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INTELLIGENT LIFE-ORIENTED DESIGN SOLUTION SPACE SELECTION

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1. Introduction

Consideration of design specifications is a vital part of the product design process. When design specifications are met, not only is customer satisfaction increased, but product development times and costs are reduced through less iteration. Product quality is also likely to be higher if these specifications are systematically addressed. However, focusing on the functionality specifications of the product is not enough. For the product to be really successful, design engineers have to take into account the specifications for the whole product life cycle, not only those for the use phase. This means that fabrication and assembly specifications, product servicing, product retirement and other specifications of the product from conception to grave should also be taken into account.

Traditional CAD tools tend to provide support for the solution phase of the design process, with the design specifications being overlooked. This is a major limitation of these tools given the vital importance of considering design specifications during the design process. Due to this, specifications management is still very paper-based and is kept separate from the actual solution generation as there is no way for the designer to know, via traditional CAD tools, whether a given specification is satisfied in the solution being developed unless it is manually checked each time the question arises. What engineering designers do in practice is they start off with reading the design specifications from the Product Design Specification (PDS), then move on to generate a Quality Function Deployment (QFD) chart to convert the customer 'wants' into technical specifications, then start to take decisions based on what has been stored in their memories from the PDS and QFD [Grech 2009]. Hence, in practice, it is quite difficult to trace whether the design solution satisfies the design specifications or not.

This paper describes the ongoing work being done to develop a computer-based design support tool aimed to meet these limitations. The tool, apart from assisting the designer to take into account the specifications arising from the whole product life-cycle also aims to merge the design specification space with the design solution space in a single tool, thus making it easier for the designer to realize when a design specification is going to be violated.

The rest of the paper is structured as follows: Section 2 is a review of the work that has been done previously in this area. Section 3 then describes the process that is generally used to arrive at a specification and then to a solution for the design. In Section 4, four different approaches to incorporate design specifications in the design process are discussed and the approach which is used in our design support tool is described. In Section 5, the implementation of the prototype tool is described followed by a case-study in Section 6 which shows how the tool can be applied in a typical design situation. Section 7 then draws key conclusions, particularly highlighting the contribution of this paper.

2. Previous work

From a review that has been carried out of 30 intelligent design support tools that were developed during the past 15 years, very few tools include specifications in the system. Some of these include the ones developed by [Omar, et al., 1999, Marx, et al., 1995, Gayretli and Abdalla, 1998, Zhang, et al., 2001, Rehman and Yan, 2007, Mamat, et al., 2009]. However, although these systems incorporate design specifications, they still have some limitations as discussed below.

The QFD DSS system [Omar et al. 1999] aims to guide the design engineer to collect, modify and evaluate information for QFD analysis. Although this system is useful for collecting design requirements and map them to design specifications, it does not help the designer to actually map these specifications to the design solution space. Furthermore, the focus of the system is on Design for Customer Satisfaction and therefore specifications arising from other life-cycle phases such as manufacturing and assembly are not taken into account.

The CADDB system [Marx et al. 1995] aims to help designers design the strongest, lightest possible wing structure at the least cost for a specified aircraft range. Furthermore, it aids in the selection of the manufacturing processes for the wing structural components. Similarly, the system developed by [Gayretli and Abdalla 1998] aims to perform manufacturing process optimization by considering manufacturing possibilities and constraints in the early design of a product. However, although these systems help the designer to consider manufacturing specifications, other specifications arising from other life-cycle phases such as maintenance and disposal are not taken into account.

The EFDEX system [Zhang et al. 2001] applies a knowledge-based approach to the functional design of engineering systems so that functional design can be performed intelligently. More specifically the system, given a specific function, tries to find a behaviour with a functional output that satisfies the required function. Although this system assists the designer in considering functional specifications, other specifications arising from the different product life-cycle phases are not considered.

The PROCONDES system [Rehman and Yan 2007] aims to identify suitable solutions to a functional specification given by the designer and then helps him/her to select the best solution using context knowledge reasoning. Therefore this system actually helps the designer to map functional design specifications to the design solution space and then it automatically generates context knowledge, that is, knowledge about the external world, the life phases of the product, its environment and its users to help the designer select the best solution from those presented. However, a limitation of this system is that it is not integrated with a CAD environment and therefore the designer has to leave the design environment he/she is familiar with in order to acquire support. The importance of integrating the design support tool with a commercial CAGM (Computer-Aided Geometric Modelling) environment such as Solidworks, Pro-E or Inventor is discussed further in Section 5.

The system developed by [Mamat, et al., 2009] aims to provide support during the design of automobile seats by integrating two product life cycle specifications – comfort and assembleability in an engineering CAD system (Autodesk Inventor). This system therefore incorporates design specifications in a Computer-Aided Geometric Modeling environment, however, the only specifications that are incorporated relate to the product use phase (from a user comfort point of view) and assembly phase.

