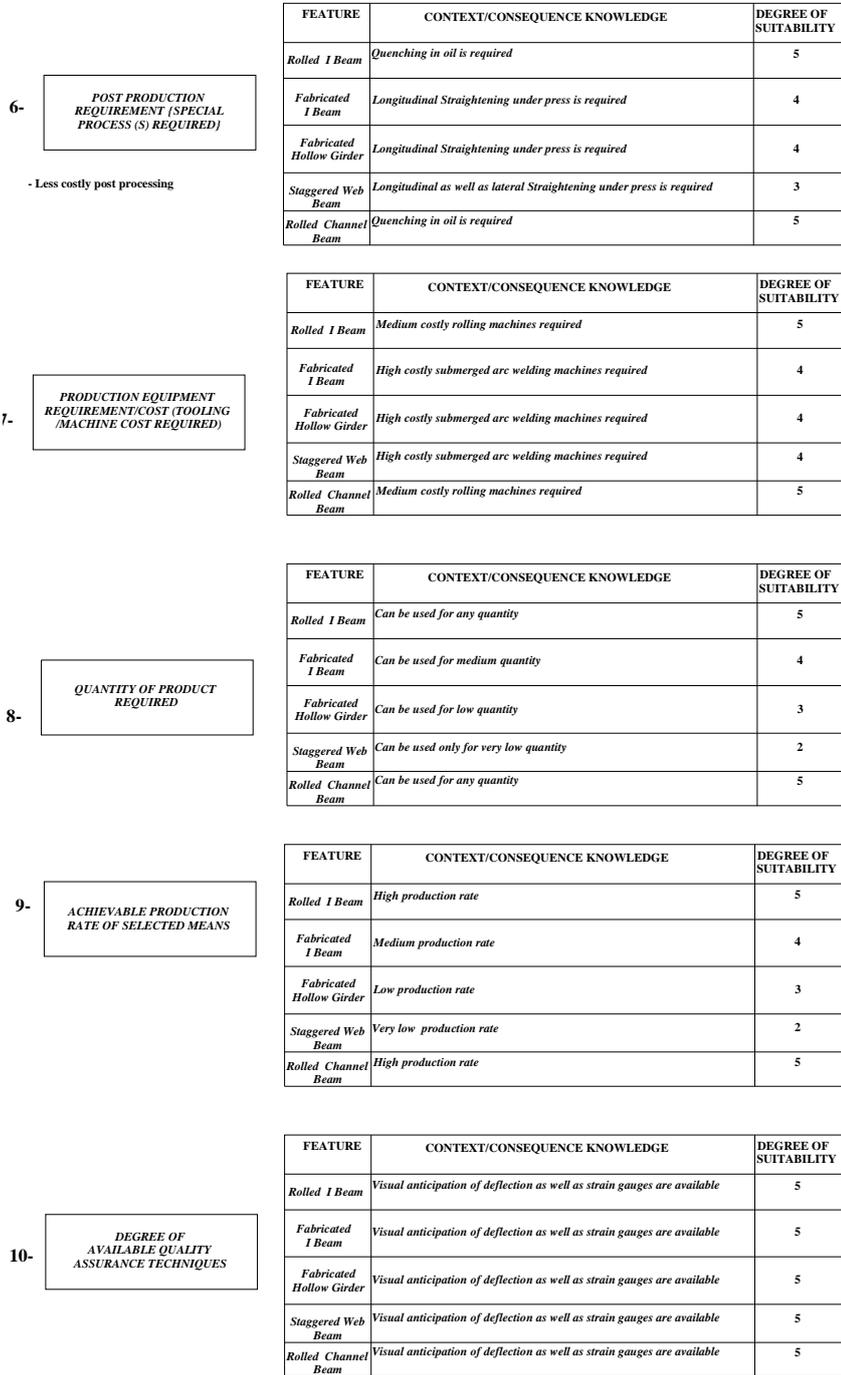


Figure 4b: Degree of Suitability of a solution to a particular context knowledge category for last 5 categories

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1: Both criteria of equal importance

