ECAD functionality suitable for web-based optimised automated product variant generation

Dirk Schaefer*

Systems Realization Laboratory,
The George W. Woodruff School of Mechanical Engineering,
Georgia Institute of Technology,
Savannah, GA 31407, USA
Fax: +1-912-966-7928
E-mail: dirk.schaefer@me.gatech.edu
*Corresponding author

Paul Baguley

Decision Engineering Centre,
Cranfield University,
Cranfield, Bedfordshire MK43 0AL, UK
Fax: +44-0-1234-754-605
E-mail: p.baguley@cranfield.ac.uk

Abstract: Product variant generation is fundamentally different in Electrical Computer-Aided Design (ECAD) rather than Mechanical Computer-Aided Design (MCAD). The difference lies in the logical relationships between ECAD components. It is not straightforward to select a previous product design to aid product variant generation. Therefore, a new methodology suitable for web-based delivery to support ECAD product variant design is described. Part of the methodology proposed is based on fuzzy logic to select previous ECAD designs from a database of case bases. An additional cost engineering module is proposed to provide the functionality of cost optimisation of the subset of the designs fulfilling a predefined criteria list. The other parts of the methodology have been fully implemented to allow automatic generation of designs in software.

Keywords: computer-aided design and engineering; variant design; design automation; product configuration; fuzzy logic; cost optimisation.

Reference to this paper should be made as follows: Schaefer, D. and Baguley, P. (2007) 'ECAD functionality suitable for web-based optimised automated product variant generation', *Int. J. Internet Manufacturing and Services*, Vol. 1, No. 1, pp.4–18.

Biographical notes: Dirk Schaefer is an Assistant Professor in The G.W. Woodruff School of Mechanical Engineering at Georgia Tech Savannah, USA. His research interests are focused on the high-impact interdisciplinary area of information engineering for complex engineered systems. He has published about 50 papers on Computer-Aided Engineering and Design in conference proceedings, journals and books. He is a Member of ASME, a registered professional European Engineer (Eur Ing), a Chartered Engineer (CEng), a Chartered IT-Professional (CITP) and a Fellow of The Higher Education Academy (FHEA) in the UK.

Paul Baguley is a Research Fellow in Cost Engineering at Cranfield University in the UK. His research interests are in cost engineering and soft computing. Prior to Cranfield University, he was a Research Engineer in Cost Engineering and Digital Enterprise Technology at Durham University in the UK from 2003 to 2006. He was a Research Assistant at De Montfort University in the UK and gained his PhD in Fuzzy Logic and Cost Model Development. He is an author of 30 publications mainly in the field of cost engineering. He also helps in teaching Computer-Aided Design and Computer-Aided Engineering forming a continuing interest in digital tools for engineering.

1 Introduction

One of the most substantial disadvantages of contemporary CAD systems in the field of electrical/electromechanical engineering (Electrical Computer-Aided Design (ECAD)) is that existing designs cannot be reused in an efficient manner. Furthermore, the reuse process is usually carried out in a manual manner (i.e. copy and paste) and as such error-prone. In view of continuously increasing pressure of competition, companies have to make their design processes more and more efficient to sustain competitiveness. Products and associated variants have to be designed in shorter times, with reduced costs and at the same time an improvement in the quality. Consequently, an important requirement to be taken into account with regard to the development of future ECAD/ECAE systems is to allow for the reusability of existing designs or projects in an efficient manner. To reach this aim, future systems have to incorporate intelligent approaches for realising design modifications as well as sophisticated techniques for automatically generating variants of existing products. Thus, the introduction of novel variant design technology approaches into the field of electrical engineering may release an enormous potential for synergy effects. In the field of Mechanical Computer-Aided Design (MCAD), one of the most important innovations within the last ten years has been the introduction of parametric modelling (Roller, 1995). Today, this particular approach to variant design is well understood and has been successfully employed in the majority of contemporary high end MCAD systems. Unfortunately, parametric modelling developed for mechanical engineering CAD systems cannot be applied to electrical engineering due to their very different technical nature (Mink and Roller, 1997). In MCAD environments parameters are usually related to geometry, whereas in ECAD the type of information to be modelled and parameterised is of a logical nature. Consequently, different avenues to variant design in the electrical engineering context have to be explored.