3. Requirements and specifications in design

The definition of requirements that is being adopted in this paper is: Information related to the product, that is provided by product stakeholders, is limited by the given problem and is specified through the explicit and implicit problem requisites. Furthermore, requirements are often unstructured, informal and volatile and therefore they need to be managed before they can be used by the designer and also during the actual design. The process of requirements management, which starts off with requirements elicitation and ends with a list of documented and verified requirements, is described in detail in [Davis, et al., 2006] and therefore will not be discussed here.

3.1 From product requirements to design specifications

After the requirements are documented and verified (Step 1 in Figure 1), analysis begins (Step 2) during which a PDS, which includes an accurate description of what the product should do, is first set up. In the PDS, the customer requirements are translated into technical terms and are now known as product design specifications. Each specification will at this stage consist of a metric and the target value for that metric. For example, the weight and size of the product, the temperature and the radiation it must withstand etc. are all quantified. From the quantified targets defined in the PDS, the QFD chart can then be derived, in which the technical specifications (the 'hows') to achieve the quantified targets are defined. Hence, at this stage, the criteria (or specifications) of the product design (Step 3) in terms of product functions and properties are known. Once the criteria are specified, the design synthesis activity begins (Step 4) where the desired function of the product is divided into subfunctions and means to realize these subfunctions. These are then combined to form a structure for the product and finally its form [Tjalve, 1979].

To ensure that the design solution is in line with the design specifications, the designer has to go back to Step 3 (i.e. has to refer to the criteria). However, as shown in Figure 1, this is generally done much later during the design (during the evaluation activity), and therefore high changing effort will be required if some of the criteria are not met. Furthermore, since requirements tend to change during the design process (and therefore also the criteria), changes tend to be required more often. To meet these limitations, we are thus proposing a computer-based design support tool which, by merging the design specification space and design solution space in a single environment, makes it easier for the designer to realize *before* making a synthesis decision that a design specification is going to be violated. The activity of the design cycle which is being supported by the tool is illustrated by the dotted oval in Figure 1.

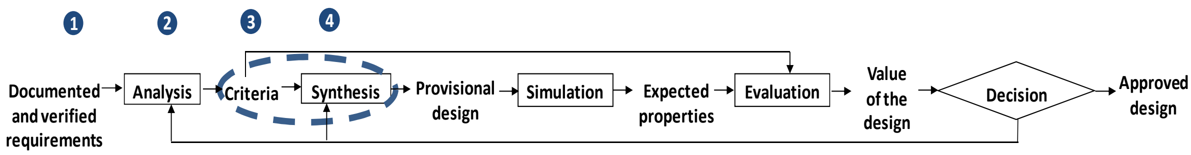

Figure 1. Activity of design cycle being supported [adapted from Roozenburg and Eekels 1995]

Our *hypotheses* for this research is therefore that by merging the design specification space with the design solution space in a single tool the following advantages result:

- Since the design specifications would be present in the tool, the support provided would be in agreement with what is actually required from the customer. For example, if one of the product specifications is that the product would be subject to high temperatures during use, the tool would actually suggest to the designer materials that have a high melting point;
- If the specifications change, say due to changing requirements, the tool would be able to adapt to these changing specifications;
- Given the inherent complexity in the design process, where a multitude of issues have to be taken into account, it would be advantageous to have the design specifications constantly present in the designer's working environment (rather than, for example, being hidden inside a file somewhere). This would reduce the chances of one or more specifications being overlooked.

3.2 Design specifications arising from the product life-cycle

From the literature review, it is clear that very few design support tools take into account design specifications that arise from the whole product life-cycle. Instead, many design support tools tend to focus on the functional specifications of the product and how these can be met. Although product function is of vital importance, because it is after all the main reason why the product exists in the first place, it is not the only issue which should be considered. Design specifications arising from the product life-cycle phases such as manufacturing, assembly, use, cleaning, servicing, recycling and disposal are also of utmost importance. For example, it is useless designing a component with very small features that meets the functional specifications but which cannot be manufactured with the existing tooling and equipment. Similarly, it would not be a good idea to design a component with sharp-cornered depressions if the product needs to be cleaned often.

During the use phase, not only the product function but also the environment plays a very important role. This is especially true in the case of special environmental conditions, where if all the functional specifications are met but one of the environmental specifications is violated, the product would totally fail. An example of this is the field of surgical instruments, where special consideration should be given to the choice of materials that are to be inserted inside the human body due to corrosion, biocompatibility issues etc. The problem is complicated further when the product subassemblies are exposed to different environments. For example, in the case of surgical instruments some subassemblies are used in a "normal" environment whereas others are placed inside the patient's body which is a very different environment due to the blood, saline and tissue present.

Therefore, the design support tool being developed aims to incorporate knowledge concerning a range of product life-cycle phases to make the designer aware of the long-term consequences of his/her decisions on the product life-cycle. An illustration of how the tool is taking into account the specifications from different product life-cycle phases is shown in Figure 2.

