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A PROTOTYPE SYSTEM TO SUPPORT CONCEPTUAL DESIGN SYNTHESIS FOR MULTI-X

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Abstract

Design for X guidelines methodologies tend to be reactive, that is a design solution has been generated firstly, it is then analysed according to a particular X or life cycle phase. There is a need to incorporate different life cycle constraints before the solution generation i.e. at the conceptual design synthesis stage, but as design solutions are abstract at conceptual design stage, there is a lack of availability of product life cycle knowledge. This research explores the true meaning of design context knowledge/information by studying how these pieces of knowledge can be used in a computer based environment through the classification of different categories of context knowledge and reasoning using them to support function based conceptual design synthesis for Multi-X. This paper describes the system architecture, development and working of prototype system by conducting a case study of a sheet metal component conceptual design in order to show the selection of conceptual design solutions not only satisfying functional requirements but also catering for different life cycle implications/constraints by generating potential good/problematic life cycle consequences. The implemented prototype system has been evaluated by different researchers regarding support to conceptual design synthesis for Multi-X and the results are also presented in the paper.

Keywords: Conceptual design, design for X, context knowledge, functional reasoning

1 Introduction

The demand for higher quality, on-time delivery, and lower cost products with shorter design and manufacturing lead time for the dynamic global market is forcing companies to introduce concurrent product and process design strategies. The intent of concurrent engineering is to break the barrier between design and other product development processes especially manufacturing. In the early 1980s, researchers began to realize the impact of design decisions on downstream activities. As a result, different methodologies such as design for assembly, design for manufacturing and design for disposal/recycling have been proposed. Software tools that implement these methodologies have also been developed. However, most of these tools are only applicable in the detailed design phase. Yet, even the highest standard of detailed design cannot compensate for a poor design concept formulated at the conceptual design phase.

The importance of conceptual design to the overall success of the product is crucial as once the conceptual design process has been finished, the majority of product cost and quality has been fixed by selecting particular concepts/solutions as the subsequent product life cycle activities (manufacturing, assembly, use, recycle/dispose) depends on these conceptual solutions. Moreover detail design and manufacture cannot make-up for a poor or inadequate conceptual design. Nicholls [1] has shown that upto 85% of the life cycle costs of a product can be committed at the end of the conceptual design phase, while only about 5% of the actual life-cycle costs have been spent. Decisions, which seem good for one life cycle requirements can pose problems on other life cycle phases [2]. A generic methodology to proactively supporting function based conceptual design using design context knowledge consequences, which occur due to the selection of product design element(s) (PDEs) [3] as means to realise functions performed by metal components has already been developed. The foregoing sections in this paper discuss this methodology to support conceptual design synthesis for multi-x, its implementation to develop a computer based prototype system, system architecture as well as a case study to support design synthesis for multi-X of a sheet metal component design problem.

2 Decision consequences' awareness

The design concept selection done while exploring solution space makes the conceptual design a decision intensive process [4] [5]. Each decision taken by the designer is associated with consequences [6][7][8] that can be intended /unintended and good/problematic [9]. Hubka & Eder [2] argue that every design decision has an influence on product later life cycle stages in terms of measures such as cost and time. It is therefore necessary for the designers to be aware of the consequences of his/her decisions taken at conceptual design stage only on later life phases of product. Design for X (DFX) methodologies are one of the most effective approaches to make designer aware of the consequences of his/her decision on later life cycle stages of product.

2.1 DFX guidelines

"Design for X" guidelines method is essentially a tool in the form of a check list [10] of *do and don't rules* to ensure that a design solution satisfies an 'X' area. These guidelines allow designers to converge on a solution satisfying X-ability [11]. For example, a design for assembly (DFA) guideline is to 'minimize' the number of parts in an artefact to reduce assembly operations. DFX guidelines make the designer aware of single 'X' like (DFA) thereby guiding designers in generating solutions that satisfy a single life phase aspect. Although use of multiple design guidelines popularly called as DFX Meta methodology [10] allows the application of multi DFX guidelines. But DFX Meta methodology result in conflicting recommendations and the user has to identify the interacting relationships between different X abilities. Moreover DFX guideless help in the generation of solutions satisfying an X-ability for a specific domain like Design for manufacturing guidelines for sheet metal components is completely different from that of thermoplastic components. Therefore there is a need to consider the implications of design decision on different later life cycle stages simultaneously at conceptual design stage that is conceptual design synthesis for Multi-X. This demands the whole consideration of the *context* of design problem under consideration from the designers.

2.2 Design context

There are many uses of the word 'Context' in design, and information/knowledge described as 'Context' is used in several ways. One dictionary definition of context is *the set of facts or circumstances that surround a situation or event* [12]. This research intends to define and use design context knowledge in a broad term as a knowledge having information about surrounding factors and interactions which have an impact on the behavior of the product and therefore the design decision making process which results in design solutions. Therefore it can be defined as "*the related surrounding knowledge of a design problem at a given moment of time in consideration*" [13].

2.2.1Design context knowledge formalism

Based on the above definition, this research has proposed and implemented a classification in order to structure the design context knowledge for 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* [14] (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 domain and company independent, therefore this research has classified these three groups in ten different categories of context knowledge [13]. 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 [15] [16] [17]. 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 design problem under consideration, however in metal component design particularly in sheet metal component, these categories can be used to fully explore the knowledge important for consideration at conceptual design stage. These categories are briefly summarised here: -

2.2.2User requirements/preferences

This category of context knowledge deals with the users of the product. Any specific requirements of the user are defined here e.g. colour preference, time impression of a product, less sharp edges, easy to handle, modular etc. Reasoning using product user requirements can help designer by gaining an insight about the user preference in selecting a particular solution, which is more suitable to the user. An example could be a requirement of insulation for metal components to avoid hot contact in working environment.

2.2.3Product/components' material properties

Knowledge related to product material properties is essential for selecting a particular solution to a given functional requirement. It includes general material specifications of the components like strength, durability, allowable stresses, hardness etc. Timely prompting the designer using background reasoning about material properties would help designer in selecting those solutions, which are feasible.

