CAN DESIGNERS BE PROACTIVELY SUPPORTED AS FROM PRODUCT SPECIFICATIONS?

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ABSTRACT
During the design process, designers are concerned with two main types of issues - issues related to "what needs to be achieved" or "whats" and issues related to "how these needs will be met" or "hows". A literature review carried out revealed that means which proactively make designers aware of artefact life-cycle consequences (LCCs) arising from both their "whats" and "hows" and which guide them on how to minimise or avoid any negative consequences, are lacking. This research thus contributes an approach framework to meet this aim. The approach framework developed is further implemented as a prototype computer-based tool and subsequently evaluated. Based on the feedback obtained from the evaluation, future research directions are also proposed.

Keywords: life-cycle consequences, proactive support, life-oriented, requirements management

1 DESIGN PROBLEM BACKGROUND
Suh [1], argues that designers are concerned with two main types of issues during the design process - issues related to *what needs to be achieved* (hereafter referred to as *"whats")*, and issues related to *how these needs will be met* (hereafter referred to as *"hows")*.
Taking as an example a designer *"what"* (Figure 1(a)) that a part needs to be non-electrically conductive, this gives rise to a number of issues that need to be considered by the design team. For instance, certain processes such as electrical discharge machining (EDM) are not feasible (Figure 1(b)) to manufacture the part given that the part cannot be electrically conductive and therefore there would be not spark initiation. On the other hand if milling *(*a *"how")* is selected (Figure 1(d)), since it is suitable for machining non-electrically conductive parts (Figure 1(c)), problems may arise due to the limited aspect ratio (height/diameter ratio) that can be achieved by this process. As shown in Figure 1(d), if the height *h* is designed to be larger than the cut length of the tool *x (*a *"how")*, while the tool is cutting its shank will come in contact with the workpiece (Figure 1(e)). This contact in turn causes friction and high temperatures, thus affecting the tool – for example its toughness is reduced or it may even break.
Therefore, if the designer is not made aware of any such *unintended* consequences and not guided on how these consequences can be avoided, problems will arise during manufacturing and redesigns would be required. Possible guidance includes considering alternative manufacturing processes which are suitable for non-electrically conductive parts (Figure 1(c)), reducing the height of the protrusion or introducing a relief angle so that contact between the tool shank and the workpiece is avoided (Figure 1(f)). Despite these different issues that need to be considered by designers, means which *proactively* make designers aware of *artefact life-cycle consequences (LCCs)* arising from both their *"whats" and "hows"* and which guide them on how to minimise or avoid any negative consequences, are lacking [2]. For example, ICE [3], DAS [4] and KIS [5] only reveal consequences arising from the designers' "hows". On the other hand, systems such as WBCDT [6] and ConCAD Expert [7] which provide awareness of consequences arising from both designers' "whats" and "hows" are passive rather than proactive.
This paper is structured as follows. Following the design problem background, the aim and hypothesis of this research is described in Section 2. Section 3 describes the solution developed to meet the set aim followed by a description of the solution evaluation procedure and results in Section 4. A discussion of the evaluation results and possible directions for future work are presented in Section 5. Paper conclusions are finally drawn in Section 6.