To incorporate specifications from the different phases, several styles used for the PDS were reviewed by [Grech 2009]. The most common style is to formulate a *checklist* which includes subheadings for product specifications such as Product Performance, Environment, Life in Service, Maintenance, Target Product Cost, Size and Weight, Aesthetics, and Ergonomics. Another style is the *process tree* which analyzes the life-cycle of the product to foresee which situation, places and activities the product will be found in. This latter format was adopted for use in the design support tool as it considers specifications from the point of view of different product life-cycle phases.

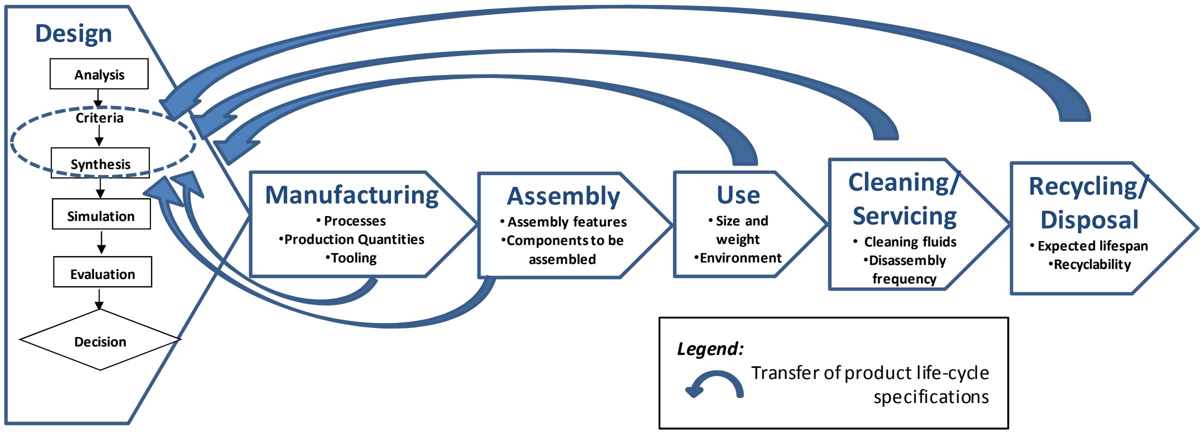

Figure 2. Consideration of specifications arising from different product life-cycle phases

4. Incorporation of specifications in the design process

There exist four different approaches, to our knowledge (mainly based on literature), to how design specifications can be incorporated in the design process. A description of these four approaches is detailed below:

1. Using the traditional "paper-based" method: Using this method, the designer has to go back and manually refer to the design criteria whenever the need arises. As mentioned in the previous section, this is generally done much later during the design (during the evaluation activity), and therefore high changing efforts will be required if some of the criteria are not met. This approach is the one adopted by the QFD DSS system [Omar et al. 1999] mentioned in Section 2.
2. Using Computationally-based design (CBD) tools: CBD tools produce designs automatically after given the design specifications. Systems that use this approach include the ones developed by [Gayretli and Abdalla 1998 and Zhang et al. 2001]. Although at first glance these tools may seem more supportive during the design, this is generally not the case. In fact many design researchers agree that while computers are an essential tool in

engineering design, it is a critical mistake to view them as the heart and soul of design as this would result in less creativity and innovation. Therefore, a better approach would be to go between the "paper-based" approach and the CBD tool approach – that is, to use Knowledge-based design (KBD) tools.

3. Using KBD tools that provide support *after* a synthesis decision is made: In this approach, the designer, after making a "bad" synthesis decision (a decision that violates one or more design specifications), as in Figure 4 (a) Step 1, is informed that the decision made has certain undesired consequences on the other product life-cycle phases (Figure 4 (a) Step 2) and therefore the designer has to choose another option (Figure 4 (a) Step 3) until no consequences result (Figure 4 (a) Step 4). A system that uses this approach is the one developed by [Mamat et al. 2009]. This is a big improvement with respect to the first two approaches as while in the first one a lot of redesigns tend to be needed until all the specifications are met, in the second one, design creativity is limited as the design is produced automatically. However, as illustrated in Figure 4 (a), this approach may still require a number of iterations (which result in loss of design time) until a solution which has minimal undesired consequences is found.
4. Using KBD tools that provide support *before* a synthesis decision is made: In this approach, which is the one being adopted by our design support tool, the designer is made aware of "bad" synthesis decisions (decisions that violate one or more design specifications), before actually making the decision. Therefore, as illustrated in the example of Figure 3, if one of the design specifications is that a subassembly should not be electrically conductive, materials that are electrically conductive, namely metals and alloys, are automatically brought to the attention of the designer and therefore the design solution space is reduced from S to S_1. Similarly if another specification is that the subassembly would be subject to high temperatures (> 125°C) during use, materials with a low melting point are again brought to the designer's attention, with the result that the design solution space is now further reduced to S_2.

