INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 03 STOCKHOLM, AUGUST 19-21, 2003

PRODUCT DESIGN ELEMENTS AS MEANS TO REALISE FUNCTIONS IN MECHANICAL CONCEPTUAL DESIGN

Fayyaz Rehman, Xiu-Tian Yan

Abstract

This paper describes the research work on the establishment of a new design support approach of generating feasible design solutions in terms of Product Design Elements according to functional requirements of mechanical artefacts using design context knowledge. Traditionally a concept or a principle solution is evaluated & selected on the basis of desired functional requirement only, neglecting the consequences of selection on the performance of other life cycle phases as well as neglecting other knowledge generated during execution of design process. This approach causes problems at later product realization stages in terms of cost & time incurred due to redesign of product. This research introduces a new meaning to term *'Feature'* as Product Design Elements and presents a novel approach of how these Product Design Elements can be used to realise functions in mechanical conceptual design. For this purpose a generic Function to PDE mapping model has been developed and is applied to mechanical component conceptual design decision making for the selection of best solution as a Product Design Element keeping in view both the functional requirements and design context knowledge consequences, thus proactively supporting conceptual design.

Keywords: Product design elements, conceptual design, features, functional reasoning

1 Introduction

Conceptual design is an early phase of the design process, which involves the generation of solution concepts to satisfy the functional requirements of a design problem. There can be more than one solution to a problem; this means that there is a scope for producing improved designs if one could explore a full solution rather than only investigating a subset of possible solutions. 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. The foregoing sections in this paper discuss the current on-going research in developing a methodology to proactively supporting function based conceptual design of mechanical artefacts using context knowledge consequences which occur due to the selection of product design element(s) (PDEs) as means to realise functions performed by metal components. A generic function to PDE mapping model is presented to show the process of evolution of PDEs as solutions/means to a particular function. This model is also used in a case study of a computer part design in the final section of the paper to highlight the effectiveness of approach and applicability of model to sheet metal design domain.

2 Functional Design

The word 'function' in design is regarded as a description of the intended action or effect produced by an object [1]. Function based conceptual design can be defined as the transition process between four different information states: 1) a set of required functions; 2) a initial set of possible concepts solutions to fulfil the function; 3) a set of behaviours that fulfil the functions; 4) Final selected concept(s)/solution(s) that generate the behaviours. *Function*, *behaviour* and *form* have been identified as the major elements of information, which are manipulated in these states. *Function* reveals the intentions of the artefact; *form* specifies what the artefact is composed of and how the components are interconnected, while *behaviour* spells out how the structure of the artefact achieves its functions. Functions and form are reasonably well understood, but the connections between them are not. Most existing design systems explicitly represent only form, making little allusion to behaviour as a reasoning step between function and structure [2].

However the functional model and form model of artefact/component alone are not sufficient to synthesize the artefact behaviour. This is because of the fact that generally functional models do not adequately capture all the properties, which are related to function and necessary to completely define the design problem. For instance, the functional requirement of designing a mating shaft and bore cannot be expressed completely by diameters of shaft/bore or by spatial relationship indicating fit condition between a shaft and a bore, since it does not provide other functional design details such as contact pressure, contact force, rotational torque, rotational speed etc. at the shaft-bore interface which varies under different working environment over a period of time. Behaviour of a function is defined to be the set of values of parameters (which are related casually) of the function either at specified time or a series over a period of time. Behaviour of a function is context sensitive and as such, behaviour comes into play only in the context of design environment. The context of design solution can include non-exhaustive list parameters and their corresponding attributes such as including *temperature, humidity, vibration, water proof* as a part of environment attributes; material attributes including *conductivity, strength, durability;* User attributes and so on. Detailed description of context knowledge and its use in developing a mechanism for function reasoning is explained in next section

3 Function reasoning and mapping

Functional reasoning in conceptual design is to derive and generate conceptual solutions to specified design problems at the functional level, and to evaluate for suitability and map the solutions to specified problems. This process involves deriving successive stages of conceptual design (discussed in section 2) starting from first stage (functional requirements) by reasoning about existing background knowledge/information about these states as well as evolution of new knowledge during this process. The first step in conceptual design is to decompose the higher-level functions into sub/smaller level functions.