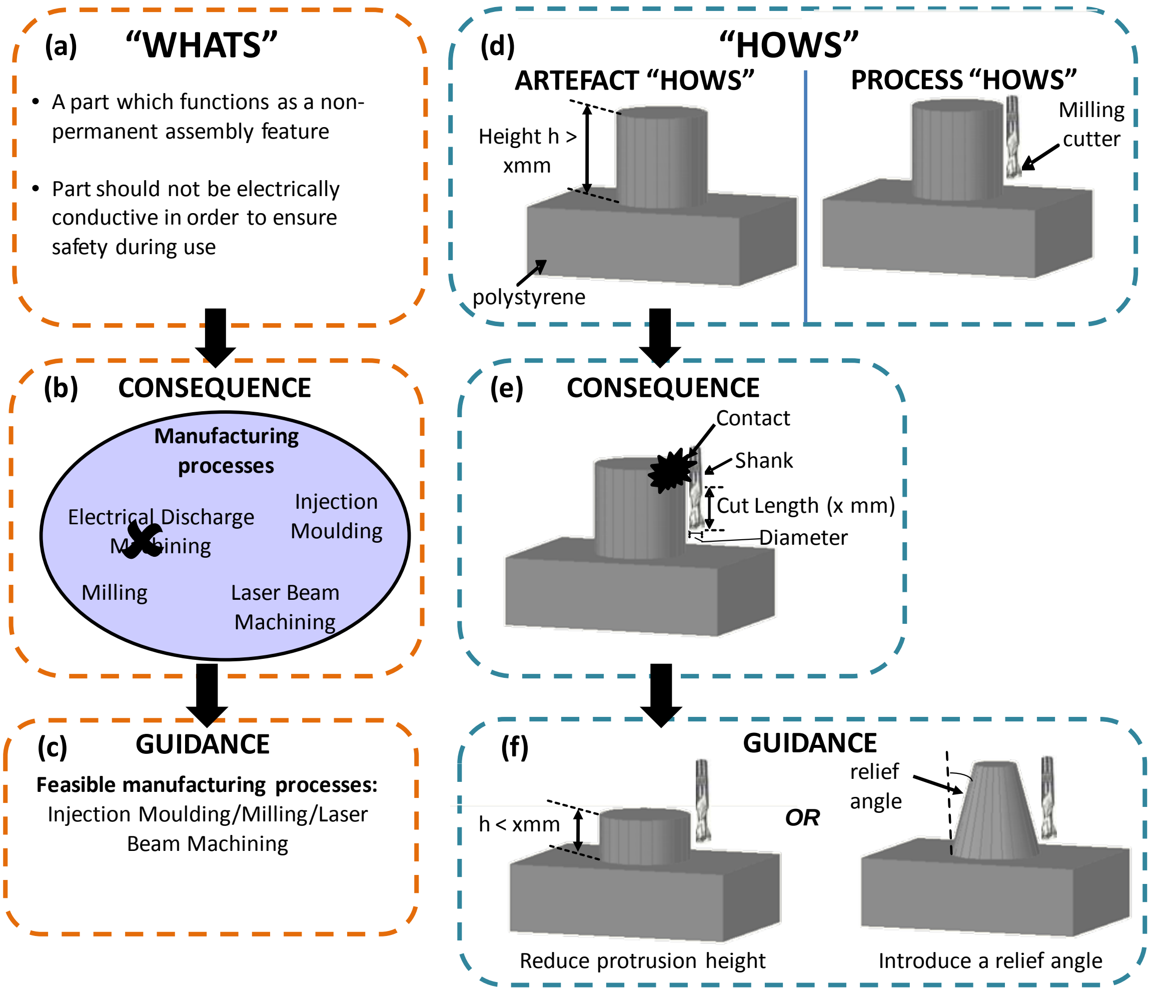

Figure 1. Examples of consequences arising from "whats" and "hows"

2 RESEARCH AIM AND HYPOTHESIS

In view of the above mentioned issues, the aim of this research is to develop a computer-based means by which designers can be made proactively aware of LCCs, arising from both their "whats" and "hows", and guided on how to minimize or avoid any negative consequences. It is hypothesised that with such a means of support, designers would be in a better position to design life-oriented solutions, that is, design solutions that cater for a host of artefact life-phases. This hypothesis is tested during solution evaluation by explicitly asking the evaluators about the extent to which they consider the means developed to support the generation of life-oriented design solutions.

3 SOLUTION DEVELOPMENT

In this section, a background to decision-making in design is first given. Based on this background, the approach framework developed, which aims to proactively make designers aware of LCCs arising from both their "whats" and "hows", is then described.

3.1 Background to Decision-making in Design

During the design process, the designer is given a design *issue*, or need, which the design solution has to meet. This is constrained by a number of *criteria* ("whats", such as maximum cost) which limit the feasible design solution space. Data, information and knowledge support the criteria and give rise to a number of *alternatives*. At the component level, these alternatives include reusable product design elements (PDEs) such as form features (e.g. slot), assembly features (e.g. screw) and materials (e.g. polymers). The designer then needs to make *decisions* ("hows") by selecting from the available alternatives [8].

The alternatives selected (or "hows"), as a result of the decision-making process, are termed by Borg [9] as *synthesis decision commitments*. The term "synthesis" is used because these commitments are

made during the synthesis activity of the design cycle. In addition, they are "synthesis decision commitments" as, once made, they are reflected in the evolving artefact solution model, termed in this research as the *Artefact Life Model* (Figure 2).
Similarly, the criteria selected ("whats") are termed by Grech [10] as *specification commitments.* The term "specification" is used because customer needs are often unstructured, informal and volatile [11] and the designer has to convert them into technical specifications before they can be used during the design process. For example, the customer need "the surgical instrument should be ergonomic" first has to be converted into corresponding technical specifications, such as the maximum weight and size limits that the instrument can have, prior to be used. These commitments are considered as "specification commitments" as, once made, they are reflected in the evolving artefact specification model, termed in this research as the *Artefact Specification Model* (Figure 2).
Thus, the specific "whats" and "hows" this research is concerned with are *specification commitments* and *synthesis decision commitments* respectively, as illustrated in Figure 2.