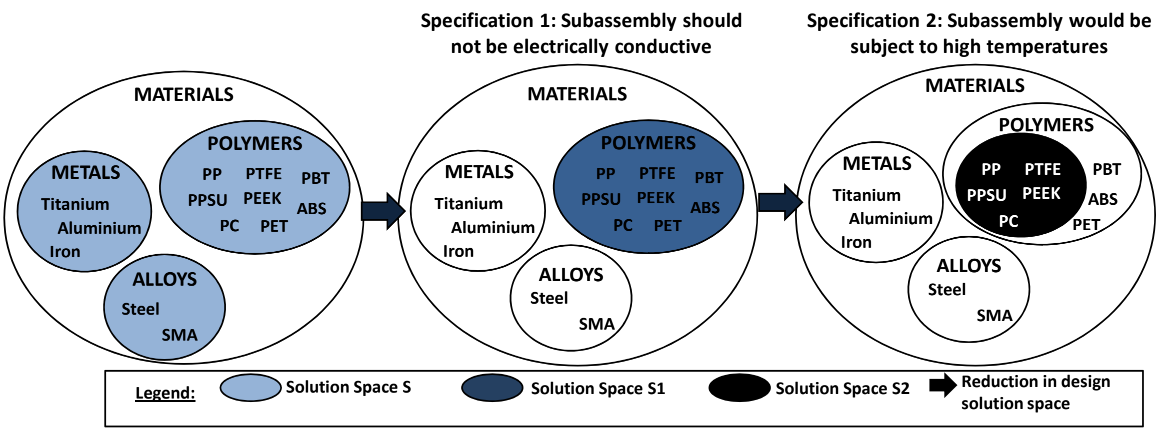

Figure 3. Reduction in design solution space by Approach 4

Therefore, compared to the previous approach, where several iterations may be required until the ideal solution is found, in this case no iterations are required as the designer is made aware of the "bad" synthesis decisions from an even earlier stage - *before* the synthesis decision is actually made. The idea behind this approach is illustrated in Figure 4 (b), which also shows the reduction in design time compared to the previous approach.

This approach is also being extended to consider not only the interaction between the design specifications and the design solution space but also the interactions between elements in the design solution space itself. These elements can be product design elements (PDEs, e.g. form, material, surface, dimension) or life-cycle phase elements (LCPEs, e.g. manufacturing and assembly processes and tooling). For example, if a designer decides on a non-conductive material such as ABS, and also decides that the manufacturing process to be used to produce the desired component is EDM

(Electrical Discharge Machining), this would result in a problem. The reason for this is that non-conductive materials cannot be machined using EDM since there would be no spark initiation.
Therefore, in this case, to prevent the designer from making choices with undesired consequences (such as having to decide on a different manufacturing process or a different material much later during product development), approach 4 can again be used. What happens in this case is that as soon as the designer decides on ABS, he/she is immediately made aware of choices that would have "bad" consequences in the future, which in this case is the EDM manufacturing process. Therefore, even *before* selecting the manufacturing process, the designer is aware of those processes (e.g. EDM) which should not be chosen.

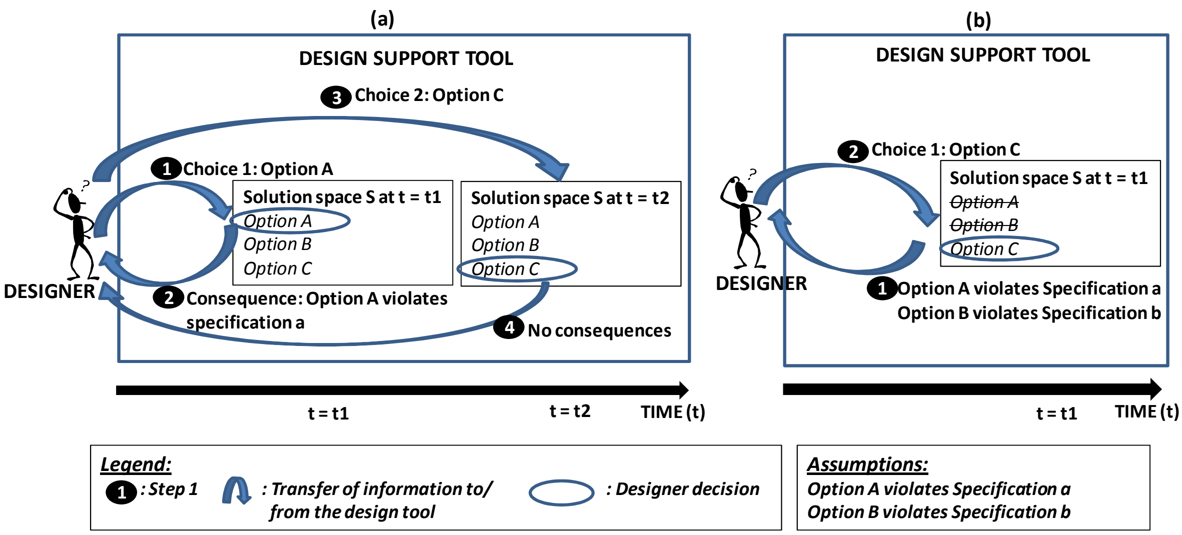

Figure 4. (a) Idea behind Approach 3 (b) Idea behind Approach 4 (adapted from [Grech 2009])