3.1 Function decomposition

This research adopts the design method by Pugh[3] and assumes that a design process starts with market research to formalise a product design specification (PDS) document. From this document, it is possible and desirable to describe and concentrate on the functional requirements – the key aspects of product engineering design, and decompose the overall high-level function into small and implement able sub-functions. This is due to the fact that rarely one can find a single solution, which can achieve a specified high-level function in engineering design. This decomposition often results in a function hierarchy. A well-decomposed function hierarchical structure represents a good understanding of customers' requirements for a product. This is particularly important to function oriented design as such a structure represents the results of the function understanding and decomposition process and this is also the basis for the function mapping.

During the functional decomposition, the functional requirements are often decomposed to a level where it is possible to identify potential means or mechanisms to realise these small sub-functions. For example, in sheet metal component design, one of the desired function requirements could be *Support & Assemble Two parts* can be further decomposed into *Provide Semi-Permanent Assembly* and *Provide Vertical Support*(Figure 1). The potential means/PDEs for *Semi-Permanent Assembly* from the function means mapping library could be a *Slot.*

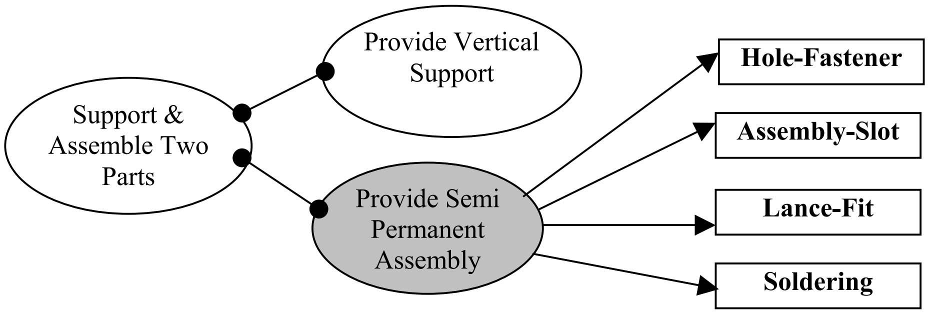


Figure 1. Function-Features Association

Observing the product from constructional point of view gives rise *to product breakdown structure (PBS*)[4]. Borg et. al. [5] presented this structure as a number of elements called *product design elements (PDE)*. They termed PDE could be

- *a product:* the artefact purposely designed for user such as a telephone.
- *a subassembly:* an element consisting of a set of components, such as telephone enclosure consists of other elements like numeric buttons, plastic cover.
- *a component*: a single material product produced without any assembly operation; for example plastic cover.
- *a component building element:* an element or a feature that constitute the component, for example material plastic, or punch holes in the cover of telephone.

For metal component design, means of achieving a function are more likely in the form of manufacturing features as shown in figure 1; as four possible manufacturing features are presented as means to realize a *Provide Semi Permanent Assembly* function. In other words, Product Design Elements (PDEs) at component building level can most likely be possible means of achieving a desired function requirement. PDEs are hence used as the key to function-oriented design in mapping PDEs to function requirements. For a decomposed function structure, this research proposes PDE based function mapping to identify the suitable means to realise a chosen function as explained in next section.

3.2 PDE based design through function to PDE mapping

Conceptual design is also referred as the process of generating alternative design solutions in addition to function decomposition. 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. The *feature* description contains the relevant properties including the values and the relations of properties of a product. Furthermore, a feature is described by properties out of several different classes of properties, thus relating these (classes of) properties to one another [6].