2.2.4Quality of means/solution during use

It is 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 adaptability of selected solution to different working conditions like temperature resistance, vibration resistance, and shock/impact load resistance. An example could be a measure of slack in friction belt due to high temperature generated at high speed of rotation of two pulleys in order to convert a rotary motion into another rotary motion at a different axis.

2.2.5Pre production requirement

Context knowledge includes preparation of components and additional items required if any during realization/manufacturing of solutions. 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 requirement information involves evaluating and comparing time and cost required incurred on pre production processes/items 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.

2.2.6Production requirement

It involves knowledge about actual manufacturing/production requirements for a solution to be manufactured onto the component. This type of knowledge is important for designer not only to analyse the ease of manufacturing solutions on the components but also to compare the cost incurred in manufacturing each of these solutions, thus giving support to the designer in selecting low cost/easy manufacturable solutions that involve less manufacturing time and low manufacturing cost.

2.2.7Post production requirement

Post-production requirement describes if a special process is needed after manufacturing/inscribing PDE on the component. An example could be retightening of a nut in case of *Hole-fastener* as solution to a '*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 nut. Therefore it is necessary to compare the time and cost of equipment required if any during use/maintenance/service phase of a product among all the potential solutions to select the low cost/time solution.

2.2.8Production equipment requirement

Timely prompting designer about the type and cost of machine/tooling that would require to manufacture/realize a selected solution will help in making a cost effective decision as more costly and increased number of machines will add up to increased 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 product.

2.2.9Quantity of product required

Quantity of product/component required plays an important role in selecting a particular solution to realize a particular function. The quantity of product directly affects the selection of production equipment. High equipment cost could be justified if large quantity of components is to be made, due to return in profit of mass production of components. Therefore the information about quantity of product, which can be cost effectively produced is necessary for estimation at conceptual design stage to select a solution.

2.2.10 Achievable production rate

Time required and level of difficulty to realize PDEs vary considerably. It is therefore necessary to consider the achievable production rate of each selected means and associated cost using the selected production equipment before making a final decision to go ahead with the selected design solution to realize a functional requirement. Higher achievable production rate will not only reduce the lead-time of the product but also reduce the lab overhead costs thus reducing the overall product cost.

2.2.11 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.

3 Product design elements based conceptual design

Observing the product from constructional point of view gives rise *to product breakdown structure (PBS)*. Borg et. al. [17] presented this structure as a number of elements called *product design elements (PDE)*. 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. For a given functional requirement, PDEs are the information carriers that allow the mapping between function requirements and physical solutions of a product. They are the vehicles to bring basic design information to the downstream product realisation phases for embodiment, detailed part design and later life cycle processes In this research, PDEs are used as the basis of function based conceptual design, in which a design solution is generated from product function point of view, using available well-understood function-PDEs relationships to identify suitable means in the form of these Product Design Elements. This research derived a library of well-proven PDEs associated with its function(s) [18].

3.1 Function to PDE mapping

Conceptual design is a function to means mapping process, during which decision-making takes place regarding the selection and evaluation of design alternatives. In order to support decision-making at conceptual design stage, a new function to PDEs/means mapping model is proposed (figure 1) in this research, which uses design context knowledge to support decision-making. The model consists of following different stages: -

3.1.1 Identification of suitable PDEs for a function

Functions are represented in natural language *verb-noun* pair form. Functional structure is derived in the form of the most abstract function at the top of hierarchy as base class whereas decomposed functions are put in the form of sub classes into finer resolutions until an implementable sub functions are derived. and their decomposition results into sub level functions in the form. The first stage identifies suitable PDEs on the basis of desired functional requirements using dictionary of proven function-PDEs association. This dictionary has been developed by writing function-PDE mapping algorithm on the basis of knowledge available about different functions, PDEs and their relationships in literature, through experience and past case studies.

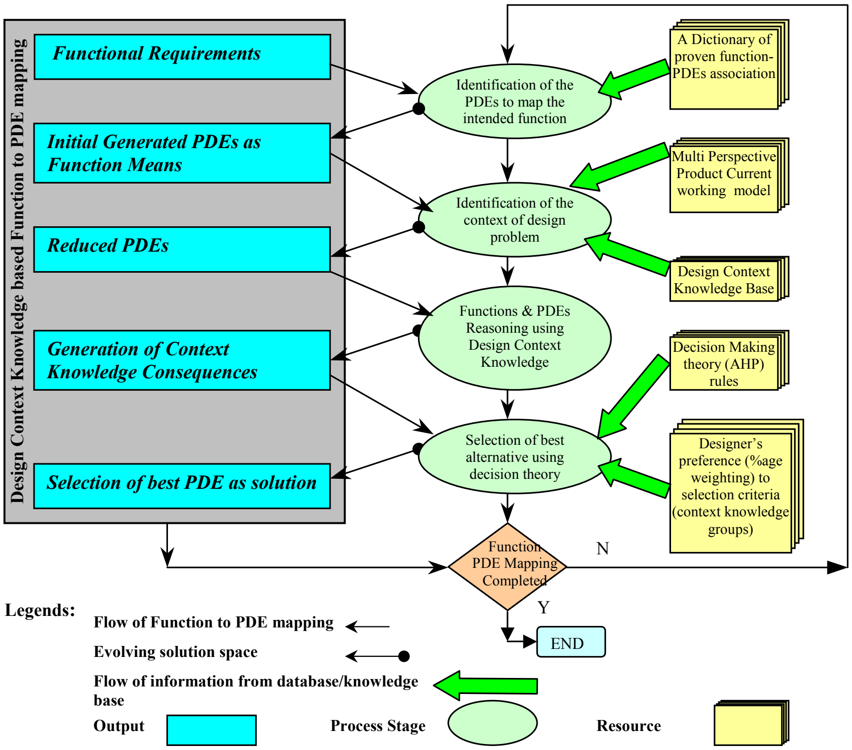


Figure 1. Design Context Knowledge Based Function to PDEs Mapping Model

3.1.2Identification of design context knowledge

Once a list of suitable PDEs is generated, then context of design problem using design context knowledgebase and multi perspective product current working model is identified in second stage. The three groups of context knowledge are further decomposed and classified into different knowledge categories to fully represent the functional requirements from different perspectives shown in figure 2.