3: Left weakly more important than top

5: Left moderately more important than top

7: Left strongly more important than top

9: Left absolutely more important than top

1/3: Top weakly more important than left

1/5: Top moderately more important than left

1/7: Top strongly more important than left

1/9: Top absolutely more important than left

Figure 5: Comparison scales to convert degree of suitability

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Rating of Alternatives on						User Requirement					
ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	1	1	1	1	ROLLED I-BEAM	0.200	0.200	0.200	0.200	0.200
FABRICATED I-BEAM	1	1	1	1	1	FABRICATED I-BEAM	0.200	0.200	0.200	0.200	0.200
FABRICATED HOLLOW GIRDER	1	1	1	1	1	FABRICATED HOLLOW GIRDER	0.200	0.200	0.200	0.200	0.200
STAGGERED WEB BEAM	1	1	1	1	1	STAGGERED WEB BEAM	0.200	0.200	0.200	0.200	0.200
ROLLED CHANNEL BEAM	1	1	1	1	1	ROLLED CHANNEL BEAM	0.200	0.200	0.200	0.200	0.200

Rating of Alternatives on						Component Material Properties/Consumption					
ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	3	5	1	1	ROLLED I-BEAM	0.283	0.290	0.263	0.283	0.283
FABRICATED I-BEAM	1/3	1	3	1/3	1/3	FABRICATED I-BEAM	0.094	0.097	0.158	0.094	0.094
FABRICATED HOLLOW GIRDER	1/5	1/3	1	1/5	1/5	FABRICATED HOLLOW GIRDER	0.057	0.032	0.053	0.057	0.057
STAGGERED WEB BEAM	1	3	5	1	1	STAGGERED WEB BEAM	0.283	0.290	0.263	0.283	0.283
ROLLED CHANNEL BEAM	1	3	5	1	1	ROLLED CHANNEL BEAM	0.283	0.290	0.263	0.283	0.283

Rating of Alternatives on						Quality of Means During Use (Degree of Fulfilling Intended Function in Different Conditions)					
ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	3	1	1	3	ROLLED I-BEAM	0.273	0.273	0.273	0.273	0.273
FABRICATED I-BEAM	1/3	1	1/3	1/3	1	FABRICATED I-BEAM	0.091	0.091	0.091	0.091	0.091
FABRICATED HOLLOW GIRDER	1	3	1	1	3	FABRICATED HOLLOW GIRDER	0.273	0.273	0.273	0.273	0.273
STAGGERED WEB BEAM	1	3	1	1	3	STAGGERED WEB BEAM	0.273	0.273	0.273	0.273	0.273
ROLLED CHANNEL BEAM	1/3	1	1/3	1/3	1	ROLLED CHANNEL BEAM	0.091	0.091	0.091	0.091	0.091

Rating of Alternatives on						Pre-Production Requirement (Preparation of Component(s))					
ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	3	3	7	1	ROLLED I-BEAM	0.356	0.366	0.366	0.280	0.356
FABRICATED I-BEAM	1/3	1	1	5	1/3	FABRICATED I-BEAM	0.119	0.122	0.122	0.200	0.119
FABRICATED HOLLOW GIRDER	1/3	1	1	5	1/3	FABRICATED HOLLOW GIRDER	0.119	0.122	0.122	0.200	0.119
STAGGERED WEB BEAM	1/7	1/5	1/5	1	1/7	STAGGERED WEB BEAM	0.051	0.024	0.024	0.040	0.051
ROLLED CHANNEL BEAM	1	3	3	7	1	ROLLED CHANNEL BEAM	0.356	0.366	0.366	0.280	0.356

Rating of Alternatives on						Production Requirement (Additional Items/Components)					
ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	3	5	7	1	ROLLED I-BEAM	0.374	0.398	0.349	0.304	0.374
FABRICATED I-BEAM	1/3	1	3	5	1/3	FABRICATED I-BEAM	0.125	0.133	0.209	0.217	0.125
FABRICATED HOLLOW GIRDER	1/5	1/3	1	3	1/5	FABRICATED HOLLOW GIRDER	0.075	0.044	0.070	0.130	0.075
STAGGERED WEB BEAM	1/7	1/5	1/3	1	1/7	STAGGERED WEB BEAM	0.053	0.027	0.023	0.043	0.053
ROLLED CHANNEL BEAM	1	3	5	7	1	ROLLED CHANNEL BEAM	0.374	0.398	0.349	0.304	0.374

Figure 6a: Rating of Alternatives using AHP scales for first five context knowledge categories with last five columns showing normalized values for each design alternative

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Rating of Alternatives on Post Production Requirement (Special Process (s) Required)

ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	3	3	5	1	ROLLED I-BEAM	0.349	0.360	0.474	0.294	0.283
FABRICATED I-BEAM	1/3	1	1	3	1/3	FABRICATED I-BEAM	0.116	0.120	0.158	0.176	0.094
FABRICATED HOLLOW GIRDER	1/3	1	1	3	1	FABRICATED HOLLOW GIRDER	0.116	0.120	0.158	0.176	0.283
STAGGERED WEB BEAM	1/5	1/3	1/3	1	1/5	STAGGERED WEB BEAM	0.070	0.040	0.053	0.059	0.057
ROLLED CHANNEL BEAM	1	3	1	5	1	ROLLED CHANNEL BEAM	0.349	0.360	0.158	0.294	0.283