Designing by functions or "functional design", therefore, refers to the process of generating a design solution from product function point of view, using available well-understood function-PDEs relationships to identify suitable means in the form of PDEs. 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. This research derived a dictionary of well-proven PDEs associated with its able function(s) (a part of it as shown in figure 2). Through this association, the function-means mapping algorithm can be used to identify suitable PDEs for a chosen implementable function.

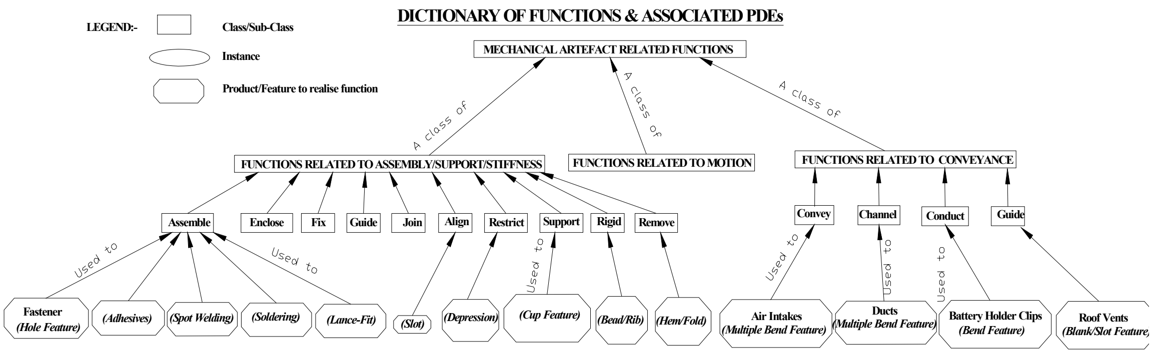


Figure 2. Some functions and associated PDEs from dictionary

3.3 Function to PDE mapping and reasoning model

Figure 3 shows a generic process model of Function to PDE mapping developed in this research. The model consists of following different stages: -

1. The first stage identifies suitable PDEs on the basis of desired functional requirements using dictionary of proven function-PDEs association. This dictionary can be 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.

2. 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. Design Context in this research is defined as *the related background information of a design problem under consideration*. A good understanding of design context information is essential to successful design and any design support system should investigate how design context information can be used to provide effective support. This approach supports the product design through background reasoning using the design context information [7]. Context information identified and grouped under different context knowledge categories. These categories range from user/functional requirement to knowledge pertaining to different life phases of product like design, manufacturing, assembly, disposal/reuse etc.

3. The context information provides useful hints, constraints to the solution space of the design problem. This helps in reducing the initially generated list of PDEs to only those PDEs, which satisfy functional requirements as well as design context knowledge.

4. Forward chaining reasoning mechanism 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.

5. 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) [8] in this model).

