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TOWARDS INTELLIGENT DESIGN TOOLS FOR MICRO-SCALE COMPONENTS

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ABSTRACT
Increasing market pressures to produce smaller, easier-to-use and cheaper products with minimal time-to-market, are putting more pressures on design and manufacturing industries to invest in better technologies in order to help them meet these needs. In micro-manufacturing, which involves the manufacturing of components whose form features, or at least one dimension, is in the order of µm, this is even more so. The reason for this is that during design and manufacture of micro components, one has to take into account not only of the size, but also issues concerning special material properties, micro tooling and equipment and micro handling. These additional requirements drive the need for more intelligent design tools to aid designers in the generation of micro components so that manufacturing and other life-cycle issues can be taken into account. This paper contributes to supporting design in this direction - by presenting a framework for an intelligent design tool that explicitly aims at assisting designers working in the micro-scale domain to take a life-cycle approach in their work.

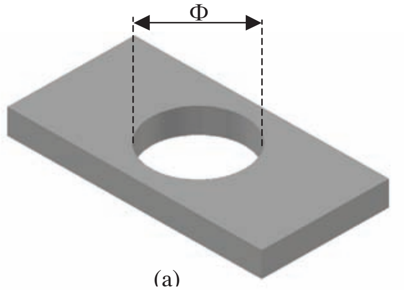
Keywords: DFX, CAD, design knowledge, design reuse, product life-cycle

1 INTRODUCTION
As technology advances, design is becoming increasingly more complex due to the shift to product miniaturization. Typical examples are mobile phones and camcorders which are becoming increasingly smaller and cheaper. Furthermore, designers are under increasing pressures to deliver artifacts that cater for a host of life cycle issues because failures that manifest themselves late in the product life cycle are very costly to repair [1]. All these coupled with the fact that designers, like all human beings, are not good at dealing with complexity [2] drive the need to aid designers, in particular, designers working in the micro-scale domain.

Since traditional CAD systems have little or no intelligence, researchers have long felt the need to make them more intelligent. Intelligence is a mental capability that involves, amongst others, the ability to learn quickly, reason, plan, understand complex ideas and solve problems [3]. Ideally, these intelligent systems assist designers in satisfying not only the functional requirements of the product, but also in considering the product life cycle phases e.g. the manufacturing, assembly and servicing phases. Hence, as from the early design stages, the designer would be provided with the Life Cycle Consequences (LCCs) [1] resulting from his/her decisions and therefore would be able to make the necessary changes early in the design. This way, products are designed "right the first time" and expensive redesigns are minimized. Examples of frequently encountered LCCs resulting specifically from micro-scale design decisions are illustrated in Figures 1 and 2.

Figure 1 illustrates that when designing a hole, care should be taken when deciding on its diameter as tools for machining very small diameters (< 0.01mm) are not commercially available as yet. Figure 2 illustrates another example when manufacturing problems can arise due to micro component design decisions, this time due to machining of form features with large protrusion heights. This is because micro tooling, which have small diameters, also have short cut lengths, usually smaller than 2mm. For this reason, unless care is taken to keep protrusion heights less than 2mm, the tool shank will come in contact with the workpiece during cutting and thus tool chatter and even tool breakage can occur.

To be more aware of such LCCs, designers, in particular those working in the micro-scale domain need pro-active design support. 'Pro-active' in this context means that the support provided should not be simply in the form of a repository of information, but in a form that actually aids the designer by presenting only the relevant LCCs when required. This paper therefore presents a framework for an intelligent design tool that assists designers of micro components by pro-actively presenting life cycle issues related to their designs.