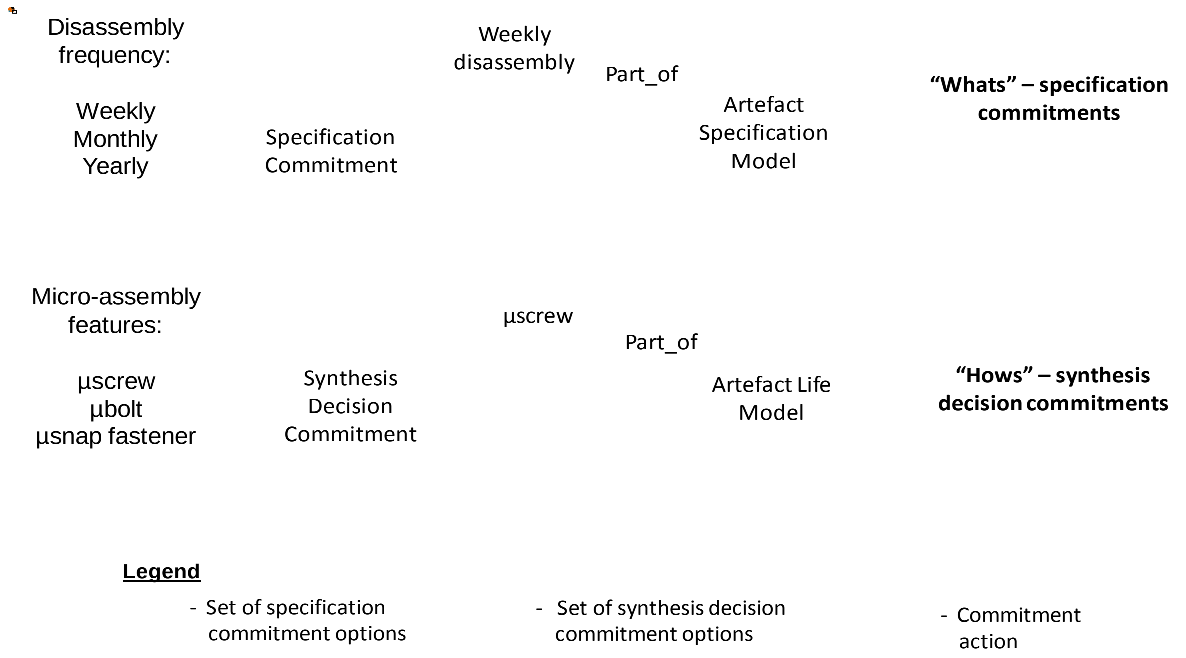

Figure 2. Specification commitments and synthesis decision commitments

3.2 The Specification and Synthesis Decision Consequence Approach Framework

The Specification and Synthesis Decision Consequence (SASDC) Approach Framework, which builds upon two other approach frameworks – the "Knowledge of life-cycle Consequences (KC)" Approach Framework [9] and the "Feasible Solution Space Filtering Approach from Specifications (FSS-FAS)" Approach Framework [12], is made up of three frames, the *Operational Frame*, the *Evolving Model Frame* and the *LCC Knowledge Modelling Frame* (Figure 3). The novelty of the approach framework lies in the fact that while the KC Approach Framework aims to present to the designer LCCs arising from synthesis decision commitments *only*, the FSS-FAS Approach Framework aims to present LCCs arising from specification commitments *only*. The SASDC Approach Framework thus aims to overcome this limitation of the two other approach frameworks by presenting LCCs arising from *both* specification commitments and synthesis decision commitments. Each of the frames making part of the approach framework will be described next.

The Operational Frame

Interaction between the human designer and the other frames in the SASDC Approach Framework takes place via the Operational Frame. This frame provides to the designer:

- sets of specification commitment options from which specification commitments relating to the artefact, its sub-assemblies and components can be made;
- sets of feasible and unfeasible synthesis elements based on previously made commitments.

Synthesis elements include Product Design Elements (PDEs, e.g. form features) and Life-Cycle Phase Elements (LCPEs, e.g. manufacturing processes), from which synthesis decision commitments can be made;

- awareness of LCCs resulting from commitments made together with brief and detailed guidance on how these consequences can be minimised or eliminated;
- any fluctuations in universal virtues [13] arising from the commitments made.