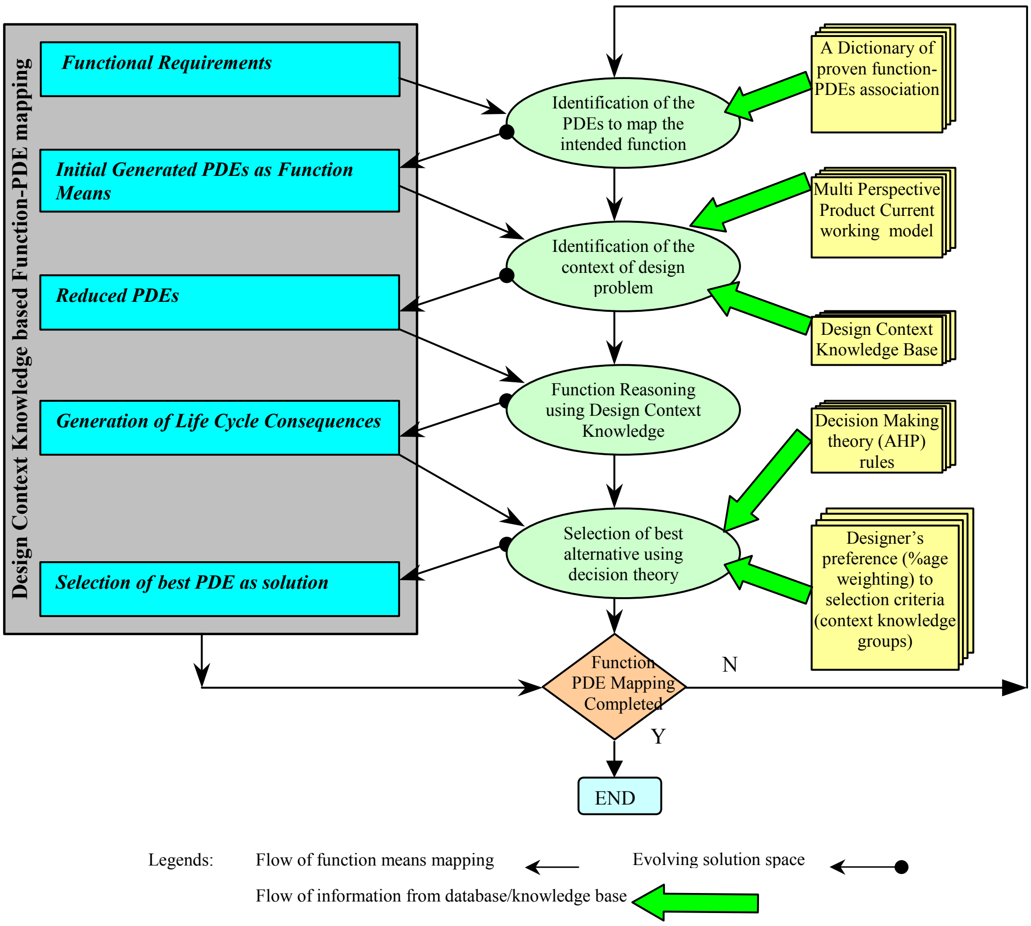


Figure 3. Function to PDE(s) mapping process model

4 Case Study

Function to PDE mapping generic model discussed in previous section is applied in mechanical engineering conceptual design decision-making using design context knowledge. A case study of supporting conceptual design of a sheet metal component using design context knowledge background reasoning is presented in this section.

Sheet metal products are made up of different types of materials like ferrous, non-ferrous and alloys. The common functions of sheet metal products are of conveyance (which are used to transmit/convey solid/liquid/gas from one point to other) nature or of assembly (which are used to join/hold different components/products) nature. For example in case of conveyance nature functions, mostly used functions are *convey, channel, direct, divide, guide*, etc. Lots of sheet metal residential & commercial products perform these type of functions such as *Air*

Intakes, Dormer Vents, Static Louvers, Roof Vents, and Ducts etc. In case of assembly type functions, mostly used functions are *assemble, constrain, enclose, fasten, fix, guide, join, link, locate, orient, position, support etc.* Industrial sheet metal products perform these types of functions like *automotives' body panels, computer casings, electrical control enclosures etc* [9]. These functions are achieved through different *manufacturing features*, which are inscribed on sheet metal during the manufacturing process. These features include *slot, hole, bend, notch, lance, hem, curl, emboss, bead, rib* etc.

The sheet metal product under consideration in this case study is the design of computer power unit as shown in figure 4. This product can be broken down to different hierarchical level as PDEs such as