(a)

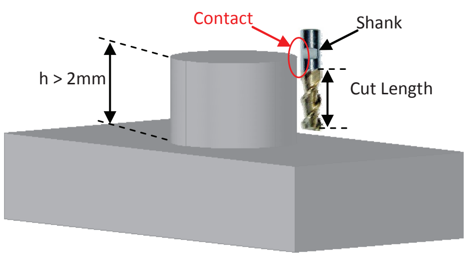
If Φ < 0.01mm AND
hole is to be milled

THEN

Problems during manufacturing: A hole with Φ less than 0.01mm cannot be milled as cutters with smaller diameters are not commercially available as yet

(b)

Figure 1. a) Hole form feature b) Example LCC resulting from choice of small hole diameter Φ – amended from [4]



(a)

If h > 2mm AND
protrusion is to be milled

THEN

Problems during manufacturing: While the tool is cutting, the shank material will be in contact with the workpiece. This contact causes friction and high temperatures will be induced, affecting the tool e.g. tool toughness is reduced or tool breakage occurs

(b)

Figure 2. a) Tool collision b) Example LCC resulting from choice of large protrusion height h – adopted from [4]

The rest of the paper is structured as follows. In Section 2, existing intelligent design tools are reviewed and from the review, a research gap is identified. In Section 3, the research approach to be adopted is defined and in Section 4, the framework of a relevant intelligent CAD tool is proposed as a first step to help designers overcome the problem identified. Conclusions and future work are then presented in Section 5.

2 REVIEW OF INTELLIGENT DESIGN TOOLS

A review of several intelligent CAD tools, which have been developed in the past 15 years, has been carried out. The tools that are considered to exhibit intelligent behavior are those that make use of some artificial intelligence (AI) technique (refer to section 2.1). The design stages (e.g. conceptual stage) and design activities (e.g. analysis activity) supported by the tools, the type of design support (e.g. Design for Manufacturing, Design for Assembly, etc.) and the domain supported (e.g. sheet metal parts) are all taken into account during the review. Based on these findings, a research gap is later identified.

2.1 AI Techniques

Artificial intelligence techniques which are frequently used in intelligent design tools include Expert Systems (ES), Knowledge-Based Systems (KBS), Case-Based Reasoning (CBR) Systems, Intelligent Agents (IA) and Genetic Algorithms (GA). A brief description of each of these techniques is provided.

- *ES* are computer programs that imitate the human thinking process in a *specific* problem solving situation in order to arrive at the same conclusions or decisions that a human expert would. This is performed by two main distinct ES modules – the knowledge base (where the expert knowledge is stored) and the inference engine (which performs reasoning using knowledge in the knowledge base).
- *KBS* attempt to understand and imitate human knowledge processing in computer systems by querying a knowledge base. Although the term KBS is occasionally used as a synonym for ES, this should not be the case as strictly speaking KBS are more general. Hence, although they can be used as components of ES, KBS use is not limited to this. For example, they can be used in *general* purpose sophisticated database systems.
- *CBR* systems use specific knowledge of previous experiences, in order to find a solution to a similar problem. Cases from past experiences are collected and 'indexed' by key elements. Hence, when a new problem is encountered, the index is used to find similar past cases. Then the CBR system adapts the cases, if necessary, and reuses them in the new problem situation. The new case is then saved and added to the knowledge base for future use
- *IA* are computer programs that help users with routine computer tasks and may be knowledge-based systems (in their most ordinary form), database systems, simulation systems or specific purpose computational tools [5],[6].
- *GA* are techniques which are mostly used for searching for good solutions in a large space of different possibilities. In design, GA can be used, for example, to find the design solution that best satisfies the constraints.

2.2 Summary of Intelligent design tools

The tools reviewed here are design *aids* rather than *autonomous* design tools. The difference between the two is that while design aids interact with a designer or designers to support their design activities, autonomous design tools produce designs automatically after given the requirements. Although at first glance autonomous design tools may seem more supportive during design, this is generally not the case. While computers are a critical 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 [7]. Also, design aids are becoming more popular since designers do not like 'automated assistants' approving every decision taken, but rather prefer assistants that suggest solutions that satisfy the requirements and assess designs [8]. The tools, which are summarized in Table 1, are just a representative sample of all the tools reviewed.