5. Prototype tool implementation

For design specifications to be effectively incorporated in the design process, these should ideally be embedded in a Computer-Aided Geometric Modelling (CAGM) Software such as Pro-E, Inventor or Solidworks. Therefore, the designer would not forced to leave the "natural" work environment in order to keep track of the design specifications.
In order to achieve this goal, our design support tool makes use of the Autodesk Inventor CAGM software, which communicates with the CLIPS Expert System Shell via Dynamic Data Exchange (DDE). Furthermore, for the interface with the CAGM software to be structured and simplified, it is assumed that the designer manipulates PDEs by the five main properties mentioned by Tjalve [Tjalve 1979]. These include the structure (for the product as a whole i.e. the elements of the product and their relationship) and form, material, dimension and surface (for each element). As described by Tjalve, these PDE properties are the ones which the designer can manipulate, and it is by successively deciding on these that a product is created.
The design support tool works as follows (see Figure 5): The designer chooses any design specifications for the product (Step 1) from the CAGM software, which are sent to CLIPS via Dynamic Data Exchange (DDE) (Step 2) so that the necessary inferences required to reduce the design solution space are made. The options which are outside the recommended design solution space together with the life-cycle consequences which would result if these options are chosen, are sent back to the CAGM software (Step 3) so that the designer is aware of these options *prior* to making a synthesis decision. Therefore, the designer is now in a position to make a life-cycle oriented choice from the design solution space (Step 4). After a choice is made from the design solution space this is immediately reflected in the 3D model in the CAGM software drawing panel (Step 5).

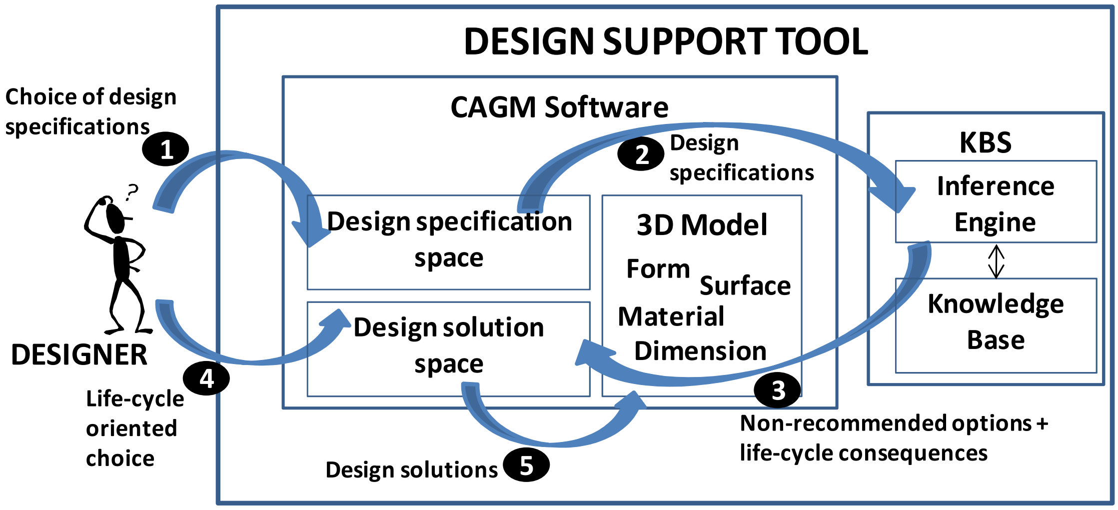

Figure 5. Working mechanism of the design support tool

6. Case-Study

In this section, a case-study which shows how the mentioned concepts have been implemented in a proof-of-concept tool is illustrated. As discussed in the previous section, the tool is implemented using Autodesk Inventor interfaced with the CLIPS Expert System Shell. Furthermore the following assumptions have been made during the tool implementation:

- It is assumed that there exist a number of "general specifications" which, as their name implies, are not specific to one particular domain. Such specifications include, for example, that a product should have a limit to its size and weight, is to be produced in certain quantities and that it can be influenced by certain environmental conditions during use, such as corrosion, high temperatures, etc. By implementing such "general specifications", the tool can be applied to a number of domains.
- It is assumed that the product to be designed has a product breakdown structure (PBS), consisting of subassemblies, components that when assembled together form the subassembly, and component elements that are the elements of the component such as form features and material. Furthermore, it is assumed that the subassemblies that make up the product can have different specifications, e.g. in the case when different subassemblies are subject to different environments. Therefore the tool provides a functionality that allows the designer to input subassembly-specific specifications.
- It is assumed that the design begins with initial specifications that tend to be incomplete. Therefore, the tool does not oblige the designer to input certain specifications from the start of the design but rather allows the designer to input them as the design progresses.