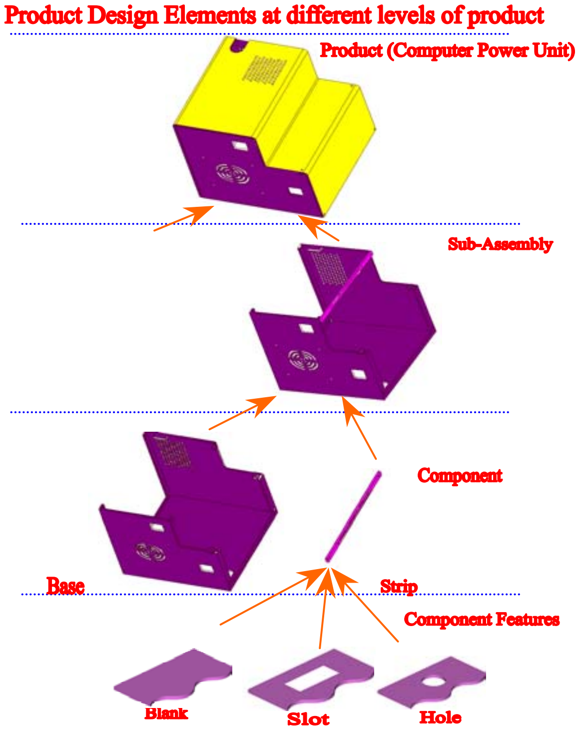


Figure 4: Product Design Elements (PDE) at different levels of a sheet metal product

- *Component building PDEs:* component design elements that constitute a component e.g. for a computer power unit's casing, component elements include the blank, slot, hole, material, snap-fits and rib features.
- *Component PDEs*: a single material product component produced without any assembly operations; e.g. the base & strip of the power unit are two separate PDEs;
- *Sub-assembly PDEs*: i.e. elements consisting of more than one product components. An example is base & support strip assembly of power unit. This sub-assembly is regarded as PDE at sub-assembly level.

Now the conceptual design problem under consideration within this product is the assembly of two components ***Base*** and supporting ***Strip*** as shown in figure 5**.**

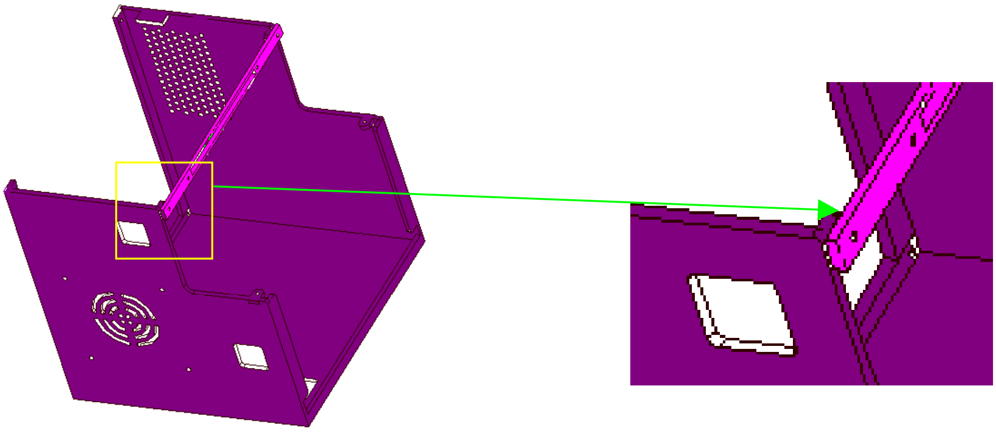


Figure 5 Assembly of Base and Strip in Computer Power Unit

Therefore the functional requirement can be defined as Provide-Assembly. This *"Provide Assembly"* function can be further decomposed as shown in figure 6 using a library of previously decomposed sub functions. This library was derived from classification of functions for mechanical design identified from literature [10][11]. Once the "Provide Assembly" function is decomposed into two functions "Assemble Permanently" and "Assemble Semi-Permanently" the next task is to generate initial possible PDEs/solutions in order to satisfy either one of the selected sub functions. In our case study as the functional requirement is of *Semi-Permanent* Assembly, therefore we continue with this sub function. Initial PDEs/solutions identified in order to realize "Semi Permanent" Assembly are *Slot-Fit, Bolting, Lance-Fit, Wrapping, Soldering* as shown in figure 6.