2.3 Research Gap

From Table 1 it can be seen that many of the tools reviewed aim to provide support during conceptual design. This, however, does not mean that there is no need for more support in this design stage. Many product design experts consider conceptual design as the most critical stage in the design process as many decisions that can result in consequences influencing the other product life phases are taken at this stage. In fact it is often stated that roughly 80 percent of the total life cycle cost of a product is determined during conceptual design [10]. In addition, traditional CAD tools are not well developed for this upstream stage of design since they do not have the built-in intelligence to perform reasoning and they therefore lack the knowledge to make decisions. For these reasons, it is concluded that there is still a need of intelligent design tools for these early design stages. However, during the development of such design tools, one should be careful not to replace the creative element in these stages by these computerized methods.

Another observation is that most of the tools reviewed support the evaluation activity, that is, support is provided *after* the provisional design is completed. This is generally not desirable as a lot of time would be lost in redesigning [1]. Rather, designers should ideally be supported during the generation of solutions, that is, during the synthesis activity. As well stated by Roozenburg and Eekels [22], synthesis is the crucial activity of the design cycle.

Table 1. Summary of reviewed intelligent design tools

Authors, Name and Year	**Domain (size)**	**AI Techniques used**	**Design Stage**	**Design Activity**	**Type of design support**
Sam Lazaro et al. (SMAART),1993 [11]	Sheet metal parts (macro)	KBS	Embodiment	Evaluation	DFM
Marx et al. (CADDB), 1995 [12]	Aircraft wings (macro)	KBS	Conceptual, Embodiment	Evaluation	DFM, DFC
Wood and Agogino (CDIS), 1996 [13]	Mechatronic products (macro)	CBR	Conceptual	Analysis	DFA, DFS, DFE
Tang (IFM), 1997 [14]	Mechanical engineering design (macro)	KBS, GA	Conceptual, Embodiment	Analysis, Synthesis, Simulation	Concurrent and Web-based design
Dalgleish et al., 1998 [15]	Product Families (macro)	ES	Conceptual, Embodiment	Evaluation	DFM, DFA
Borg (FORESEE), 1999 [1]	Thermoplastic components (macro)	KBS	Embodiment	Synthesis, Evaluation	DF∑X
Changchien and Lin, 2000 [16]	Products with machined features (macro)	KBS, GA	Embodiment	Evaluation	DFA, DFM, DFP, concurrent design
Zhang et al. (EFDEX), 2001 [17]	Terminal Insertion Units (macro)	KBS	Conceptual	Synthesis, Evaluation	DFF
Dai et al. (DAS), 2005 [9]	Micro products (micro)	KBS	Embodiment	Evaluation	DFM, DFQ, DFC
Lockett and Guenov, 2007 [18]	Moulded parts (macro)	ES	Embodiment	Evaluation	DFM
Klette and Vajna (ICE), 2007 [19]	Semi-large power generators/ electric motors (macro)	KBS, IA	Embodiment	Evaluation	DFM, DFC
Rehman and Yan (PROCONDES), 2007 [20]	Sheet metal components (macro)	KBS	Conceptual	Synthesis, Evaluation	DF∑X
Mok et al, 2008 [21]	Mould Design (macro)	KBS	Conceptual, Embodiment	Analysis	DFF, DFT, Collaborative Design

Legend:

DFM – Design for Manufacturing	DF∑X – Design for Multi-X
DFC- Design for Cost	DFF - Design for Functionality
DFA – Design for Assembly	DFQ – Design for Quality
DFS – Design for Serviceability	DFP – Design for Productivity
DFE – Design for Environment	DFT – Design for Standardization

From the table it is also obvious that few tools provide Design for Multi-X (DF∑X) support. This means that although the tools may support several 'Xs' (e.g. manufacturing, cost, quality, etc.), these are not treated in a multiple and integrated way. Hence a DF∑X approach is required to ensure that improvement in one 'X' does not result in detriment to the other 'Xs'.