One of the most important approaches to enable cost and time reduction with respect to computer-aided design for ECAD is to develop, generate and manage various design variants of a product in an efficient manner (Roller and Schaefer, 2000; Schaefer, 2004). One objective of this paper is to present an overview of a new generic approach to product variant design technology that has a high potential for an efficient reusability of existing designs. More precisely, this paper presents the procedure to allow this new approach to be implemented within arbitrary ECAD systems. The approach presented automatically generates a complete technical documentation of an electrical installation on the basis of a placed order specification. The technology behind this involves three major steps.

- Firstly, a product variant of an installation is configured on the basis of existing standardised design components.
- Secondly, a set of commands is automatically compiled that describe the generation of a typical ECAD project containing the configured components. This is a key novelty, as all these commands are expressed in a non-system specific programming language, which can be automatically translated into a so-called macro programming language of a specific ECAD system.
- Finally, the targeted ECAD system can import and process these commands to create a corresponding project file in its native data format for further processing.

With regard to step one, a second major objective of this paper is to address the issue of identifying cost optimal standardised components for the composition of product variants. The issue is resolved through a proposed methodology placed within the novel implementation described in this paper. The proposed methodology is such that a set of expert rules is generated, which allows for the identification of a set of suitable ECAD components, based on input parameters driving the logical selection of components. The essence of a technique called fuzzy logic is to measure the degree of belonging of a component to a set of driving logical requirements. For example, an existing design can provide power for a 100 storey lift to degree 0.8. Hence the analogy to geometric parametric modelling is through that of a degree of fit of a component to a logical driving requirement. Subsequent optimisation processes are varied. For example, optimisation can occur through fuzzy logic aggregation of decision parameters, cost being potentially one of them, the driving logical requirements being others. Geometric parametric models are more straightforward to define based on dimensions and features. Hence, ECAD parameterisation occurs through more abstract quantities. Such abstract quantities are vague, ambiguous and imprecise and lend themselves well to the fuzzy method. In the first instance the expert driven selection of driving logical parameters is essential.

2 ECAD product variant design

To remain competitive in the market, most companies offer their products in a range of different variants. However, new variants of existing products are often composed of existing basic components (product variant configuration) rather than newly designed. A precondition to allow this is to have modularised product structures. A sector of industry, in which this has recently become a common practice, to plant engineering and construction. In this sector, the majority of companies developing electrical or electromechanical installations tend to reuse their existing designs, plans and project documentations to develop additional customer specific variants. A typical example of such a design variant would be a product family of similar elevators and their corresponding control cabinets (see Figure 1).

Unfortunately, this process of reusing existing design for the generation of further variants is still predominantly performed in a manual manner. Obviously, this is both far from being efficient and effective, and is error-prone. Consequently, owing to the permanently increasing pressure of competition in the market it is vital to develop automatisms that facilitate the computer-aided generation of product variants (Roller et al., 1996). As alluded to earlier, the first aim of this paper is to give an overview of a generic approach to variant design technology that may be deployed in future ECAD systems. The fundamental idea behind the approach is simply to automate the natural workflow process of creating ECAD design variants as it is manually performed by most companies today. As such, the approach presented is closely related to industrial best practice and derived from day-to-day operations. Of course, as described earlier, some of the existing novel methodology has been supplemented with a possible proposed addition to it.