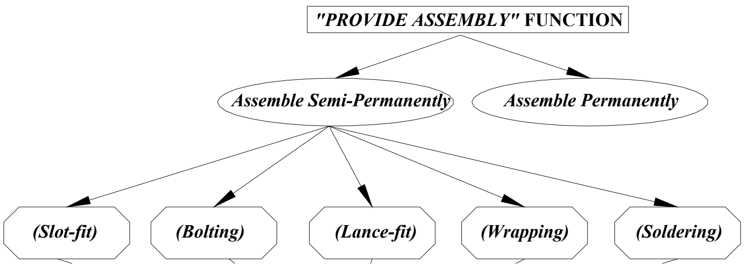
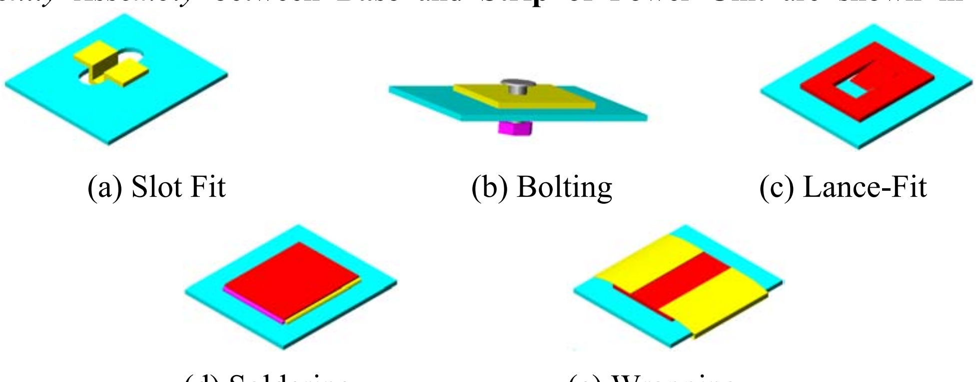


Figure 6 Function decomposition and initial PDEs/solutions to fulfil *"Semi-Permanent Assembly"* function

These solutions are generated by developing a dictionary of proven function means association. This dictionary has been developed using literature review of designing of sheet metal components [12][13]. The forms of these five solutions/means to realize *Semi-Permanently Assembly* between **Base** and **Strip** of Power Unit are shown in Figure 7.



(a) Slot Fit (b) Bolting (c) Lance-Fit

(d) Soldering (e) Wrapping

Figure 7 Form of different PDEs/solutions for *"Semi-Permanent Assembly"* function

The whole process of function to PDE mapping for “Semi-Permanent Assembly” function in this case study using generic model discussed in section 3.3 is explained through figure 8. Once the initial means/solutions are generated on the basis of decomposed functional requirement with the help of function-PDE association dictionary, the next step is to go for context knowledge identification.

Context knowledge generated for design problem under consideration in this case study requires analysis under each one of four decomposed categories of design context knowledge. These context knowledge categories are

- Material/Environmental context knowledge consists of information related to materials selected for the solution product, more specifically the properties of the chosen material and 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.
- Life cycle context knowledge includes 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.
- User context knowledge consists of information of users of the intended solution products, e.g. age, gender, product preference, company policy etc.
- Current working context knowledge includes partial solution information generated up till current stage of the design process for a given problem.

With the above context information available, the context information reasoning mechanism aims to detect any ‘unfit’ PDE from the initial mapped PDEs. The initial function requirement to **Provide Semi-Permanent Assembly** in figure 8 has been matched with four possible means to implement this requirement. Searching the context information of solution material selection reveals that material of both joining parts is aluminium. This activates a piece of knowledge that *Wrapping* means cannot be used for the function, as only non metallic components can be tape wrapped as semi-permanent assembly. Thus *Wrapping* is excluded from set of PDEs reducing it to only four PDEs for further evaluation.