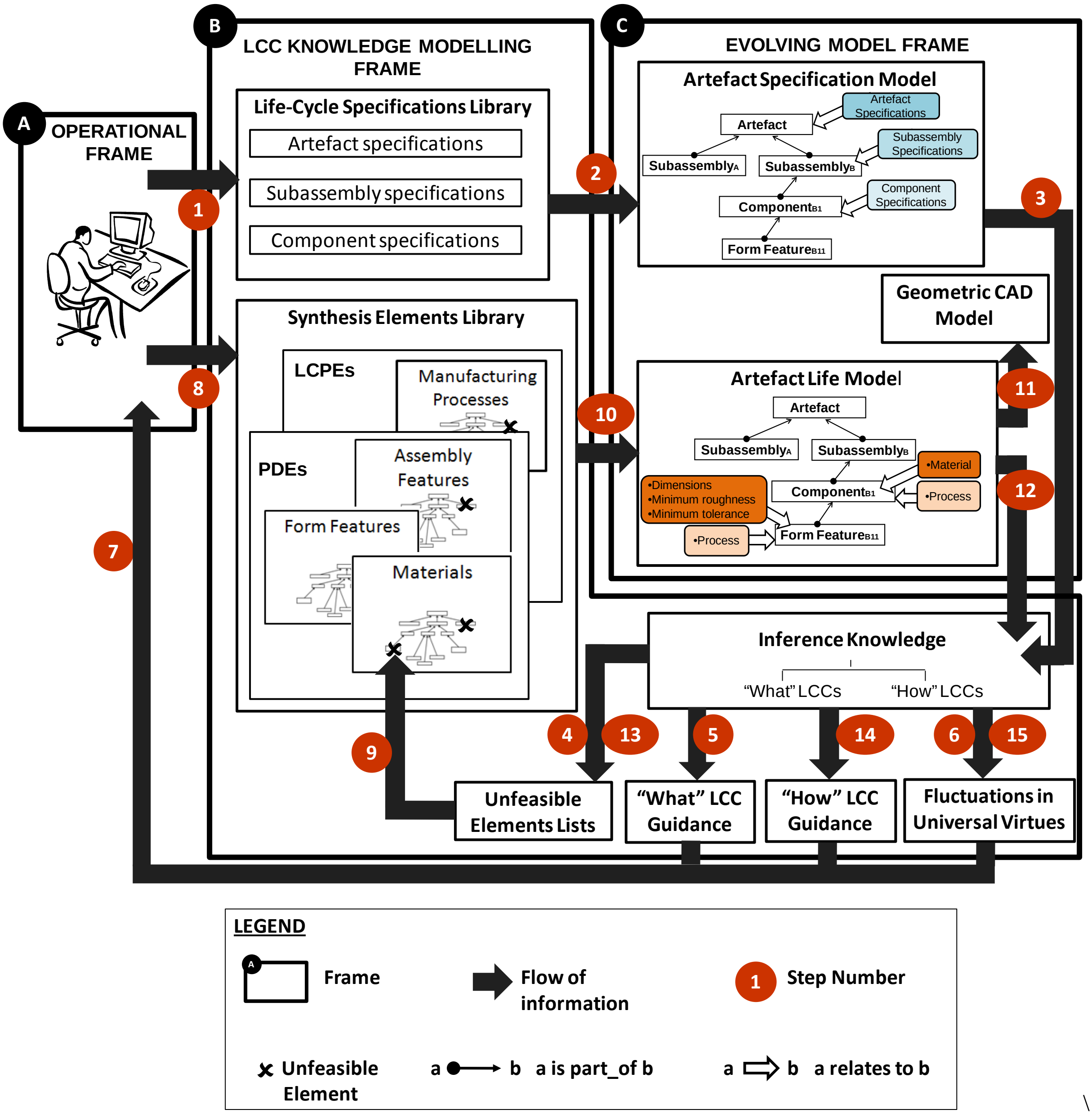

Figure 3. The Specification and Synthesis Decision Consequence Approach Framework

The Evolving Model Frame

In the Evolving Model Frame the different commitments made by the designer, via the Operational Frame, are recorded so that the relevant LCCs can be inferred. This is performed by:

- An *Artefact Specification Model* which keeps a record of specification commitments for the artefact, its subassemblies and components made by the designer;
- An *Artefact Life Model* which keeps a record of the current synthesis decision commitments (PDEs and LCPEs) made by the designer.
- In addition, the *Geometric CAD Model*, which is the geometrical representation of PDE commitments (e.g. of form feature, material and surface texture commitments) present in the

Artefact Life Model, is also part of this frame.