Figure 1 A typical example of an electromechanical product variant (elevators, control cabinet)

3 The basic concept as applied in practice

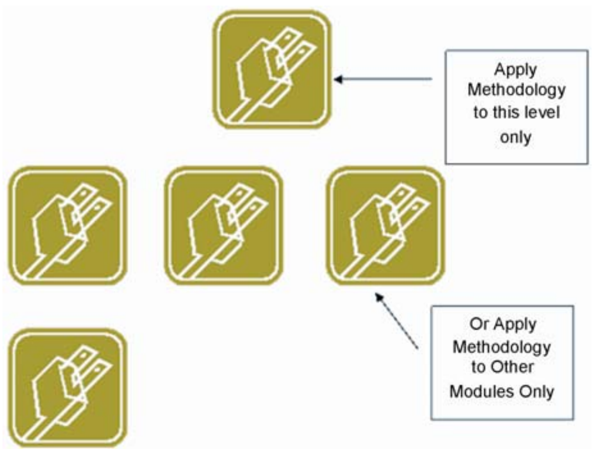
Many companies approach their potential customers by technical field sales and distribution staff. These sales persons usually have selling catalogues at their disposal, which allow customers to assemble bespoke product variants based on basic components that can be combined. Hereby, the number of components that can be chosen from (at this stage of the sales process) tends to be relatively small. Once such a rough preconfiguration is finished, design engineers usually determine a resultant technical fine configuration. This fine configuration comprises all parts and components required to make up the complete product variant desired and may consist of thousands of items (Guenter and Kuehn, 1999). The next step in creating the configured product variant requires a design engineer to start an ECAD system, generate a new (empty) project file, copy the components configured into the project and specify individual customer and order details. Subsequently, alterations necessary to the specific project may be accomplished and the process of generating an updated ECAD project documentation according to these alterations or amendments made has to be initiated. To make the development of product variants more effective, ECAD system vendors aim towards an automatic computer-aided support of the workflow process outlined above.

The research presented in this paper seeks to support the above mentioned concept but proposes a fundamental shift of top-down selection of components based on a 'parametric' function of the component. The function is achieved through fuzzy expert rules and drives the selection of potential components. Otherwise, the form of such a parametric function is extremely difficult to achieve in an analogous fashion to MCAD product variants. A top-down cost engineering capability is also implemented in parallel through parametric estimating technology (see Section 8). The general procedure is summarised below.

1 technical field sales and distribution staff identify input specifications
2 each input specification matches one of many existing specification categories to a degree between 0 and 1
3 logical combination of all input specifications creates, via an expert system mechanism, the narrow set of components possibly satisfying the entire specification.

The idea of modularisation lends itself to the application of the methodology to a hierarchical structure of detail (see Figure 2). The methodology can be applied to the top level of the hierarchy for a first crude identification of a matching product. Alternatively, more detailed solutions can be achieved at other predefined levels of the hierarchy to allow for an alternative in detail, build up and of modularised component assemblies that make a whole assembly. Hence, the problem of complexity and detail in building an ECAD solution is approached in this fashion. The problem then becomes managing the interfaces between modules at the *same* level of detail. If the modularisation is done effectively then this can be potentially simplified. This hierarchy is not a hierarchy of components but represents a hierarchy of detail in the same product description. A similar hierarchy is described in Scanlan et al. (2002), but here representing detail in cost estimates and product description.

Figure 2 Applying the method at the appropriate level of detail of the design. Hence level 1 is the same design but less detailed than level 2, than level 3, etc.

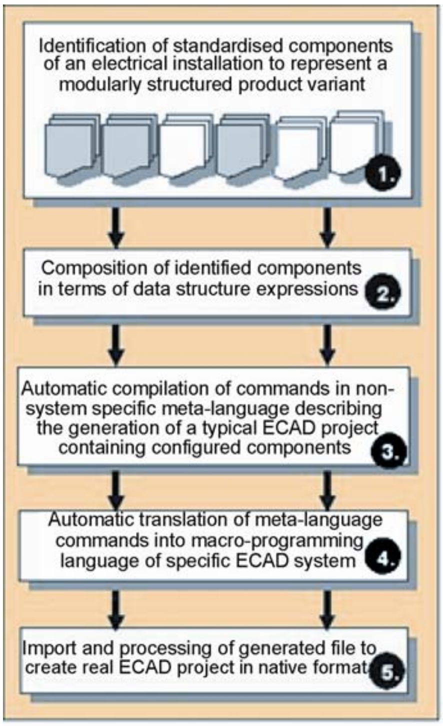


4 Functional principle

The basic functional principle of the generic variant design approach presented in this paper is now described. It is based on aspects from knowledge-based product configuration (Skonnard and Gudgin, 2001), the programming of design variants, as well as parametric product modelling and process automation (Roller and Schaefer, 2000). The fundamental idea behind the approach is to automatically generate an entire technical documentation of an electrical/electromechanical installation on the basis of a placed order specification. The overall process to achieve this involves five steps as shown in Figure 3.