The last and most important observation from the review carried out is that intelligent design tools were developed for a number of domains which are part of the macro-scale, however, tools to aid the design of micro-scale products (that is, for products that have form features in the order of μm), are still lacking. Also, given that when dealing with micro products several issues need to be considered that are not so necessary when designing macro-products [9], there is certainly a need for more intelligent design tools in this specific domain. These tools can then be used to provide design support in various fields, such as in electronic product and biomedical device design. Hence, the research gap identified from the literature review is illustrated in Figure 3.

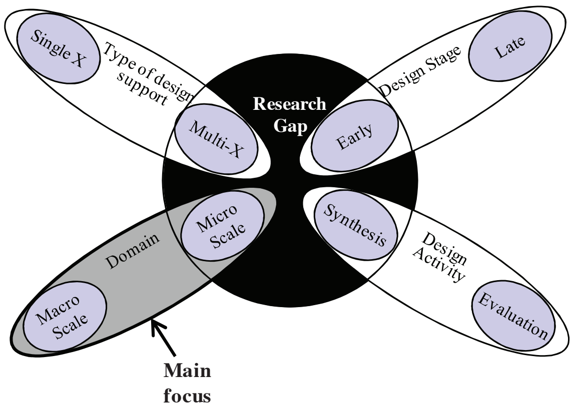


Figure 3. Research gap identified from literature review (amended from [1])

3 RESEARCH APPROACH

Having identified the research gap, the next step is to decide on the research approach to be adopted in order to come up with an appropriate intelligent design tool as efficiently as possible. The approach decided upon is based on Borg's adaptation [1] of the Design Modelling Research Approach proposed by Duffy and Andreasen [23]. The reason for adopting this approach is because it is specifically aimed to serve as guidance for the development of design tools. The approach consists of three models – the Phenomena Model, the Knowledge Model and the Computer Model (Figure 4). The Phenomena Model is derived from the reality, which in our case is the lack of support for micro-design. This model states *what* objects handled by designers should be modeled and related. In this research, the phenomena, adopted from Borg [1], is that design decisions give rise to life cycle consequences, irrespective of whether the designer is aware or not. From the Phenomena Model, the Knowledge Model is derived, which is concerned with *how* the knowledge about the objects identified earlier should be organized. The system framework is part of this model. From the Knowledge Model, the Computer Model or the tool is then derived. This model includes the system architecture. The move from framework to architecture involves mainly the mapping of the functions of the tool to its components and requires a set of system specifications in order to be set up. Finally, using the defined system architecture together with programming language(s), the tool for micro-design support can be implemented. The double sided arrows at the bottom of Figure 4 indicate that at each stage any model can be evaluated against any previous model and also against the reality to ensure that what is being done at each stage is contributing towards this reality.

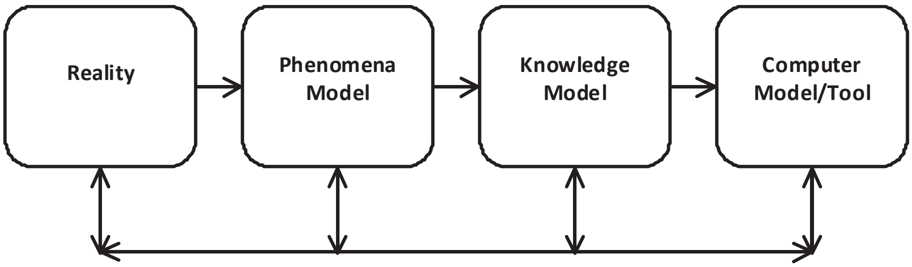


Figure 4. Research approach - adopted from [1]

4 TOWARDS INTELLIGENT CAD TOOL SUPPORT

Having identified the Reality (the gap), this paper also aims to contribute towards the Knowledge model by defining the intelligent CAD system framework. A set of system specifications is then defined, on which the system architecture can later be built. In order to come up with the system framework and specifications, the following research questions need to be answered:

- What knowledge do designers working in the micro-scale domain need?
- How can the micro domain knowledge be captured, structured and represented?
- How can it be modelled and maintained?
- What system specifications are required so that the tool can provide intelligent support during the design of micro components?

These questions are addressed separately in the following sections.