LCC Knowledge Modeling Frame

The role of this frame is to provide libraries of specifications and synthesis elements which are required by the designer to make the different commitments. This knowledge also needs to be structured to support the inference of both "what" and "how" LCCs. Thus, this frame provides:

- A *Life-Cycle Specifications Library* which includes specification commitment options from which specification commitments relating to the life-cycle of the artefact, its sub-assemblies and components can be made;
- A *Synthesis Elements Library* which includes a set of synthesis alternatives (PDEs and LCPEs) from which synthesis decision commitments can be made;
- *Inference Knowledge*, which relates the specification commitments present in the Artefact Specification Model and the synthesis decision commitments present in the Artefact Life Model to their corresponding LCCs.

To appropriately present inferred LCCs to the designer, this frame also provides:

- *Unfeasible Elements Lists*: When a reduction in the feasible design solution space following any commitments occurs, unfeasible synthesis elements need to be recorded so that they can be proactively brought to the designer's attention before further synthesis decision commitments are made. This is performed via the Unfeasible Elements Lists;
- *LCC Guidance:* LCC Guidance can be either "what" LCC guidance (that is, guidance related to LCCs arising from specification commitments) or "how" LCC guidance (that is, guidance related to LCCs arising from synthesis decision commitments). The guidance includes descriptions of how LCCs have resulted and how these LCCs can be eliminated or minimised. In addition, the guidance provided can be either brief or detailed, depending on the designer's preferences;
- *Fluctuations in Universal Virtues:* When a LCC is inferred, fluctuations in universal virtues of the different artefact life-phases can occur. These need to be updated as soon as the LCC is inferred so as to make the designer aware of the effects the commitments made have on the different artefact life-phases.

Following the numbered steps illustrated in Figure 3, the SASDC Approach Framework works as follows: The designer first selects specifications for the artefact, its subassemblies and components from the *Life-Cycle Specifications Library* (Step 1). These specifications are recorded in the *Artefact Specification Model* (Step 2) and any inferences resulting from these specification commitments are made (Step 3). From these inferences, the *Unfeasible Elements Lists* are updated with any unfeasible elements (Step 4). The *"What" LCC Guidance* and *Fluctuations in Universal Virtues* are also updated (Step 5 and Step 6) following these inferences. The designer may at this stage view the guidance and fluctuations in universal virtues related to the specification commitments made (Step 7). Furthermore, upon selection of PDEs and LCPEs from the *Synthesis Elements Library* (Step 8), the library is updated to reflect any unfeasible elements (Step 9) following previously made commitments. Selected elements from the Synthesis Elements Library are included in the *Artefact Life Model* (Step 10) and in the case of PDEs, these are also included in the *Geometric CAD Model* (Step 11). From the updated Artefact Life Model, new LCCs can be inferred (Step 12). Once again, the Unfeasible Elements Lists are updated (Step 13) together with the "How" LCC Guidance and Fluctuations in Universal Virtues (Step 14 and Step 15). At this point, further synthesis decision commitments can be made and the cycle can be repeated (Step 7 – Step 15).

3.2.1 SASDC Approach Framework Implementation

The SASDC Approach Framework has been developed further into a system architecture which was then implemented as a prototype computer-based design support tool. The tool is implemented in computational form as a centralised Knowledge-Based System (KBS) integrated with a Computer-Aided Geometric Modelling (CAGM) environment. The CAGM system used for implementation of the tool is Autodesk Inventor 2010 while Inventor VBA and CLIPS Version 6.0 were used for implementation of the graphical user interface and KBS respectively (Figure 4). Details of the approach framework implementation are beyond the scope of this paper. However, the reader may refer to [2] for further details.

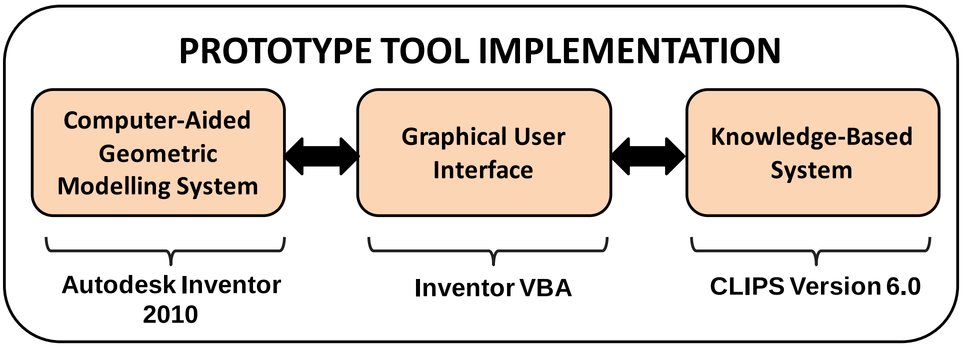

Figure 4. Software used for the prototype tool implementation

4 SOLUTION EVALUATION

To critically evaluate the SASDC Approach Framework, the prototype tool developed was demonstrated to a number of evaluators via a case-study, showing a typical application of the tool in a real-life scenario. The specific objectives of the evaluation were to assess whether:

1. evaluators consider having proactive awareness of the following LCCs important:
   (a) LCCs arising from specification commitments;
   (b) LCCs arising from synthesis decision commitments;
2. evaluators consider the integration of artefact life-cycle specifications within a CAGM environment, to be able to foresee LCCs arising from specification commitments in this environment, useful;
3. the tool is considered to support the generation of life-oriented design solutions, at least for solutions being generated in the domain of the case-study (that is, micro-scale design solutions);
4. the tool is considered to be applicable in practice.

4.1 Evaluation Background

The evaluation was carried out with 27 evaluators in total, out of which 16 were designers coming from five local design and manufacturing companies and 11 were design researchers and academics, coming from six different countries. They had an average of 11 years of design experience and 9 years of experience in using CAD systems.

Each evaluator was first given a short presentation concerning the research background followed by a background to the evaluation case-study. A live demonstration of the prototype tool was then given using the case-study. *Semi-structured interviews* were finally carried out individually with each evaluator, during which the evaluators were asked a pre-defined set of questions but were also free to add any other comments and suggestions they felt appropriate. This helped to generate not only quantitative but also qualitative results.

To accurately measure the outlook of the evaluators with respect to the questions asked, a five-point likert scale was utilised for most of the questions, where 1 indicates a strong positive attitude and 5 indicates a strong negative attitude. In certain instances, for example so that evaluators could make any comments regarding the solution, open-ended questions were also utilised. Statistical Package for Social Sciences *(SPSS)* [14] was utilised to analyse quantitative results, using a 0.05 level of significance.

4.2 Evaluation Case Study

The evaluation case-study concerned part of the design of an instrument used for minimally invasive surgical procedures. More specifically, the case study focused on a particular component of the instrument – one jaw of the end-effector subassembly which has several small (micro-scale) features. Both specification commitments and synthesis decision commitments concerning the design of the jaw component were carried out.

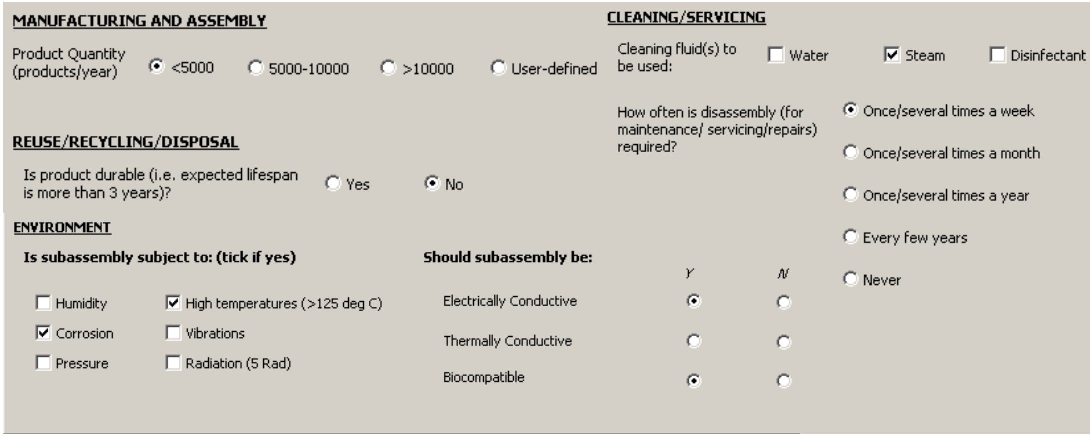

Figure 5. Specification commitments for the jaw component

Figure 5 shows some specification commitments made for this component while Figure 6 shows the LCCs that arise when these commitments are made. For example, the corrosive environment commitment limits the solution space of materials that can be selected for the jaw (Figure 7). Similarly, the synthesis decision commitment concerning the selection of the manufacturing process for the jaw component (an LCPE) limits the range of dimensions that can be selected for particular form features (Figure 8).