- Firstly, a design variant of an installation is configured by composing standardised modules of existing (previously developed) components. In addition, this research proposes a top-down approach based on such concepts of knowledge, ontology, expert rules and 'logical drivers'. 'Logical drivers' can be specification-related variables. A hierarchical approach to design is taken at which an ECAD design is considered at several levels of detail. The system relies on a case base of previous designs and components on which to draw and structure a new design. Expert knowledge plays an essential role in this.
- Secondly, all components identified to compose a specific variant are stored in a data file based on a bespoke data structure that describes ECAD design projects in general.
- Thirdly, a set of commands describing the generation of a typical ECAD project containing all the components configured together is automatically compiled.
- Fourthly, the above variant project description expressed in non-system specific commands is automatically translated into commands of a specific macro programming language associated to a particular ECAD system.
- Finally, the specific ECAD system targeted can import and process these commands to create a corresponding project that may be handled or dealt with in any way the ECAD system allows.

Figure 3 Functional principle of ECAD variant design technology approach

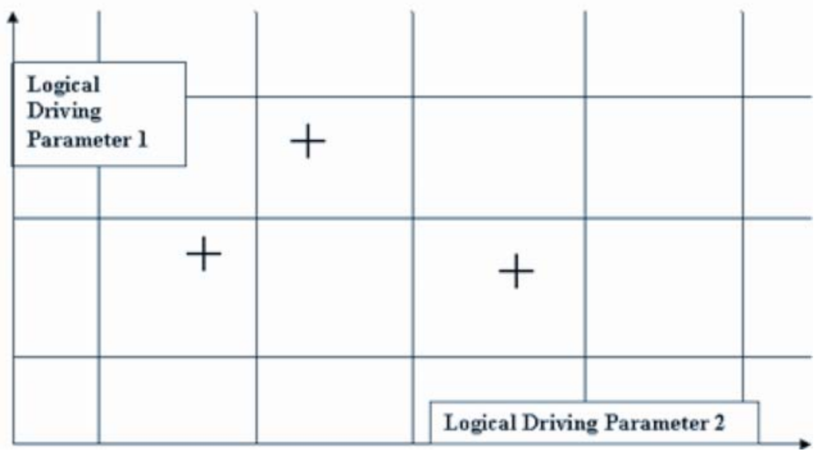


5 Technology approach

A brief overview of a technical approach to realise the functional principle described above is now given. Step one requires a software tool to manage, browse, identify and select existing components. Product Data Management (PDM) systems may be used for this purpose. Alternatively, a variety of commercial product configuration tools are available on the market, and even low cost table-based solutions based on, for example, Microsoft-Excel™ may be deployed if appropriate in terms of complexity (Guenter and Kuehn, 1999; Mešina and Roller, 2004). A case-based reasoning mechanism is a strong possibility in utilising previous designs and standardised components. A description of the additional proposed methodology is: identification of the logical driver starts a process of expert rule driven selection of components based on a fuzzy category containing many components. Figure 4 provides insight into how just two categories forms a structure of clusters. The fuzziness allows for rapid selection rather than a long precisely driven process. Hence, the focus of the problem is on choosing the most appropriate logical drivers. Cost optimisation is facilitated through a parallel top-down parametric cost estimate. The rapid estimate of costs through a cost model (Hicks et al., 2002), for a subset of possible designs then allows for optimal choice of design through conventional or fuzzy optimisation techniques. A list of such techniques includes:

- genetic algorithms
- linear programming methods, for example the Simplex method
- non-linear programming and
- fuzzy optimisation methods (Ross, 1995).