Figure 6 is a screenshot of the tool user-interface, when the Product Life-Cycle Specifications tab (marked by label (1)) is chosen. As can be seen from the figure, the designer only enters those specifications that he/she is ready to commit at this stage. Furthermore, the specifications are divided according to the product life-cycle phase they make part of (2).

When the "Define Subassembly" tab is chosen (see Figure 7 label (3)), the designer can choose to add a subassembly, delete a subassembly or modify the specifications of a particular subassembly. Similarly, when the "Define Component" tab is chosen (4), the designer can choose to add a component to a particular subassembly, delete a component or modify the properties of a particular component (5). As shown in Figure 7, a rod has been chosen as the base feature of the component Outer Pipe, and this was automatically added to the drawing panel of the CAGM Interface (6). Then as illustrated in the figure, when the designer decides to select the material for this component, the list of materials is displayed with the non-recommended materials striked through (7). The reason why a particular material is not recommended is also displayed in the tool tip upon hovering on the non-recommended option (8).

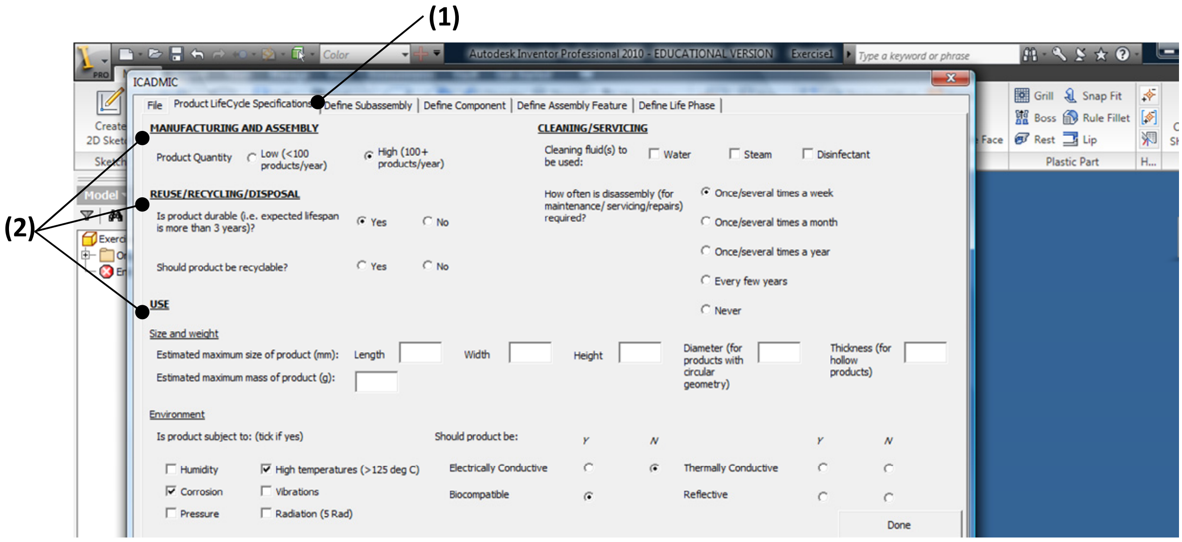

Figure 6. User-interface – Product Life-cycle Specifications tab

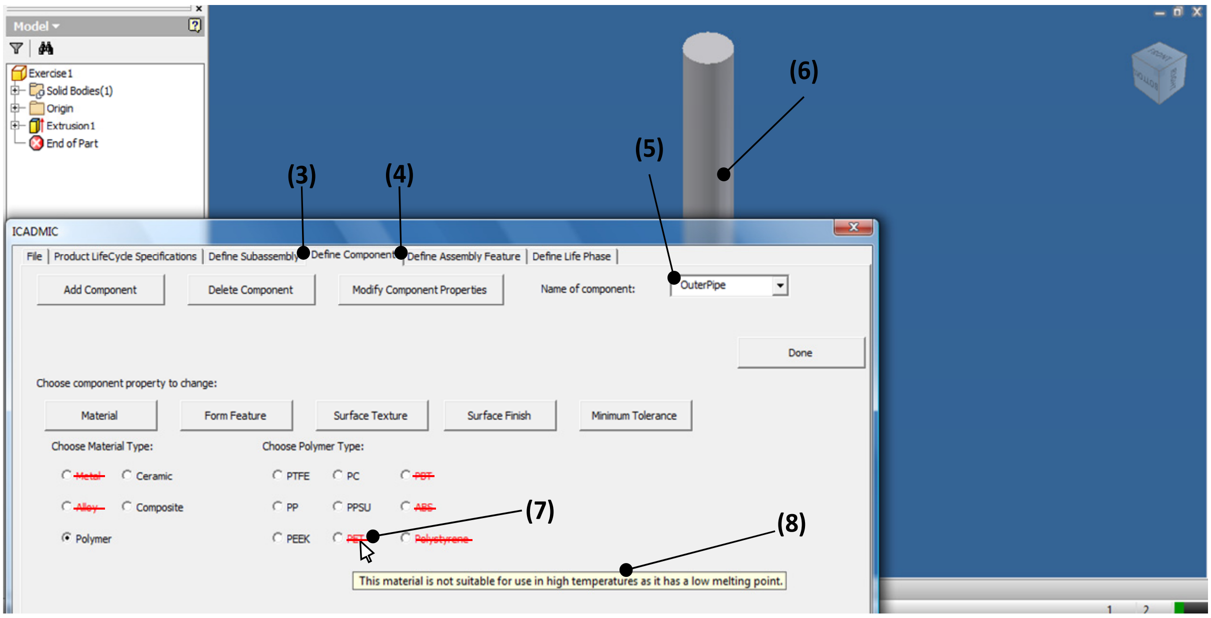

Figure 7. User-interface – Define Component tab

Therefore, as shown in Figure 7, PET in this case is not recommended as it is has a low melting point, and therefore it is not suitable for the high temperature environment that was committed in the product life-cycle specifications tab. Similarly, as shown in Figure 8, when the "Define Life Phase" tab (9) is chosen, and the designer chooses to modify the fabrication process of the component Outer Pipe (10), the processes that are not suitable to manufacture this component are striked through and the reason behind their unsuitability is displayed in the tool tip upon hovering on the non-recommended process (11). Therefore, as shown in Figure 8, MicroLBM is not recommended in this case as the process is more suitable to produce low product quantities, and therefore the high quantity specification which was specified in the product life-cycle specifications tab cannot be met economically using this process.

A situation may arise in which the designer enters specifications that are conflicting and therefore no feasible option which satisfies all the set specifications exists. For example, assuming that the end-effector of a micro-surgical instrument needs to be designed with the following specifications: biocompatible and corrosion resistant (since it needs to be inserted inside the human body during the use phase), thermally and electrically conductive (since it is should allow current to pass through it to electrocauterize tissue) and magnetic (so that it does not present clamping problems during machining).

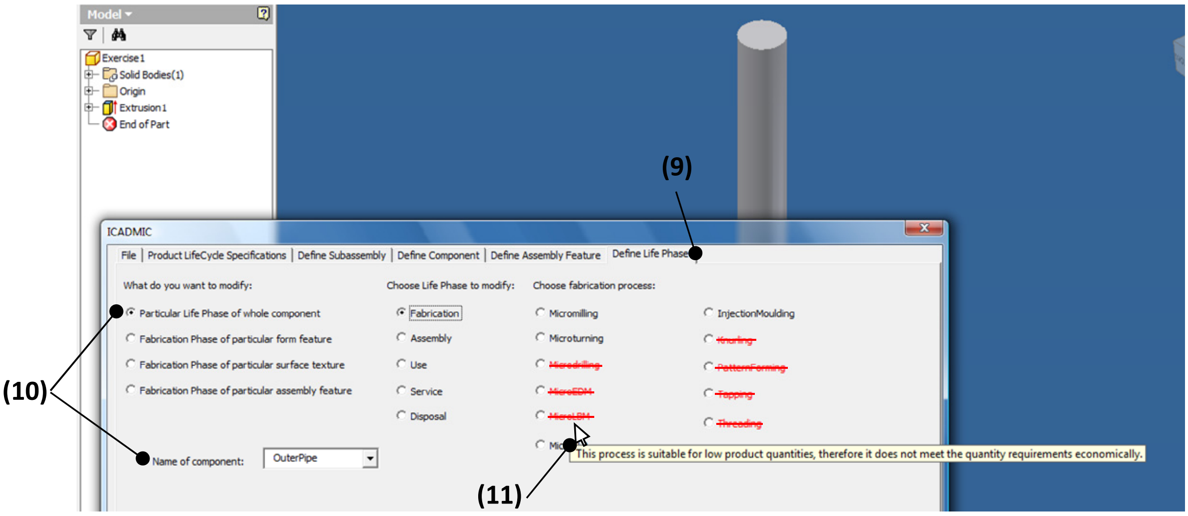

Figure 8. User-interface – Define Life Phase tab

Given these specifications, when the designer is choosing the material for the end-effector (e.g. metal) as shown in Figure 9, a difficulty arises since they all violate some specification in one way or another. However, by hovering on the materials and viewing the reason (or reasons) behind the unsuitability of each material, the designer would be in a better position to decide which specification can be safely retracted with minimal consequences.