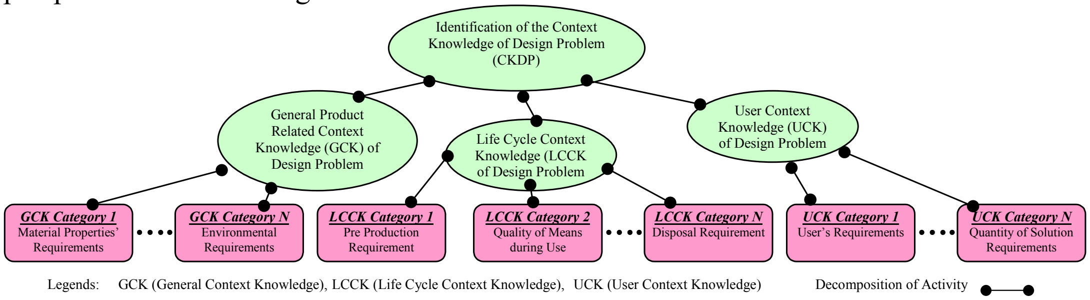


Figure 2. Identification of Design Context Knowledge

The generated PDEs can be further decomposed into different attributes like *Material attributes* (Name, Physical properties), *Form attributes* (Shape, Form, Structure) and *Surface Finish* attributes (Type of Finish, Degree of Finish). PDEs/solutions whose material, form and surface finish attributes do not comply with those required in the function are discarded for further evaluation, thus leaving a reduced set of PDEs for further exploration Current working knowledge (information generated up to the current stage of design process) is elicited from these decomposed PDEs using design context knowledge base. This current working knowledge is further decomposed into same number of knowledge categories starting from the 1st to nth as that of functional requirements under three different groups as shown in figure 3. But these pieces of knowledge are in the form of available/generated properties for each of the design solution/PDE under consideration.

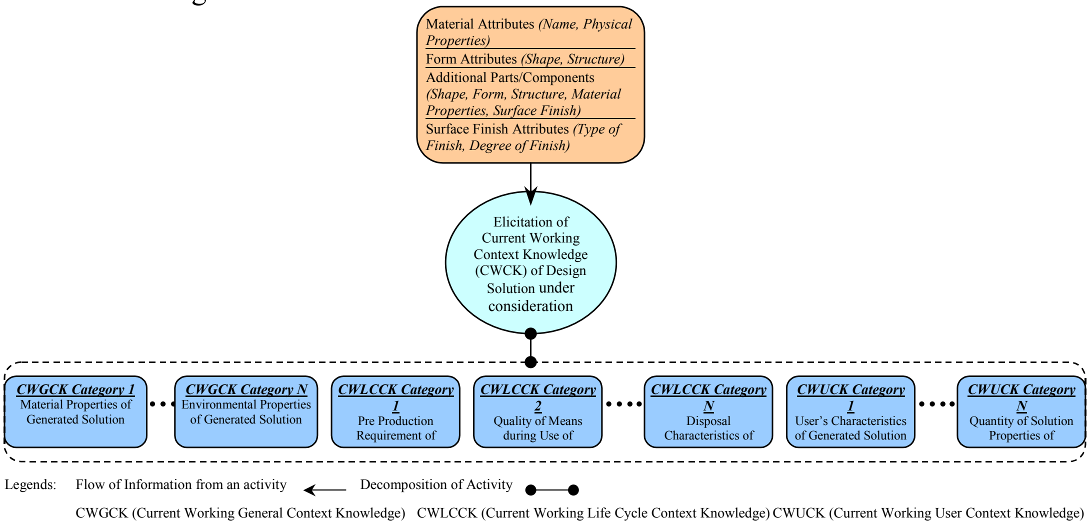


Figure 3. Elicitation of current working knowledge

3.1.3Reasoning mechanism

Having functional requirements as context knowledge requirements in different categories as well as generated information about each solution/PDE in terms of same categories on the other hand, rule based reasoning is used to elicit the context consequences for each category. The architecture of the implemented reasoning mechanism (shown in figure 4) is used to help designer to explore different life cycle consequences and other design solution consequences that would be occurred at a later life cycle stage due to decision commitment of a PDE as design solution at conceptual design stage. The generated knowledge about a selected PDE solution in a particular life cycle knowledge category is compared with the required/specified solution qualities in the same category to infer the consequence of selecting a solution on that life cycle phase. Thus potential good or problematic consequences by simultaneously reasoning the required context knowledge in one category and generated context knowledge of the PDEs/solution under consideration for selection at the moment.

3.1.4Final solution selection

Once the design solution/life cycle consequences are illustrated for different scenarios for each of the PDE, it is possible to select a PDE with least negative consequences as best solution to a conceptual design problem by using designer's preference in terms of weighting and decision theory rules (like Analytic Hierarchy Process (AHP) [19] in this model).