Figure 4 Categorising ECAD designs by expert driven or data driven fuzzy classification methods



As already mentioned, a data structure specifically tailored for representing configuration based on variant projects is required. This data structure primarily has to cover components and documents typically used to make up an entire ECAD project documentation. To process and automatically evaluate variant projects based on such a data structure in subsequent processes, a standardised data format has to be used. In the approach described in this paper the variant project data structure has been expressed in Extensible Mark-up Language (XML) (Skonnard and Gudgin, 2001). XML is a language for describing hierarchically composed objects that distinguishes between the structure of objects, their content and layout. Realising step three of the functional principle involves formulating commands expressing the generation of a configuration-based ECAD project in a non-system specific form. Hence, a suitable meta-language has been developed and applied. This meta-language covers a variety of system commands similar to those being typical for contemporary ECAD system's macro languages. Following the functional principle presented, a variant project stored as XML file can now be transferred into a new data format describing the generation of an ECAD project containing the configured components. Technically, this means to enhance the original XML data structure of a configuration-based variant project in such a way that it allows to model and express ECAD system commands in a non-system specific language. To sum-up, the components of a configured ECAD variant project stored as XML file have been picked-up and transferred into another, more sophisticated and powerful XML data structure containing non-system specific commands to describe the generation of an ECAD project made up of the components configured.

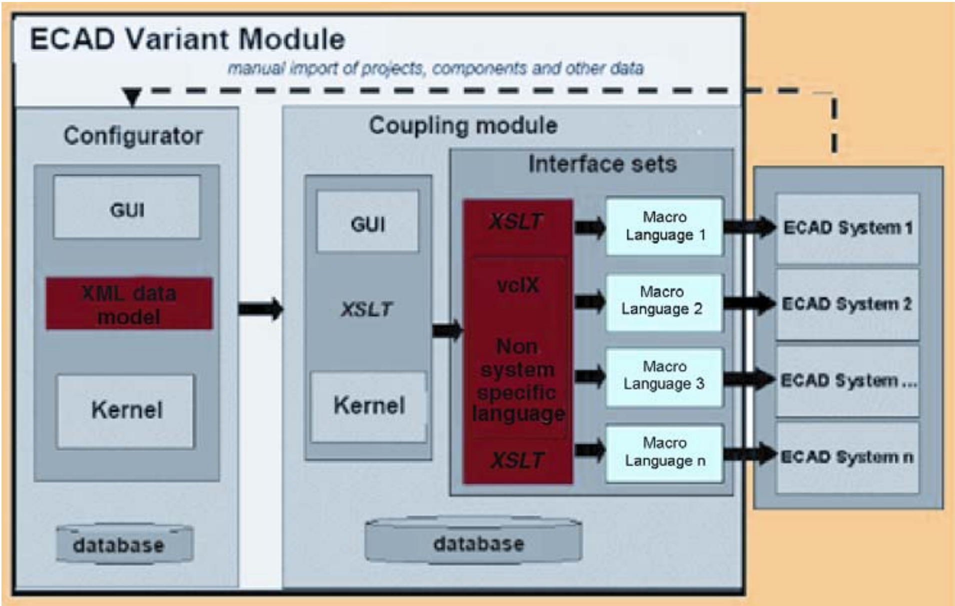
This transformation process is carried out automatically using Extensible Style sheet Language (XSL) and a software tool called XSL Transformation (XSLT) (Skonnard and Gudgin, 2001). XSL is a language specifically developed to facilitate transformation purposes and allows defining rules describing the transformation from one XML structure into another. The transformation rules necessary to perform the desired transformation are stored within a specific XSL data file. The actual data transformation is then carried out by XSLT.