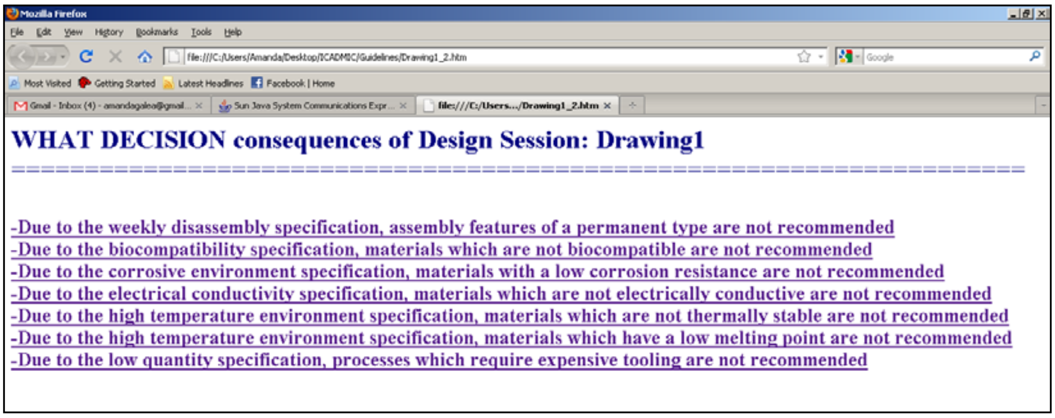

Figure 6. LCCs arising from the specification commitments

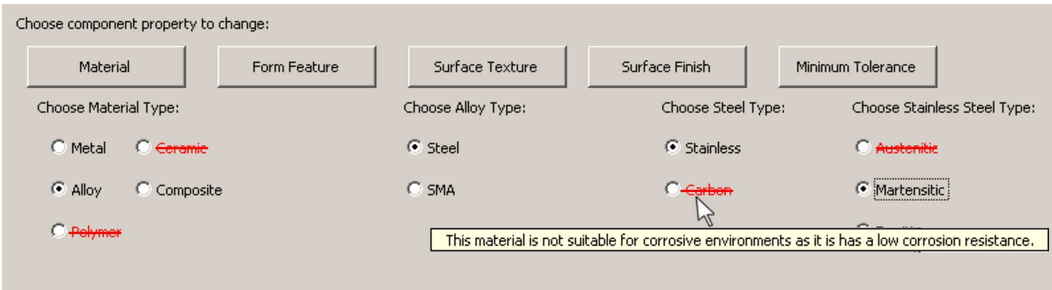

Figure 7. Example LCC arising from the corrosive environment specification commitment

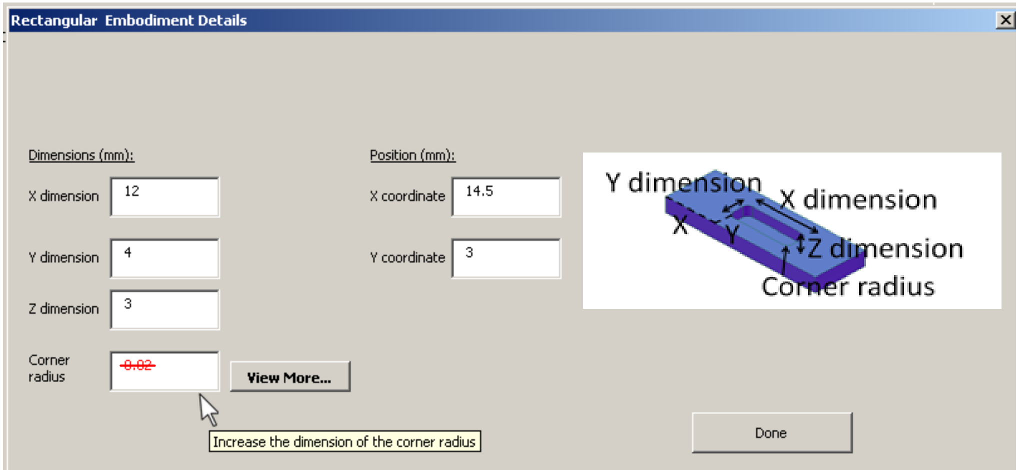

Figure 8. Example LCC arising from a synthesis decision commitment

4.3 Evaluation Results

The results obtained for evaluation objective (1a) revealed that the mean rating given by evaluators regarding the importance of proactive awareness of LCCs arising from specification commitments was 1.41, thus indicating a positive attitude (a rating of 1 indicates a strong positive attitude). The mean rating obtained for evaluation objective (1b), concerning the importance of proactive awareness of LCCs arising from synthesis decision commitments was 1.37, thus also indicating a positive attitude. One evaluator commented that as a designer who spends a lot of time alone in his office, this awareness would assist him by providing the required technical information and thus reduces the need of consulting others. 67% of the evaluators agreed that such proactive awareness reduces design time since omissions are minimised and therefore less iterations are required. Three of the evaluators however commented that such awareness is more suitable for novice designers than for experienced ones. The reason provided was that experienced designers are likely to already possess such knowledge and thus be familiar with most of the LCCs provided.