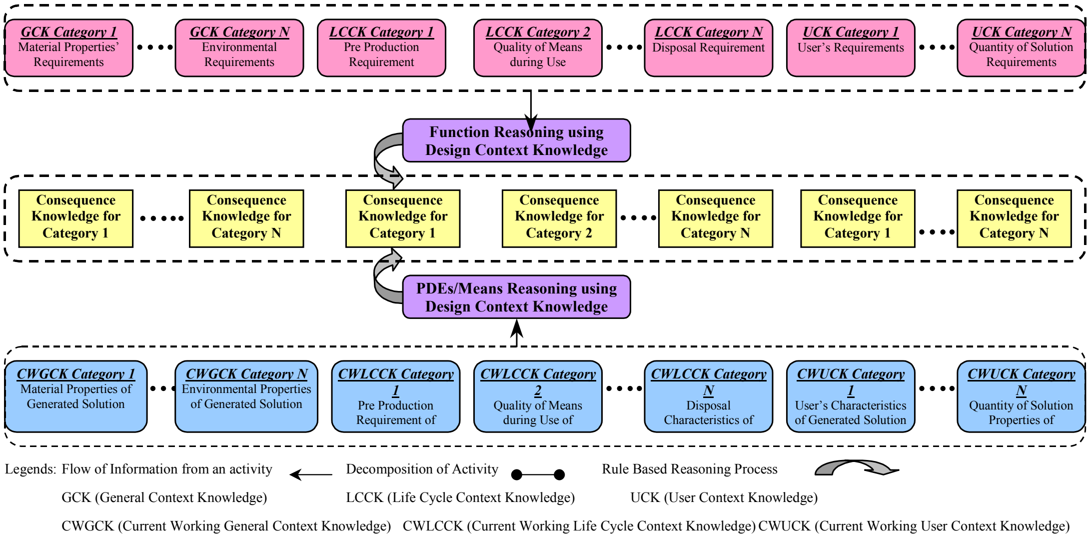


Figure 4: Reasoning mechanism of Function to PDEs Mapping Model

4 The implementation of the framework model

It can be a demanding task if each of the PDEs generated is fully manually evaluated. In addition, the deadline for a design solution can be quite tight. To support effectively designers in these scenarios and too illustrate the effectiveness of the approach, function to PDE mapping model has been implemented into a *Knowledge-Intensive-CAD* prototype system known as PROCONDES acronyms of Pro-Active Conceptual Design for the sheet metal component domain.

4.1 PROCONDES system architecture

PROCONDES system architecture as shown in figure 5 comprises a knowledge base, working memory, inference engine, tools and user interface.

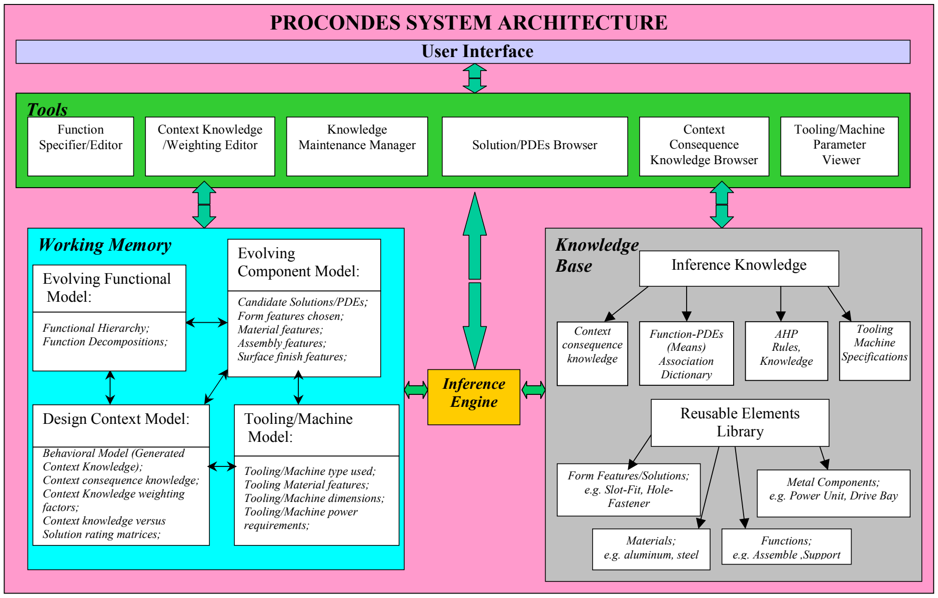


Figure 5. PROCONDES system architecture

The *Knowledge Base* consists of Inference knowledge containing design consequence knowledge, function-PDEs association knowledge and Tooling/Machine specifications whereas Reusable Elements library consists of different types of features like form features, material features, functional features and standard components. *Working memory* stores the resultant information about the functional model, context knowledge model, evolving component model and its manufacturing life-phase model (Tooling/Machine model) derived from a concurrent synthesis. The *Inference engine* is the context knowledge based reasoning mechanism, containing rules to reason with the generated and required information. Based on the understanding of Manufacturing/Assembly consequences (MACs), it is possible to generate basic Machine & Tooling features from *Form* features of sheet metal component thus realising the concept of concurrent product and process design of sheet metal components. The process design involves the selection of tool and machine for the part to be manufactured.

A set of tools has also been designed to facilitate the communication between a user and the Knowledge Base. These include: a *Function Specifier/Editor* to select or change a desired function, *Solution/PDEs Browser* to visualise the generated solutions, a *Context Consequence Knowledge Browser* to see the consequences that would occur during product development caused by design decisions, a *Context Knowledge Weighting Editor* in order to specify the designer's weighting to different criterion of decision making, a *Tooling/Machine Parameter Viewer* to see the design parameters required to manufacture a form feature.

4.2 System Implementation

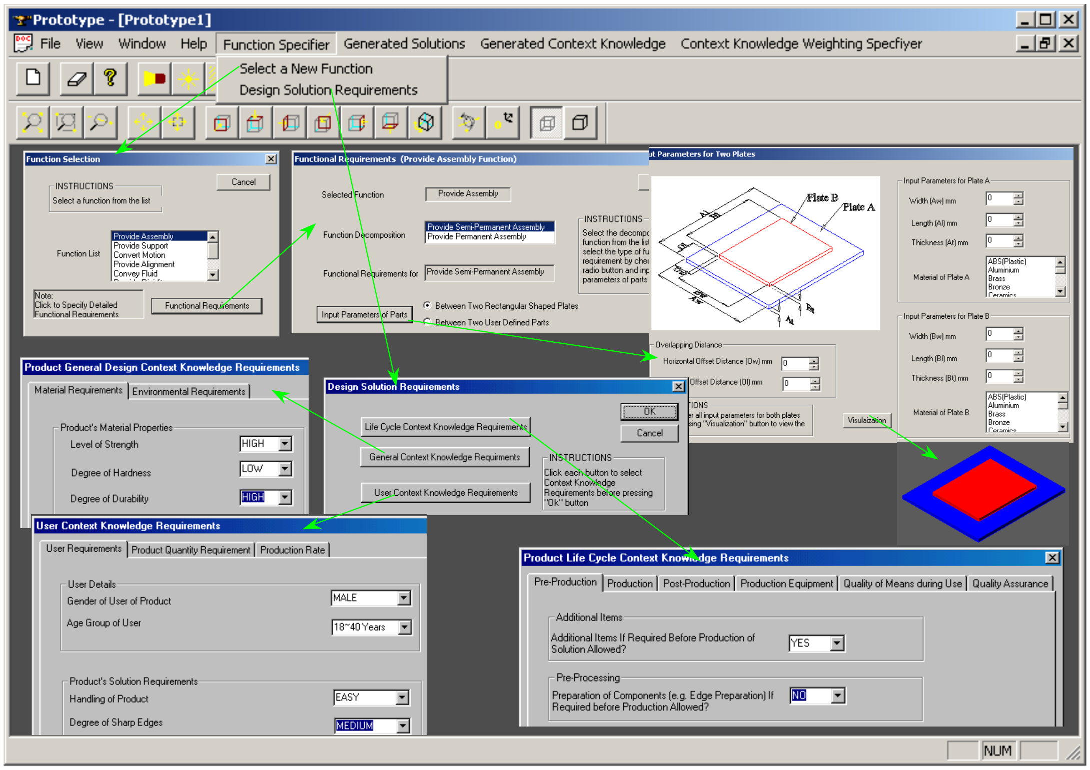
The architecture has been implemented using Microsoft Visual C++ version 6 on Windows 2000 and an open GL libraries based system called Open CASCADE [20]. The prototype has been tested by demonstrating case studies to various researches of engineering design and in the process of further development and refinement. Development of a computational prototype incorporating this research approach provides real time support for designers during designing. Next section provides an illustration of the use of the system through captured screen images of a case study.