Based on context knowledge based reasoning mechanism, life cycle consequences are generated for each one of the four PDEs in the list. In the figure 8 due to space limitation only one life cycle consequence associated with each of the PDEs is illustrated, but in practical terms both positive/negative and intended/unintended consequences are generated at this stage for the consideration of designer. This allows the designer to use his/her experience/personal preference on the basis of some decision making theory rules (Analytic Hierarchy Process AHP which is a general decision making theory is used in this case study) in evaluating all these remaining PDEs to come up with the best alternative. As the reasoning mechanism and evaluation of all these four PDEs based on the life cycle consequences is beyond the scope of this paper, therefore it is not described here. However the result of this procedure describes *Slot-Fit* as the best alternative PDE in this case study out of all these four PDEs satisfying all functional requirements with least negative life cycle consequences.

5 Conclusion

From this research, it can be concluded that:

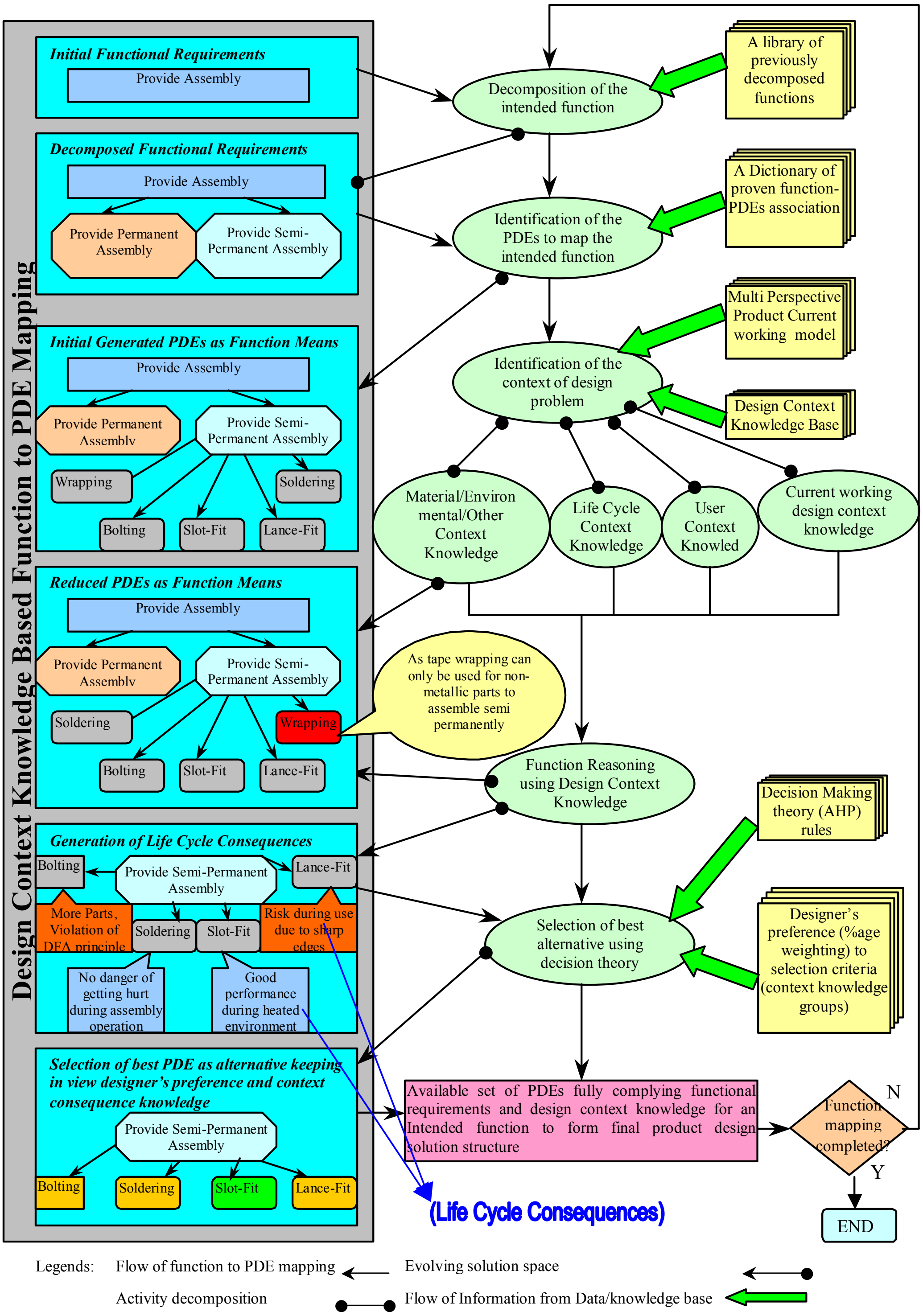


Figure 8. Function to PDE mapping for "Semi-Permanent Assembly" solution

- PDEs at component building level in metal components can be used as potential means to realise different categories of functions;
- Product Design Elements can therefore be generalised and modularised from past design solutions and collected to form a library of well-proven and used design solution building primitives. Once these PDEs are formalised into the reusable library, they become an important source of solution ideas to any given new design problem. As these are well-proven partial design solutions, they can be used with confidence to provide satisfactory partial solutions. The overall solution to a given design problem can thereafter be derived

by combining these partial solutions for the design problem. In this paper sheet metal products are considered and relevant PDEs are used to illustrate the approach for product solution modelling;

- An integrated computer based approach can be developed to model, represent and decompose part functions as well as corresponding PDEs/solutions into a useful format which can be used for conceptual as well as for detailed design including addressing issues involving life cycle phases like manufacturability, assemblability etc;