When asked whether they consider the integration of artefact life-cycle specifications within a CAGM environment, to be able to foresee LCCs arising from specification commitments in this environment, useful (evaluation objective (2)), the majority of the evaluators rated this positively (mean rating of 1.74). The most frequent motivation provided was that this approach reduces design time as it allows the designer to foresee future problems earlier. One of the evaluators also pointed out that in practice the specifications, which are kept separate from the CAGM environment, are normally not fully considered and thus this approach helps to avoid omitting important specifications. Some evaluators however commented that although the concept is good in theory, in practice there is the issue of designers' reluctance to adopt new approaches and who tend to prefer the traditional approach of obtaining this knowledge from other people. When explicitly asked whether this approach reduces the possibility of omitting specifications, 89% of the evaluators agreed. Also, 81% of the evaluators agreed that this approach reduces the time required to carry out research about the feasible synthesis elements.

When explicitly asked about the extent to which they consider the tool to support the generation of life-oriented design solutions at the micro-scale (evaluation objective (3)), the majority of evaluators replied in the affirmative (mean rating of 1.59). Additionally, a number of evaluators pointed out that the tool is applicable irrespective of the scale of the design solution, this providing a degree of evidence on the hypothesis formulated. The Pearson correlation coefficient (R) was also utilised to explore any possible correlation between the ratings obtained and years of experience in using CAD systems the evaluators had. Results showed that there is an insignificant correlation ($R = 0.296$ at a level of significance $p = 0.134$). An independent t-test was also carried out to analyse if there were any significant differences between the mean ratings provided by academic design researchers and industrial designers. Results ($t = 0.267$ at $p = 0.792$) again showed that there is no significant difference in the means of the two groups, thus further substantiating the hypothesis.

The results obtained for evaluation objective (4) revealed that overall, the evaluators find the tool applicable in practice (mean rating of 1.96). However, some concerns were also raised regarding the practical applicability of the tool, namely that currently it is not suitable to design very complex parts and that since the designer has to select from a set of pre-defined specifications and synthesis elements, creativity is inhibited.

5 DISCUSSION AND FUTURE WORK

The positive results obtained for all the evaluation objectives show that overall the evaluators found the SASDC Approach Framework useful for foreseeing LCCs arising from both specification commitments and synthesis decision commitments, and thus be in a better position to generate life-oriented design solutions. Furthermore, it is widely known that designers, as human beings, can only deal with a few facts simultaneously [15]. Thus, it is argued that the approach framework still has some usefulness to experienced designers by acting as "an extension" to the designer's memory when a number of issues have to be considered simultaneously. Additionally, despite the different approach adopted by the prototype tool implementation from traditional design practice, since the designer is required to first select the specifications and afterwards proceed with generating the design solution, the results revealed that overall the evaluators would consider using this tool in practice, given that the knowledge inside it is up-to-date and applies to their company.

A spin-off which emerged from the evaluation was that the SASDC Approach Framework is applicable irrespective of the artefact scale and domain as each is concerned with bringing the "whats" closer to the "hows". Also, the prototype tool, being implemented in computational form as a KBS, can be populated with design knowledge of multiple domains [16], thus providing support to any desired design domain and scale.

Based on the feedback of the evaluators, the following future research directions are proposed:

- Exploring how the approach framework can cope with fuzzy specifications. For example, specifications which are related to aesthetics are usually not well-defined and thus the suitability or otherwise of synthesis elements resulting from these specifications is not clear cut.
- Allowing the designer to specify the importance of a particular specification with respect to the other specifications so that different levels of feasibility of the synthesis elements can be distinguished.
- Currently, LCCs pertaining to a particular specification commitment or synthesis decision commitment are assumed to arise with 100% certainty once the commitment is made. However, in reality each LCC has an associated probability of occurrence [9]. Thus, further research is needed to include LCC certainty factors.

6 CONCLUSIONS

This paper presented a novel approach framework, which has also been implemented as a prototype computer-based tool, by which designers can be made proactively aware of LCCs, arising from *both* their specification commitments and synthesis decision commitments, and guided on how to minimize or avoid any negative consequences. The procedure carried out for evaluation of the approach framework together with the results obtained were also presented. The evaluation results provide a degree of evidence on the hypothesis formulated - that by using this approach framework, designers would be in a better position to generate life-oriented design solutions, as from the selection of specifications. Thus, the results reflect that designers can indeed be proactively supported as from the selection of product specifications. Future work is however required to fully meet this objective.

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