5 Case Study

A case study of supporting conceptual design of a sheet metal 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. Following paragraphs show the step-by-step procedure of performing this case study using the prototype system.

The main window of PROCONDES prototype system is shown as screen dump in figure 6. The first step is to select a new function from the *Function Selection* dialog box specified under the menu of *Function Specifier.* A *"Provide Assembly*" function is selected in this case study from the list of functions and functional requirements are specified in *Functional Requirements* dialog box. "*Provide Semi-Permanent Assembly Between Two Rectangular Plates"* has been selected as a decomposed function in this dialog box for further exploration. Detailed parameters of these plates are input by using 'Input Parameters of Parts' button, which displays a new dialog box. Different parameters of two plates like width, length, material etc. are selected and the two plates can be visualized using *Visualization* button option. Detailed functional requirements are input by using *Design Solution Requirements*

Dialog Box through which *Life Cycle, General and User Context Knowledge Requirements* can be specified by selecting different parameters under different categories of knowledge in each one of the three groups as shown in figure 6.



INSTRUCTIONS
Select a function from the list

Function List: Provide Assembly, Provide Support, Convert Motion, Provide Alignment, Convey Fluid

Note:
Click to Specify Detailed Functional Requirements

Selected Function: Provide Assembly

Function Decomposition: Provide Semi-Permanent Assembly, Provide Permanent Assembly

Functional Requirements for: Provide Semi-Permanent Assembly

● Between Two Rectangular Shaped Plates

○ Between Two User Defined Parts

Input Parameters for Plate A

Width (Aw) mm: 0

Length (Al) mm: 0

Thickness (At) mm: 0

Material of Plate A: ABS(Plastic), Aluminium, Brass, Bronze, Ceramics

Input Parameters for Plate B

Width (Bw) mm: 0

Length (Bl) mm: 0

Thickness (Bt) mm: 0

Material of Plate B: ABS(Plastic), Aluminium, Brass, Bronze, Ceramics

Overlapping Distance

Horizontal Offset Distance (Ow) mm: 0

Offset Distance (Ol) mm: 0

Product's Material Properties

Level of Strength: HIGH

Degree of Hardness: LOW

Degree of Durability: HIGH

INSTRUCTIONS
Click each button to select Context Knowledge Requirements before pressing "Ok" button

User Details

Gender of User of Product: MALE

Age Group of User: 18~40 Years

Product's Solution Requirements

Handling of Product: EASY

Degree of Sharp Edges: MEDIUM

Additional Items

Additional Items If Required Before Production of Solution Allowed?: YES

Pre-Processing

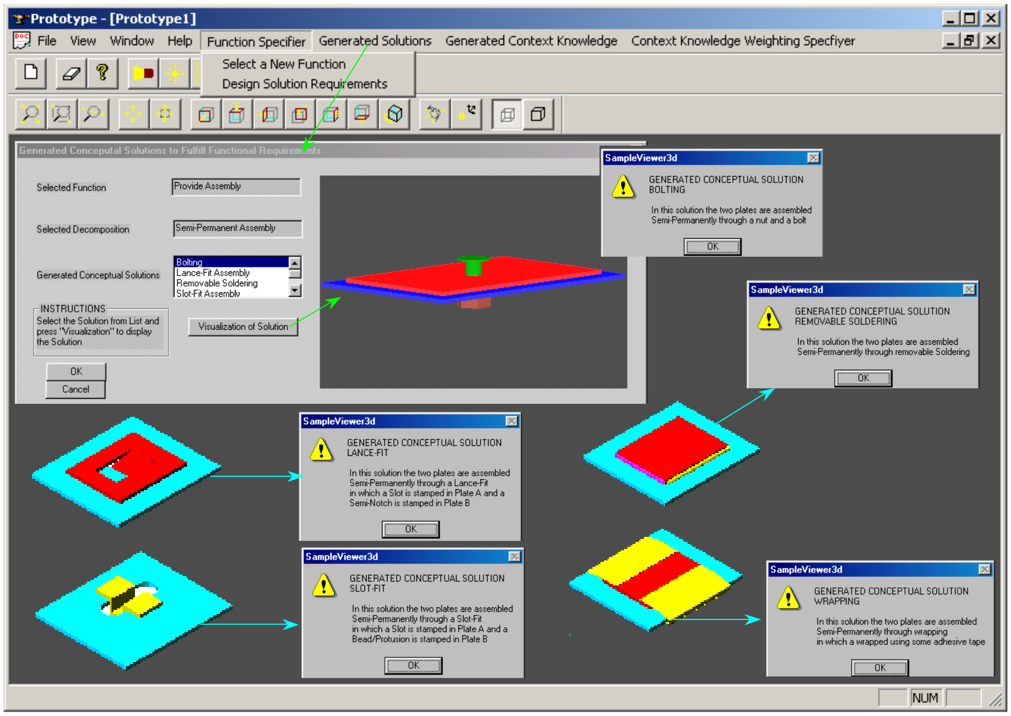
Preparation of Components (e.g. Edge Preparation) If Required before Production Allowed?: NO