References

[1] Welch, R.V. and Dixon, J.R., "Representing function, behaviour and structure during conceptual design", Proceedings of ASME Design Theory and Methodology Conference, Vol. 42, 1992, pp 11-18.

[2] Gero, J. S., Tham, K. W. and Lee, H. S., "Behaviour: A link between function and structure in design", Intelligent Computer Aided Design, D. C. Brown, M. B. Waldron and H. Yoshikawa (eds), 1992.

[3] Pugh, S, "Total Design", Addison-Wesley Publishers Ltd., Essex, 1991.

[4] Andreasen, M. M., Hanse, C.T., "The structuring of product and product programs", 2nd WDK workshop on product structuring, Delft University, The Netherlands, 1996.

[5] Borg, C. J., Yan, X. T., Juster, N., "Guiding component form design using decision consequence knowledge support", Artificial Intelligence for Engineering Design, Analysis and Manufacturing , Vol. 13, pp 387-403, 1999.

[6] Brunetti, G., Golob, B., "A feature based approach towards an integrated product model including conceptual design information", Computer Aided Design, Vol. 32, pp. 877-887, 2000.

[7] Yan, X.T., Rehman, F., Borg, J.C. "FORESEEing design solution consequences using design context information", Proceedings of the Fifth IFP Workshop in Knowledge-Intensive Computer –Aided Design, 2002, pp 18-33.

[8] Saaty, T.L., 'How to Make a Decision: The Analytic Hierarchy Process', European Journal of Operational Research, Vol. 48, pp 9-26,1990.

[9] Rehman, F, Yan, Xiu-Tian, "Proactive support for conceptual design synthesis of sheet metal components", Proceedings 4th International Conference on Integrated Design and Manufacturing in Mechanical Engineering IDMME 02, Queyriaux Design & Communication publishers, Clermont-Ferrand, France, 2002, pp 83.

[10] Kirschman, C. F. and Fadel G. M., "Classifying Functions for Mechanical Design," ASME Journal of Mechanical Design, Vol. 120, pp. 475-482, 1998,

[11] Kirschman, C. F. and Fadel G. M., and Jara-Almonte, C. "A function based decomposition in mechanical design" Design Theory and Methodology Conference, ASME Design Technical Conferences, Irvine, CA, Published in Conference proceedings, modified and forwarded to ASME Transactions of Design, August 1996.

[12] Carlson, R. F., "Metal stamping design: practical and economical design of stamped metal parts", 1961.

[13] Precision Metal Forming Association, "Design Guidelines for Precision metal stampings and fabrications", PMA, 1995.