The procedure described above analogously recurs in step four of the technology approach. However, this time an XSL file describing the transformation from the non-system specific command list structure into another structure encompassing commands of a specific ECAD system's macro language is required. The result of this final transformation is a batch file to be imported and processed by the specific ECAD system chosen. In other words, a real ECAD project in a native data format has been created. Since the technology approach outlined above is highly sophisticated further reading is required for an in-depth understanding (Schaefer, 2003, 2004).

6 Software module conception

An architecture of an ECAD variant software module for realising the variant design technology approach discussed in this paper is now presented. Part of the already existing novel architecture, as has been discussed, is in a proposed state only, that is, the fuzzy and cost part. The overall variant module architecture basically comprises of two submodules, notably the 'configuration module' and the 'coupling module'. It is developed as a self-contained unit that may be coupled to one or more ECAD systems rather than directly implemented within a specific system (see Figure 5) (Schaefer, 2003). The configuration module contains the proposed parametric estimating and the component identification capability. Cost optimisation can be obtained by transferring information to an appropriate optimiser, for example, through a suitably constructed objective function.

Figure 5 System architecture of the ECAD variant module



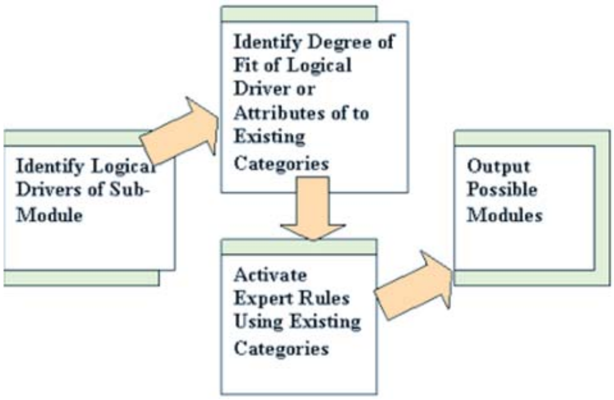
The purpose of the configuration module is to either create new product variant configurations or adjust existing ones using existing basic components. Hereby, the various plans of an electrical documentation (e.g. schematics, terminal plans, part lists, etc.) are drawn on as configuration components. Prior to being able to work with the configuration module all the components (projects, subprojects, etc.) already existing on ECAD site and meant to be available for variant projects have to be imported to the configuration module's database. Using the features of a comfortable Graphical User Interface (GUI), the imported ECAD components can be used to combine new variant projects, to adjust previously created design variants and to add further basic components to the database. The design knowledge with regard to constraints describing possible combinations and configurations has to be brought into the database as well. The system kernel of the configuration module therefore has to incorporate an intelligent mechanism to maintain, check and control the compliance of the constraints modelled. Owing to the complexity of knowledge-based configuration systems the development of proprietary knowledge-based configuration tools is not recommended (Guenter and Kuehn, 1999). There are many commercial solutions for almost any configuration tasks available on the market as pointed out earlier. The mechanism of the configuration is proposed to be aided via fuzzy logic and cost optimisation as presented in this paper.

The purpose of the coupling module is to automate the steps of the workflow process, that today, are usually performed manually by an engineer once the components for a variant configuration have been determined. A first task for the coupling module is to import a variant configuration from the configuration module. Subsequently, it has to create a file of non-system specific commands describing the relevant steps to open a new ECAD project and to include the configured components. After that, the coupling module has to transfer these non-specific commands into a data file to be imported by a specific ECAD system for further processing.

7 Top-down fuzzy expert rule approach

Optimisation using fuzzy logic is a popular research topic, (e.g. Vercher et al., 2007) maximise portfolios under risk. Part of the novelty in this paper is the proposition of clustering ECAD components via a top level driver, for instance a so-called 'logical driver'. In contrast to geometric parametric models 'Variational' differences between ECAD models are based on logical parameters. Clustering the ECAD components can be achieved through expert judgement. Hence, there can be the formation of fuzzy clusters of ECAD components or submodules based on their functionality or of a logical-related attribute. An important alternative is through fuzzy clustering methods which can automatically cluster components into fuzzy sets. Clustering can occur through relating a set of inputs, which can be attributes of any type, to their output, which should be the logical driver in this discussion. Fuzzy clustering methods include subtractive clustering, and fuzzy *c* means clustering (Jang et al., 1997; Ross, 1995). Hence, a database of records of design parameters can be input into the fuzzy clustering algorithm to form the required rule base (Figure 6).