Figure 6. Screen dump of PROCONDES showing input of functional requirements

Once the functional requirements are specified, the next step is to find the initial generated solutions in terms of PDEs. Generated solutions can be viewed through *Generated Conceptual Solutions to Fulfil Functional Requirements* dialog box. Five initial PDEs namely *Bolting, Lance-Fit Assembly, Slot-Fit Assembly, Removable Soldering and Tape Wrapping* are identified from dictionary of Function-PDEs association. Detail of each one of these solution PDEs can be illustrated graphically & textually by pressing *'Visualization of Solution'* button option as shown as a screen dump in figure 7.

Once a list of suitable PDEs is generated, then context of design problem using design context knowledgebase and multi-perspective product current working model is identified. Thus generated context knowledge for different solution PDEs can be viewed in different categories of context knowledge through three groups of dialog boxes *Generated Life Cycle Context Knowledge, Generated User Context Knowledge and Generated General Context Knowledge* as shown in figure 8.

Context consequence knowledge/information is generated regarding each one of these means/solutions in each one of the categories of context knowledge. This information is generated by simultaneously reasoning the design solution requirements as well as generated context knowledge for the design solution under consideration. This type of early awareness knowledge pertaining to later life cycle phases about a design solution provides proactive support to the designer in selecting a solution, which will cause fewer problems in later life cycle phases.



Selected Function: Provide Assembly

Selected Decomposition: Semi-Permanent Assembly

Generated Conceptual Solutions: Bolting, Lance-Fit Assembly, Removable Soldering, Slot-Fit Assembly

INSTRUCTIONS
Select the Solution from List and press "Visualization" to display the Solution

GENERATED CONCEPTUAL SOLUTION
BOLTING
In this solution the two plates are assembled Semi-Permanently through a nut and a bolt

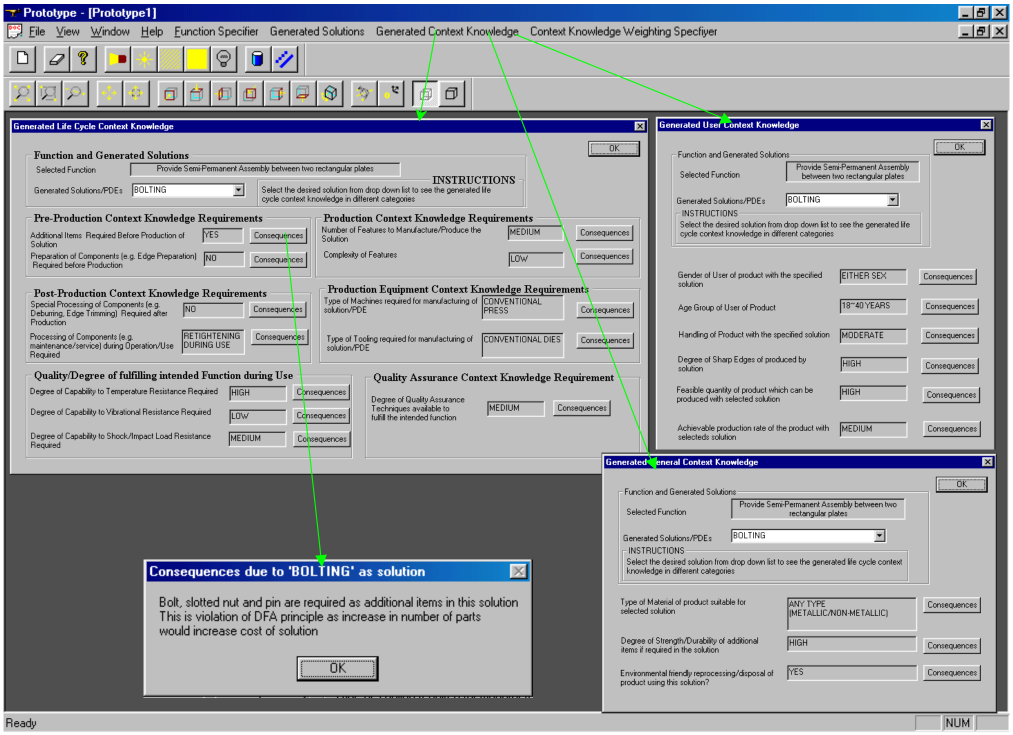
GENERATED CONCEPTUAL SOLUTION
REMOVABLE SOLDERING
In this solution the two plates are assembled Semi-Permanently through removable Soldering

GENERATED CONCEPTUAL SOLUTION
LANCE-FIT
In this solution the two plates are assembled Semi-Permanently through a Lance-Fit in which a Slot is stamped in Plate A and a Semi-Notch is stamped in Plate B

GENERATED CONCEPTUAL SOLUTION
SLOT-FIT
In this solution the two plates are assembled Semi-Permanently through a Slot-Fit in which a Slot is stamped in Plate A and a Bead/Protusion is stamped in Plate B

GENERATED CONCEPTUAL SOLUTION
WRAPPING
In this solution the two plates are assembled Semi-Permanently through wrapping in which a wrapped using some adhesive tape

Figure 7. Screen dump of PROCONDES showing initial generated PDEs



Generated Life Cycle Context Knowledge

Function and Generated Solutions
Selected Function: Provide Semi-Permanent Assembly between two rectangular plates
Generated Solutions/PDEs: BOLTING

INSTRUCTIONS
Select the desired solution from drop down list to see the generated life cycle context knowledge in different categories

Pre-Production Context Knowledge Requirements
Additional Items Required Before Production of Solution: YES
Preparation of Components (e.g. Edge Preparation) Required before Production: NO