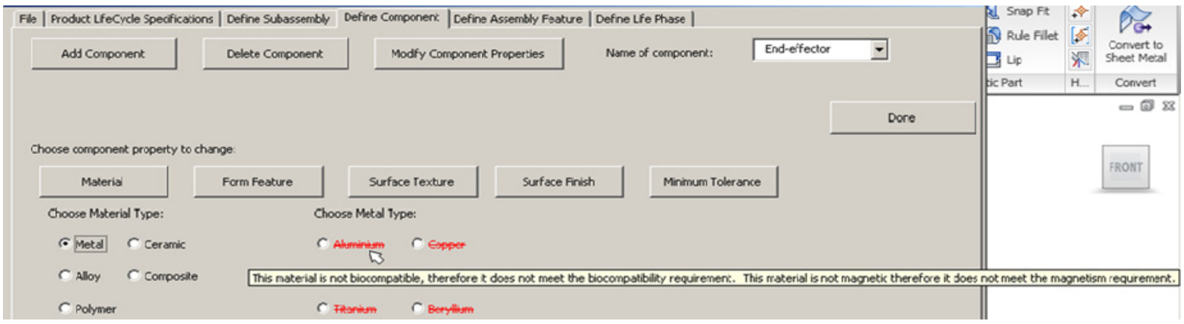

Figure 9. Problem with choosing a material given conflicting specifications

7. Discussion and Conclusions

This paper described ongoing work being done to come up with a new concept for a design decision support tool. The concept is novel because apart from assisting the designer to take into account specifications arising from the whole product life-cycle, it also aims to merge the design specification space with the design solution space in a single tool, thus making it easier for the designer to realize when a design specification is going to be violated. Furthermore, since assistance is provided *before* any synthesis decisions are committed, iterations are decreased and the design time is considerably reduced.

A major strength of the tool is that since it is integrated with a CAGM software, the designer is not forced to leave the "natural" work environment in order to make use of the tool and keep track of the design specifications. Therefore, the designer would be more motivated to employ this new "add-on" in the daily design work.

The tool also has a number of limitations. First and foremost, since evaluation with practicing engineering designers is still underway, the degree of usefulness of the tool is still, to a certain extent, unknown. Furthermore, since the tool has a fixed number of specifications and synthesis elements present, from which the designer may choose, another limitation is that user-defined specifications and synthesis elements cannot be inserted in the tool as yet.
Directions for future work therefore include evaluating the tool with practicing engineering designers to verify the effectiveness of the tool and to check whether the hypotheses stated in Section 3 can be verified or otherwise. Additionally, a module which allows the designer to add user-defined specifications and synthesis elements in the tool can also be added to meet the limitation mentioned above and to make the tool more usable. Furthermore, since generally not all specifications tend to have the same importance in a particular design situation, to minimise problems arising from conflicting specifications, the tool should ideally allow the designer to specify the importance of a particular specification with respect to other specifications. Then, a colour coding scheme can be used to indicate non-recommended synthesis decisions, depending on the importance of the specification that is violated.

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References

Davis, A. and Zowghi, D., "Good Requirements Practices are Neither Necessary Nor Sufficient", Requirements Engineering Journal, Vol. 11, No. 1, 2006, pp 1-3.

Gayretli, A. and Abdalla, H. S, "A Knowledge-Based System for Manufacturing Process Optimisation", Proceedings of the 2nd International Symposium Tools and Methods for Concurrent Engineering, TMCE '98, Horvath, I. and Taleb-Bendiab A. (ed.), Manchester, 1998, pp 419-427.

Grech, A. K. "Customer Requirements and the Filtering Concept", PhD Working Document, CERU/IDELAP/ITR/07/2009, 2009

Mamat, R., Wahab, D. A. and Abdullah, S., "The Integration of CAD and Life Cycle Requirements in Automotive Seat Design", European Journal of Scientific Research, Vol. 31, No. 1, 2009, pp 148-156.

Marx, W. J., Schrage, D. P. and Mavris, D. N., "An Application of Artificial Intelligence for Computer-Aided Design and Manufacturing", Proceedings of the International Conference on Computational Engineering Science, ICES-95, Atluri, S. N., Yagawa, G. And Cruse, T. A. (ed.), Springer, New York, 1995.

Omar, A. R., Harding, J. A. and Popplewell, K., "Design for Customer Satisfaction: An Information Modelling Approach", Integrated Manufacturing Systems Journal, Vol. 10, No. 4, 1999, pp 199-209.

Rehman, F. and Yan, X.-T., "Evaluation of a Context Knowledge Based Tool to Support Decision Making in the Conceptual Design", Proceedings of the International Conference on Engineering Design, ICED '07, J.-C. Bocquet (ed.),2007.

Roozenburg, N. F. M. and Eekels, J., "Product Design: Fundamentals and Methods", Wiley, West Sussex, 1995.

Tjalve, E., "A Short Course in Industrial Design", Butterworths, London, 1979.

Zhang, W. Y., Tor, S .B. and Britton, G. A., "A Knowledge-Based Functional Reasoning Strategy to the Conceptual Design of Mechanical Products", Proceedings of the 13th International Conference on EngineeringDesign (ICED 01): Design Methods for Performance and Sustainability, Culley, S., Duffy, A., McMahon, C. and Wallace, K. (ed.), Professional Engineering Publishing, London, 2001, pp. 291-298.

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