Rating of Alternatives on Production Equipment Requirement/Cost (Tooling/Machine Cost Required)

ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	3	3	3	1	ROLLED I-BEAM	0.333	0.333	0.333	0.333	0.333
FABRICATED I-BEAM	1/3	1	1	1	1/3	FABRICATED I-BEAM	0.111	0.111	0.111	0.111	0.111
FABRICATED HOLLOW GIRDER	1/3	1	1	1	1/3	FABRICATED HOLLOW GIRDER	0.111	0.111	0.111	0.111	0.111
STAGGERED WEB BEAM	1/3	1	1	1	1/3	STAGGERED WEB BEAM	0.111	0.111	0.111	0.111	0.111
ROLLED CHANNEL BEAM	1	3	3	3	1	ROLLED CHANNEL BEAM	0.333	0.333	0.333	0.333	0.333

Rating of Alternatives on Quantity of Product Required

ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	3	5	7	1	ROLLED I-BEAM	0.374	0.398	0.349	0.304	0.374
FABRICATED I-BEAM	1/3	1	3	5	1/3	FABRICATED I-BEAM	0.125	0.133	0.209	0.217	0.125
FABRICATED HOLLOW GIRDER	1/5	1/3	1	3	1/5	FABRICATED HOLLOW GIRDER	0.075	0.044	0.070	0.130	0.075
STAGGERED WEB BEAM	1/7	1/5	1/3	1	1/7	STAGGERED WEB BEAM	0.053	0.027	0.023	0.043	0.053
ROLLED CHANNEL BEAM	1	3	5	7	1	ROLLED CHANNEL BEAM	0.374	0.398	0.349	0.304	0.374

Rating of Alternatives on Achievable Production Rate of Selected Means

ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	3	5	7	1	ROLLED I-BEAM	0.374	0.398	0.349	0.304	0.374
FABRICATED I-BEAM	1/3	1	3	5	1/3	FABRICATED I-BEAM	0.125	0.133	0.209	0.217	0.125
FABRICATED HOLLOW GIRDER	1/5	1/3	1	3	1/5	FABRICATED HOLLOW GIRDER	0.075	0.044	0.070	0.130	0.075
STAGGERED WEB BEAM	1/7	1/5	1/3	1	1/7	STAGGERED WEB BEAM	0.053	0.027	0.023	0.043	0.053
ROLLED CHANNEL BEAM	1	3	5	7	1	ROLLED CHANNEL BEAM	0.374	0.398	0.349	0.304	0.374

Rating of Alternatives on Degree of Available Quality Assurance Techniques

ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	1	1	1	1	ROLLED I-BEAM	0.200	0.200	0.200	0.200	0.200
FABRICATED I-BEAM	1	1	1	1	1	FABRICATED I-BEAM	0.200	0.200	0.200	0.200	0.200
FABRICATED HOLLOW GIRDER	1	1	1	1	1	FABRICATED HOLLOW GIRDER	0.200	0.200	0.200	0.200	0.200
STAGGERED WEB BEAM	1	1	1	1	1	STAGGERED WEB BEAM	0.200	0.200	0.200	0.200	0.200
ROLLED CHANNEL BEAM	1	1	1	1	1	ROLLED CHANNEL BEAM	0.200	0.200	0.200	0.200	0.200

Figure 6b: Rating of Alternatives using AHP scales for last five context knowledge categories with last five columns showing normalized values for each design alternative

CRITERIA	WEIGHTING (%)
User Requirement	15
Component Material Properties/Consumption	10
Quality of Means During Use (Degree of Fullfilling Intended Function in Different Conditions)	10
Pre-Production Requirement {Preparation of Component(s)}	20
Production Requirement (Additional Items/Components)	15
PostProduction Requirement {Special Process(s) Required}	10
Production Equipment Requirement/Cost (Tooling/Machine Cost Required)	10
Quantity of Product Required	2.5
Achievable Production Rate of Selected Means	5
Degree of Available Quality Assurance Techniques	2.5
<i>Consolidated Rating of Each Alternative</i>	<i>100</i>

Table 1: Relative weighting among 10 different design context knowledge criterion

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CRITERIA	WEIGHTING (%)	RATING OF SUITABILITY 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 Fulfilling 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

Table 2: Evaluation and selection of alternatives according to Analytic Hierarchy Process