Production Context Knowledge Requirements
Number of Features to Manufacture/Produce the Solution: MEDIUM
Complexity of Features: LOW

Post-Production Context Knowledge Requirements
Special Processing of Components (e.g. Deburring, Edge Trimming) Required after Production: NO
Processing of Components (e.g. maintenance/service) during Operation/Use Required: RETIGHTENING DURING USE

Production Equipment Context Knowledge Requirements
Type of Machines required for manufacturing of solution/PDE: CONVENTIONAL PRESS
Type of Tooling required for manufacturing of solution/PDE: CONVENTIONAL DIES

Quality/Degree of fulfilling intended Function during Use
Degree of Capability to Temperature Resistance Required: HIGH
Degree of Capability to Vibrational Resistance Required: LOW
Degree of Capability to Shock/Impact Load Resistance Required: MEDIUM

Quality Assurance Context Knowledge Requirement
Degree of Quality Assurance Techniques available to fulfill the intended function: MEDIUM

Generated User Context Knowledge

Function and Generated Solutions
Selected Function: Provide Semi-Permanent Assembly between two rectangular plates
Generated Solutions/PDEs: BOLTING

INSTRUCTIONS
Select the desired solution from drop down list to see the generated life cycle context knowledge in different categories

Gender of User of product with the specified solution: EITHER SEX
Age Group of User of Product: 18~40 YEARS
Handling of Product with the specified solution: MODERATE
Degree of Sharp Edges of produced by solution: HIGH
Feasible quantity of product which can be produced with selected solution: HIGH
Achievable production rate of the product with selecteds solution: MEDIUM

Generated General Context Knowledge

Function and Generated Solutions
Selected Function: Provide Semi-Permanent Assembly between two rectangular plates
Generated Solutions/PDEs: BOLTING

INSTRUCTIONS
Select the desired solution from drop down list to see the generated life cycle context knowledge in different categories

Type of Material of product suitable for selected solution: ANY TYPE (METALLIC/NON-METALLIC)
Degree of Strength/Durability of additional items if required in the solution: HIGH
Environmental friendly reprocessing/disposal of product using this solution?: YES

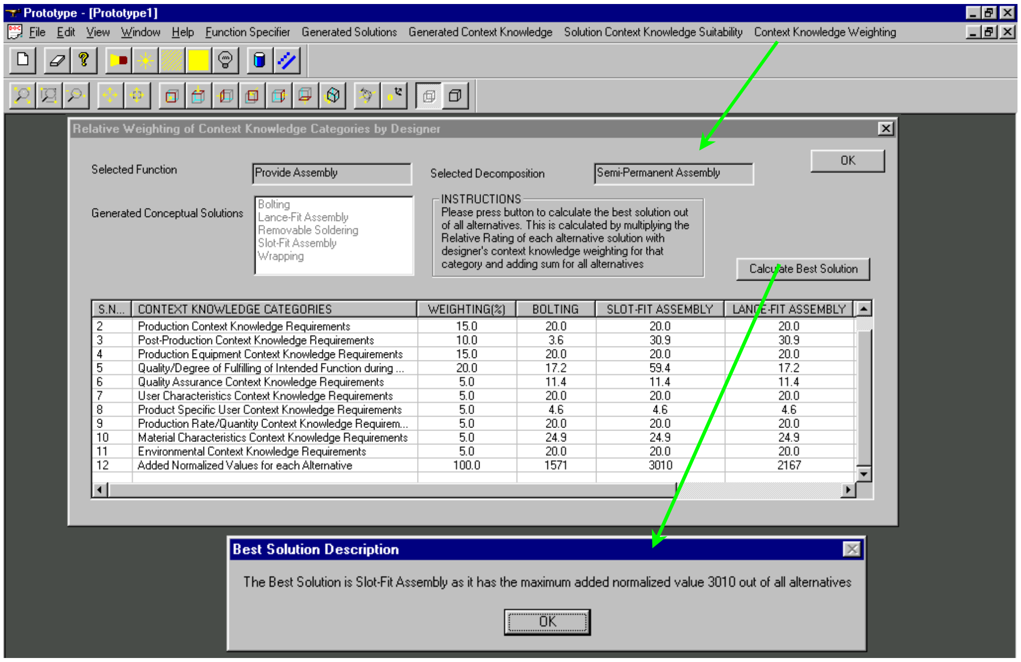
Consequences due to 'BOLTING' as solution

Bolt, slotted nut and pin are required as additional items in this solution
This is violation of DFA principle as increase in number of parts would increase cost of solution

Figure 8. Screen dump of PROCONDES showing generated context knowledge of PDEs

For example a *"Bolting"* solution requires "YES" against the slot of *'Additional Items Required before Production of Solution'* under Life Cycle Context Knowledge Group. Reasoning process illustrates consequences due to 'Bolting' as solution, which are *Bolt, Slotted Nut and Pin as additional items in this solution*. This is violation of DFA principle, as it would increase the cost and time of solution to manufacture. Timely prompting designer about this manufacturing phase consequence forces designer to think about other possible solutions as well before making a final decision.

Once the design solution/life cycle consequences are illustrated for different scenarios for each of the PDE, it is possible to rate each design solution/means in terms of degree of suitability for that particular context knowledge category. The higher the degree the more suitable is solution regarding the category under consideration. The fewer the problematic consequences, the higher the degree of suitability. The assignment of numerical ratings to each of design alternatives under each context knowledge criterion category is done by converting degree of suitabilities of each alternative described in previous section into weighting factor [13]. This is done by using the comparison scales defined in Analytic Hierarchy Process (AHP) [19] a decision making theory for decision-making and selection of optimal PDE alternative at conceptual design stage for mechanical artefact design. These numerical ratings against each criterion in terms of percentage weightings are shown as a screen dump in figure 9 under different columns of PDEs such as BOLTING, SLOT-FIT ASSEMBLY etc. The relative weighting among different knowledge criteria (preference of one criterion over other) can be done by giving percentage weighting out of 100 for each context knowledge categories. Assignment of relative weighting is controlled by the designer and depends upon lots of factors like consideration of cost, designer's preference, and company policy. For example some companies prefer low cost of products, compromising the quality of products. In this case study the relative weightings taken as designer's preference are shown in figure 9 under WEIGHTING (%) column. After determining relative weighting of each criterion and the numerical rating of alternatives, the final task in this case study is to find the best design solution/alternative against the predefined weightings out of these five alternatives *(Lance-Fit Assembly, Slot-Fit Assembly, Bolting, Removable Soldering, Tape Wrapping)*. This is done by calculating the highest added normalized value for each design alternative PDE. Figure 9 shows that that the highest added normalized value is *3010* for ***Slot-***