Figure 6 Proposed module selection functionality in the configurator



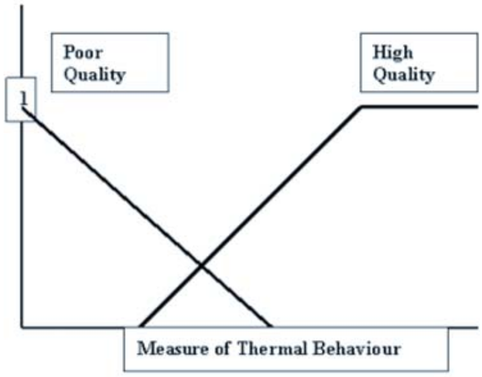
The crucial step in the methodology is the identification of the logical drivers. These logical drivers might refer to degree of suitability for 'Engine Control', or a component's 'Thermal Behaviour'.

Large clusters of components belonging to one of the logical drivers to a varying degree, allows for rapid narrowing of possible components in the first instance of design. Very narrow and focused selection criteria are bypassed and such detail is delayed and improved in focus for the latter stages of design. Such latter stages of design are aided through the possible application of the optimisation processes.

Therefore, the essence of the component selection process relies on imprecision in definition of specification. Fuzzy logic is a matter of degree (Zadeh, 1965). Instead of describing a variable as having a certain attribute or not, the variable possesses that attribute to a degree between 0 and 1. There are many references to explaining fuzzy logic (e.g. Jang et al., 1997). An example is shown in Figure 7, where components may be classified into having poor or high quality 'Thermal Behaviour' to this degree.

Type-2 fuzzy logic (Mendel, 2001; Mendel and John, 2002) provides a potentially more refined model and offers the potential for the Computing with Words (CWW) paradigm. Because of the sheer number of components and to promote team working, Type-2 fuzzy logic can be more effective, although more complex to implement. Type-2 fuzzy logic is the first recommendation in this paper.

Figure 7 A Type-1 fuzzy set measuring the degree of membership of an ECAD module to the concept of 'measure of thermal behaviour'



Other examples of using fuzzy logic to retrieve past cases have been used, for example Tan et al. (2006), use fuzzy ARTMAP and case-based reasoning in utilising and learning knowledge for financial justification of manufacturing technology investment in a changing business environment. Referring to case-based reasoning as in Tan et al. (2006), the most appropriate similarity metric for the logical requirements of a new design is required. This problem also potentially occurs in our case adaptation for ECAD. In addition, there is a need for an assessment of the logical drivers and also risk of subtleties causing problems. In other words, the subtlety of logical structures of ECAD design and their components eluding the expert driven rule making process.

The proposed methodology determines a structure of drivers, for example electrical-related drivers, for electro-magnetic-related problems; or function-related drivers, for light giving related components or power pack-related concerns by a category such as 'Country of Use'.

Hence the main challenge of the proposed methodology is to develop expert rules using top-down drivers as input variables and component type output variables. For example, a rule might be formed: "If Thermal behaviour is High Quality then Component X (fits this criteria) to a Degree x. Aggregation of the several criteria is achieved through the AND or the OR operators". Fuzzy logic has its own set of mathematical operations corresponding to these operators.

8 Cost engineering approach

Cost engineering activity has been observed in several sectors. For example, aerospace, oil and gas industry, nuclear decommissioning (Amos et al., 2002) and the automobile industry (Baker et al., 2002). The cost engineering community are generally in agreement of the three types of estimate (Scanlan et al., 2002). These are detailed, analogy and parametric estimations. Detailed estimating includes the bottom-up summation of all the costs recorded against the product or process in question. The estimate is generally very accurate (to within 5%) but involves resource intensive data collection. There is also a high likelihood of mistakes in a large and unwieldy calculation (typically achieved through the use of spreadsheets). Analogous estimating identifies a previous comparable product's cost estimate and adjusts it, compared to the attributes of the new product.