4.1 Knowledge required

When designing micro products it is not merely a matter of downscaling macro products to the required size, but a different approach and additional knowledge are generally required. Nilsson [24] argues that in macro product design it does not matter whether the material or process is considered first during the design, after deciding on the product form. However, Alting et al. [25] state that in micro product design, the material should be chosen first followed by the micro-manufacturing process. Additional concerns when designing on the micro-scale level include handling and manufacturing of small features as well as fixturing of small components and clamping of small cutters. Also, monolithic design, which involves designing in single components, is preferred in micro product designs. These concerns could be greatly reduced if the intelligent CAD tool to be developed provides this and other relevant knowledge pro-actively to designers when required.

The knowledge related to micro-scale designs, which should be present in the tool, is divided into three main categories – knowledge related to form, knowledge related to material and knowledge related to the manufacturing process. These knowledge categories are briefly described below.

- Micro Form features: Form features are either 2D, 2.5D or 3D. 2D features are those that when machined require tool movement in two dimensions (x and y) only e.g. a flat outline. When tool movement in the third dimension (z) is also required, the feature would be considered as 2.5D e.g. a circular pocket. 2.5D features, unlike 3D features, have a constant cross section throughout. Examples of 3D features include protrusions and depressions with varying cross sections. Irrespective of the type of form feature used, when designing on the micro-scale, designers should first consider the capability of the manufacturing process to be used. For example, in the case of micro-machining, one has to check the availability and capability of the tooling as these constrain the design. Similarly, in the case of micro-forming, form features affect the flow of the material and also the stiffness of the final components.
- Material: When designing micro components, study of certain material properties is required as these can be influenced by size effects during manufacturing. For example, thermal, electrical and magnetic properties as well as grain size of the material can be affected during micro-forming [9], leading to undesirable properties in the final component.
- Manufacturing process: Various innovative micro-manufacturing processes are being developed. For example, Rajurkar et al. [26] describe electro-physical and chemical micro-machining processes as having important roles in this field due to their special material removal

mechanisms. When designing micro components, the manufacturing process plays a very important role - form feature dimensions are generally constrained by the capabilities of the manufacturing process and the selection of the material is also constrained in certain circumstances. For example, if micro-forming is used, considerable local temperature increases may result in changes in the material properties, which may not be desirable e.g. in the case of micro sensors [9]. Hence, in these cases, the manufacturing process should be chosen prior to the material.

4.2 Knowledge capturing, structuring and representation

Micro-design knowledge can be captured from three main sources – from available documents and handbooks, from various stakeholders e.g. micro-manufacturing firms and workshops, and also by executing experiments in order to relate design decisions made concerning various micro component design parameters (e.g. material, form feature dimensions) and the resulting constraints and parameters on the micro-manufacturing process.

After the knowledge is captured, it should be appropriately structured. Good knowledge structuring in the design tool enables the designer to access the right knowledge at the right time. Knowledge structuring involves organizing the knowledge in a classification and generating a taxonomy. Albers et al. [27] propose a classification that is micro production-technology based. This, however, limits the effective support it can provide to designers whilst generating solutions, since designers typically generate micro-scale design solutions in terms of form features rather than manufacturing processes [28]. For this reason, a form-feature based classification would be more feasible. Taxonomies represent a basis on how the knowledge will be classified so that the designer can retrieve the right knowledge when required. Examples of available taxonomies include Pratt and Wilson's [30] Form Feature Taxonomies (for 2.5D form features) and Cheutet's [31] (for 3D form features). The choice of taxonomy depends on the situation at hand and in our case it still has to be decided.

Guidelines, which are defined as 'statements or other indications of policy or procedure by which one can determine course of action' [29] are an ideal way of pro-actively presenting designers with the relevant knowledge when required. In order to be understandable, guidelines should have the appropriate format and they should also be structured in order to be easy to retrieve. Nowack [32] proposes an 'action-centred' design model which can be used for the guideline format, and which states that a *consequence* is produced by an *action* chosen by a designer trying to resolve an *issue*. This leads to rules, with the format shown in Figure 5, to be a potentially good form of representing knowledge in our tool.