Selected Function: Provide Assembly

Selected Decomposition: Semi-Permanent Assembly

Generated Conceptual Solutions:
Bolting
Lance-Fit Assembly
Removable Soldering
Slot-Fit Assembly
Wrapping

INSTRUCTIONS
Please press button to calculate the best solution out of all alternatives. This is calculated by multiplying the Relative Rating of each alternative solution with designer's context knowledge weighting for that category and adding sum for all alternatives

S.N...	CONTEXT KNOWLEDGE CATEGORIES	WEIGHTING(%)	BOLTING	SLOT-FIT ASSEMBLY	LANCE-FIT ASSEMBLY
2	Production Context Knowledge Requirements	15.0	20.0	20.0	20.0
3	Post-Production Context Knowledge Requirements	10.0	3.6	30.9	30.9
4	Production Equipment Context Knowledge Requirements	15.0	20.0	20.0	20.0
5	Quality/Degree of Fulfilling of Intended Function during ...	20.0	17.2	59.4	17.2
6	Quality Assurance Context Knowledge Requirements	5.0	11.4	11.4	11.4
7	User Characteristics Context Knowledge Requirements	5.0	20.0	20.0	20.0
8	Product Specific User Context Knowledge Requirements	5.0	4.6	4.6	4.6
9	Production Rate/Quantity Context Knowledge Requirem...	5.0	20.0	20.0	20.0
10	Material Characteristics Context Knowledge Requirements	5.0	24.9	24.9	24.9
11	Environmental Context Knowledge Requirements	5.0	20.0	20.0	20.0
12	Added Normalized Values for each Alternative	100.0	1571	3010	2167

The Best Solution is Slot-Fit Assembly as it has the maximum added normalized value 3010 out of all alternatives

Figure 9. Screen dump of PROCONDES showing context knowledge weighting and best-selected solution PDE

Fit Assembly, therefore ***Slot-Fit*** is the best alternative for the given weighting out of five alternatives in order to provide *Semi-Permanent Assembly* between *two rectangular plates.*

5.1 PROCONDES evaluation

The above case study of sheet metal component design problem was performed on PROCONDES system with a sample size of fifteen different people who were researchers, designers and engineering design students. A detailed comprehensive questionnaire which contains questions related to different functionalities of PROCONDES system as well as the overall function to PDE mapping model were presented to them after performing the case study in order to evaluate both the model and the system in detail. Some of the critical evaluation results are presented here regarding performance/output of system in different areas.

5.1.1Context knowledge and consequences' awareness

67% of the evaluators agreed that the context knowledge generated under three different groups in different categories is detailed enough to foresee the impact of selecting a particular solution on different life cycle phases, user of product and environment of product. Some evaluators suggested that there could be more context knowledge categories that should be considered in the case study performed as well as in each category there could be more knowledge that should be considered in addition to what presented in the case study. 59% of the evaluators confirmed that they were made aware of all the consequences related to a chosen context knowledge category early at design stage of selecting a particular conceptual design solution in detail. However most of the evaluators suggested in explaining a consequence in detail as well as more consequences should be generated related to each context knowledge category under three different groups while selecting a particular conceptual design solution.

5.1.2Context knowledge suitability

All evaluators (100%) agreed with the concept of assigning degrees of suitability to a particular solution based on context knowledge reasoning as a just indication of appropriateness of a conceptual design solution against a criterion. 67% of evaluators agreed that the scale of suitability from 0 to 5 set in PROCONDES is a fair indication of appropriateness of a solution against a criterion. Moreover 92% of evaluators agreed with the idea of allowing designer's preference in percentage weighting instead of linguistic rating scales.

5.1.3Decision support

Responses to the question about decision support capabilities indicated that PROCONDES demonstrated its abilities in providing a proactive decision support to a designer during case study by a) generating and highlighting the potential consequences of selecting a particular solution (92% of evaluators); b) evaluating all candidate design solutions against different context knowledge criteria (75% of evaluators); c) selecting a best solution for the case study which not only fulfils functional requirements, designer's preference but also suitable for later life cycle stages thereby reducing the cost and time which would be incurred of selecting a particular solution without knowing its suitability for later life cycle stages (67% of evaluators).

5.1.4PROCONDES system and overall approach

Upon asking about recommendations/suggestions to overall approach and PROCONDES system, most of the researchers appreciated the approach of proactively supporting decision making at conceptual design stage using context knowledge reasoning as one of the evaluators said: -

> *"It is good for designers and helps in the course of designing"*

Some researchers expressed their opinion to add more context knowledge and consequences in each context knowledge category. Regarding PROCONDES system functionalities, most of the evaluators appreciated the graphical user interface of the system and corresponding functionalities to view and display conceptual solutions. However as far as textual interface and explanation of solutions is concerned, majority of them stressed to make it more presentable in clear textual form in detail. Some evaluators suggested to add concurrent design process of component (i.e. generation of basic tooling and machine parameters) along with conceptual design solutions as originally proposed in the architecture of the system, which could not be accomplished in this version. Some researchers also suggested codifying some more complex case studies in the PROCONDES system.

6 Conclusions

From this paper, it can be concluded that:

- Design context knowledge in the background of design process helps designers to process vast amount of potentially related design information and prompt useful insights when they are available through reasoning and 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 life cycle implications and increased costs earlier at conceptual design synthesis stage due to the selection of a particular solution;
- The developed PROCONDES system successfully highlights the potential good and bad/problematic consequences to the designer earlier at the conceptual design stage. This provides proactive decision support as well as establishes a mechanism to select best solution against functional requirements and different life cycle implications thus supporting conceptual design synthesis for Multi-X.

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