As seen from Figure 5, each rule would consist of an 'if part', which includes design variables and parameters that produce consequences, described in the 'then part', on the design. During design synthesis, decisions are intentionally made to achieve certain desired consequences. However, designers, like other decision makers, do not always know all the consequences of their alternatives. This means that decisions can also result in unintended consequences that affect various other product life phases. Therefore, the consequences in the 'then part' can be negative (problems) or positive (opportunities) and can be encountered in any of the product life-cycle phases e.g. design, manufacturing, use, disposal and recycling phases, hence the term life-cycle consequences (LCCs).

Rule X: Title

IF: <design variable/parameter>

AND < design variable/parameter >

THEN: <Consequence>

THEREFORE: <advice>

(a)

Rule 2.3: Reduce protruding features to be machined

IF: <Form Feature is a kind of Protrusion>

AND <Form Feature Depth > 10 mm>

AND <Manufacturing Process is a kind of Machining>

THEN: <Manufacturing time will increase as a lot of material has to be removed>

THEREFORE: <Redesign the part to include a Protrusion with Depth < 10mm>

OR <Choose a Manufacturing Process which is not a kind of Machining

(b)

Figure 5. a) Knowledge representation using rules - adopted from [28] b) Rule example

Recommendations would also be presented to guide the designer in reducing or enhancing the consequences encountered and which propagate an influence on time, cost and quality measures of the components.

4.3 Intelligent CAD Tool Approach Framework

From the research gap, the main aim of the intelligent CAD tool framework being proposed can be stated as 'to provide *early* design support to designers of *micro-scale* components by presenting them, during design *synthesis*, with the whole LCCs of their decisions in a *multiple and integrated* way'.

The framework of the tool, nicknamed *ICADMIC* (Intelligent CAD tool for Micro-Scale Components), is shown in Figure 6, which illustrates how the knowledge can be modelled and maintained by the tool. The framework collectively supports the following:

- Selection of feasible element(s) for a specific problem (e.g. in the case of micro form features, a circular hole, a circular protrusion etc.).
- Awareness of life-cycle consequences resulting from decisions made during early micro product design and guidance as to how these consequences can be enhanced (positive consequences) or avoided (negative consequences).
- Maintenance of knowledge present, when required by the designer.

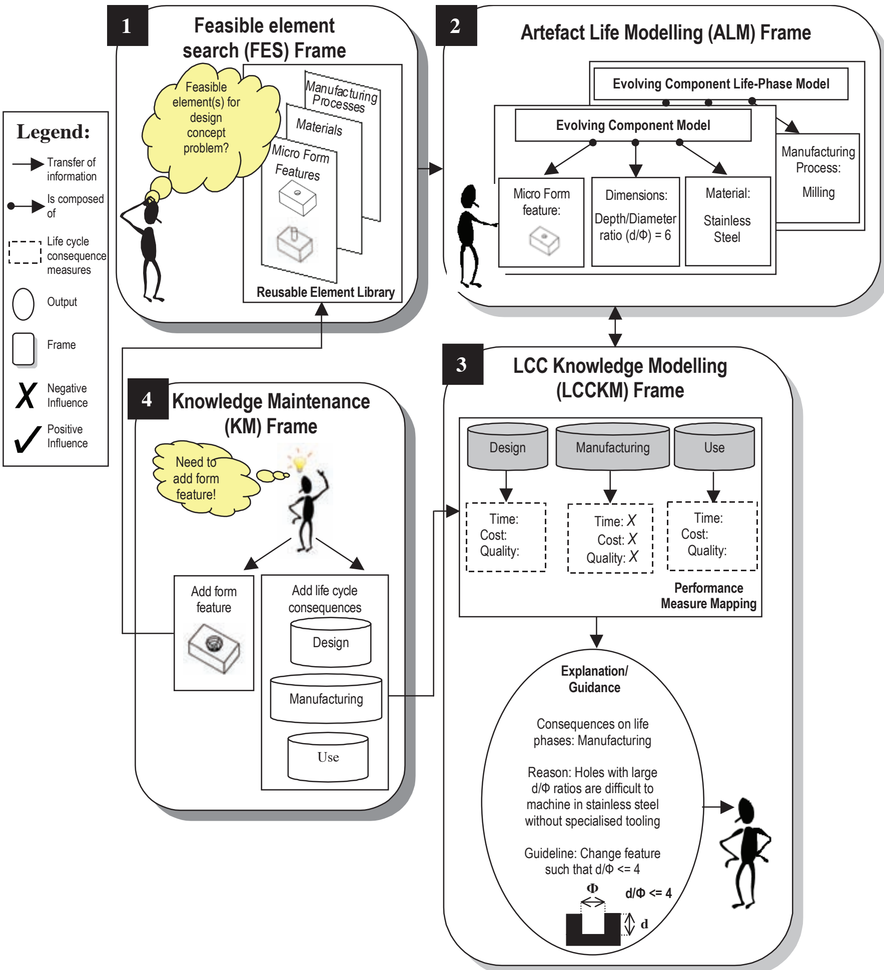


Figure 6. Framework for *ICADMIC*

The framework presented is based on the following four frames:

Feasible Element Search (FES) Frame: In this frame, the designer, given a specific problem, refers to the Reusable Element Library, which consists of micro form features (e.g. circular hole, circular protrusion, etc.), materials (e.g. stainless steel, aluminium), manufacturing processes (e.g. milling, forming), etc. and chooses the preferred element(s) for the problem.

Artefact Life Modelling (ALM) Frame: Here, the library elements selected by the designer are built into an Evolving Component Model and their corresponding life-phase elements are built into an Evolving Component Life-Phase Model. These models are processed by the subsequent frame as they are being built, that is, *while* the designer is making synthesis decisions, *not afterwards*.

LCC Knowledge Modelling (LCCKM) Frame: Any life cycle consequences resulting from designer decisions are inferred in this frame. These consequences may also be interacting Life Cycle Consequences (for example, both stainless steel and large d/Φ ratio are prerequisites for negative consequences during manufacturing). First, these consequences are quantified using performance measures, such as time, cost and quality and then the results are outputted to the designer as guidelines (with the format shown in Figure 5). Then it is up to the designer to decide on how to best minimize or enhance these consequences.

Knowledge Maintenance (KM) Frame: Knowledge maintenance is essential if the tool is not to become obsolete. This maintenance is done in the KM Frame, which requires the designer to enter any elements required together with their life cycle consequences. The new elements are then inserted into the Reusable Element Library and their corresponding life cycle consequences are inserted into the LCCKM Frame for future use.

From the tool framework, one can identify the most suitable AI technique(s) to use. For example, the properties of ES, mainly their ability to provide expert knowledge in a *specific* problem solving situation and their easily maintainable structure (as a result of separate modules for knowledge and reasoning) make them well suited for the problem at hand.

4.4 System specifications

In order to provide intelligent support during the design of micro components, the tool has to meet certain specifications. For example, if the tool is complex to use or provides incorrect guidance, designers would consider it a burden rather than a design aid. Since this is obviously not desirable, a number of specifications have been set down prior to starting the tool implementation. These specifications are divided into five sections: 1) General design tool requirements 2) Requirements for early design support 3) Requirements for synthesis activity support 4) Requirements for DF∑X support 5) Requirements for micro domain design support.

General design tool requirements:

- Reliable: The tool must be accurate during its search for possible life cycle consequences, otherwise it would not be reliable.
- Simple to use: It must facilitate the acquisition of information from the designer and also the presentation of inferred information to the designer.
- Transparent: The designer can request to see further explanations and design rationale associated with the guidance given.
- Suggests strategies for solutions: The tool should not only locate consequences but also suggest strategies for solutions.
- Supports different users: The tool should support all of its users, from first time users through expert users and from users involved in design to users involved in manufacturing.
- Supports multiple context problem solving: It should support multiple context problem solving so that a design problem can be explored from different perspectives by a team of designers e.g. using different design requirements, evaluation criteria, etc.
- Supports truth maintenance: The tool should be capable of maintaining and updating dependencies when the designer commits or retracts decision commitments i.e. it should support truth maintenance.
- Supports concurrent engineering: Ideally, the tool should support concurrent engineering and encourage collaboration.
- Facilitates integration: The tool must ideally facilitate integration with other tools and systems

e.g. CAD systems.
- Evolving content: The tool should allow the knowledge inside it to evolve in terms of volume and accuracy, otherwise it becomes redundant.
- Ensures satisfaction: To ensure satisfaction of all its stakeholders, the tool should encourage use by the designer while requiring minimal intervention from the field expert and the knowledge engineer involved in its development.

Requirements for early design support:
- Supports with incomplete and inconsistent requirements: In order to provide support during the early design stages, the tool should help designers derive solutions quickly from initial, not necessarily complete and consistent design requirements.
- Provides real-time support: The tool should provide support to the designer while design decisions are being made, not afterwards, so that the required design changes are made as early as possible.

Requirements for synthesis activity support:
- Supports creativity: Creativity plays a major role during design synthesis. For this reason, the tool should not replace the creativity of the designer but should support him/her with useable knowledge.

Requirements for DF∑X support:
- Includes life-cycle knowledge: The tool should include life-cycle knowledge as content to generate more added-value in design. 'Value' can be in terms of several 'Xs' such as manufacturability, assemblability, reusability etc. The goal is therefore to maximize these values in design while minimizing its costs and environmental impacts.
- Supports trade-off analysis: The tool should handle trade-offs which arise from design decisions. For example, by choosing a harder material for a certain component, the quality of the component in the use phase is likely to improve, however, the cost in the manufacturing phase is also likely to increase. By presenting the designer with such trade-offs of his/her decisions, DF∑X support is provided and the designer can choose the option which best suits his/her own preferences e.g. to go for better quality with a detriment to cost or vice versa.

Requirements for micro domain design support:
- Uses different knowledge categories: As can be seen from Section 4.2, the tool is required to represent knowledge from different sources in order to be able to provide appropriate support to designers working in the micro-scale domain. Therefore, the tool should support different categories of knowledge e.g. theoretical and empirical knowledge, problem domain and design task oriented knowledge, public and private (company specific) knowledge and historical knowledge.
- Correct level of abstraction: The tool must be able to reason about the artefact being designed at a level of abstraction that is close to that of the designer. For example, in the case of micro-scale components, a rectangular hole should be considered as such and not as a group of interconnected lines.

5 Conclusions and future work

By reviewing a number of intelligent design tools which have been developed in the past few years, a research gap was found. It was concluded that there is indeed a need for additional intelligent tools to support the early design of micro-scale components given the lack of tools available in this domain and also the additional knowledge required compared to designing on the macro-scale. From the research carried out, it was also clear that few tools are currently available to support the synthesis activity, despite its crucial role in the design cycle. Also, although many tools support several 'Xs', they do not treat them in an integrated way and therefore improvement in one 'X' may easily result in a detriment to the other 'Xs'.

This paper has therefore contributed an intelligent CAD tool framework as a first step to provide early design support to designers of micro-scale components by presenting them, during design synthesis, with the whole life-cycle consequences (LCCs) of their decisions in a multiple and integrated way. Although this framework is targeted to aid designers working in the micro-scale domain, it is envisaged that it can easily be adapted to aid designers in other fields. However, implementation and experimentation still has to take place to confirm this or otherwise. A list of specifications for the CAD tool, which is to be kept in mind during tool implementation has also been contributed. This list is the ideal specification, that is, the tool should preferably meet all the requirements set, however the extent to which these requirements are met depends largely on research constraints.

Future work involves coming up with the tool architecture and deciding on the programming language(s) to be used. Then the tool will be implemented based on the architecture developed and finally evaluated with practicing engineering designers.

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