Parametric estimating is considered state-of-the-art in industry for cost estimation (Foussier, 2006). Parametric estimating is the statistical analysis of historical cost records to develop a Cost Estimating Relationship (CER). CERs can be combined in a logical and structured manner to produce a final estimate. There are commercial estimating tools for complex products such as aerospace vehicles in the parametric estimating community. NASA is considered the state-of-the-art in such practice. The International Society of Parametric Analysts (ISPA) is an organisation concerned with parametric estimation. The Parametric Estimation Handbook is in the website. Rush and Roy (2001) further investigated the analogy method by surveying the way estimators think in developing analogous estimates. In particular, expert judgement and associated reasoning was classified during the activity of adjusting estimates of similar products to reflect the cost of a new product. Scanlan et al. (2002) describe optimisation by life cycle cost at the conceptual design stage. There is found to be lack of tools. The 2 types of estimating of parametric and generative estimating are described along with their drawbacks. For example parametric estimating can be used with high-level design parameters, but at the same time it cannot distinguish between two projects with the same value high-level parameter but different value low-level parameters. Generative estimating can depend on identifying features and their mapping between design related and other type features, for example manufacturing-related features.

It is noted in this research that some unusual cost modelling methods have occurred. Research at MIT (Gutowski, 1998) relates product size to process time in hand lay-up of plastic composites, using a first order differential equation, that is, Equation (1). The idea of using the equation came from noticing the plot of hand lay-up times and component size and using the experience of the behaviour of 'first order dynamics' in Equation (1).

$$v_\lambda = \frac{\mathrm{d}\lambda}{\mathrm{d}t} = v_0\left(1 - e^{-t/\tau_0}\right) \tag{1}$$

where λ represents size (e.g. length, area or volume), v_0 is the steady state, t is time and τ_0 is a time constant.

Two new concepts are introduced, that would not be seen in conventional curve fitting methods: steady state and an associated time constant. The research aimed to relate the steady state and the time constant to physical processes. Gutowski (1998) describes how hand lay-up of composites can be related to wall papering or carpeting, using the idea of steady state and time constants, and the general differential equation form (1). In this way, process time estimates can be produced for processes that have no data associated with them, but can be linked to other well known processes through a family of solutions of a differential equation form.

Zangwill and Kantor (1998) use the predator-prey model or the Lotke-Volterra differential equation form, to model the effects of continuous improvement, as shown in Equation (2). Continuous improvement is described as a process that occurs on a weekly basis, where teams are involved in identifying and eliminating process imperfections or non-value adding work, for example: 'rework, waiting, changes, delays, erroneous information, defects, waste, preparation time, transportation, idle time and inspection'. The predators are likened to the continuous improvement teams, whereas the prey is likened to the process imperfections. One of the families of solutions to the differential equation form shows a non-asymptotic solution, where all the imperfection in the process is removed, rather than always removing some waste but not removing all of it. The other two solutions are an exponential and a power law, both forms of learning curve, used in adjusting costs over a number of units of production. Zangwill and Kantor (1998) criticise power laws for modelling learning curves because of the absence of parameters linked to management policies, that is, a meaningful physical significance.

$$\frac{\mathrm{d}N}{\mathrm{d}q} = -cE(q)N(q) \tag{2}$$

where $N(q)$ = 'amount of metric left to eliminate', $E(q)$ = 'effectiveness of management', c is a constant and q is the number of units of production made thus far.

Solving Equation (2) provides more information about solutions to the problem of continuous improvement of costs rather than traditional curve fitting methods found in the study of statistics.

The cost engineering approach adopted in this work is the parametric estimating type. Within the proposed methodology a database of historic cost records should be developed at the target company upon which cost estimates should be based. The top-down approach to ECAD variant design generation can therefore be supported by a top-down parametric Cost Engineering approach.

9 Overview of the proposed approach within the configurator

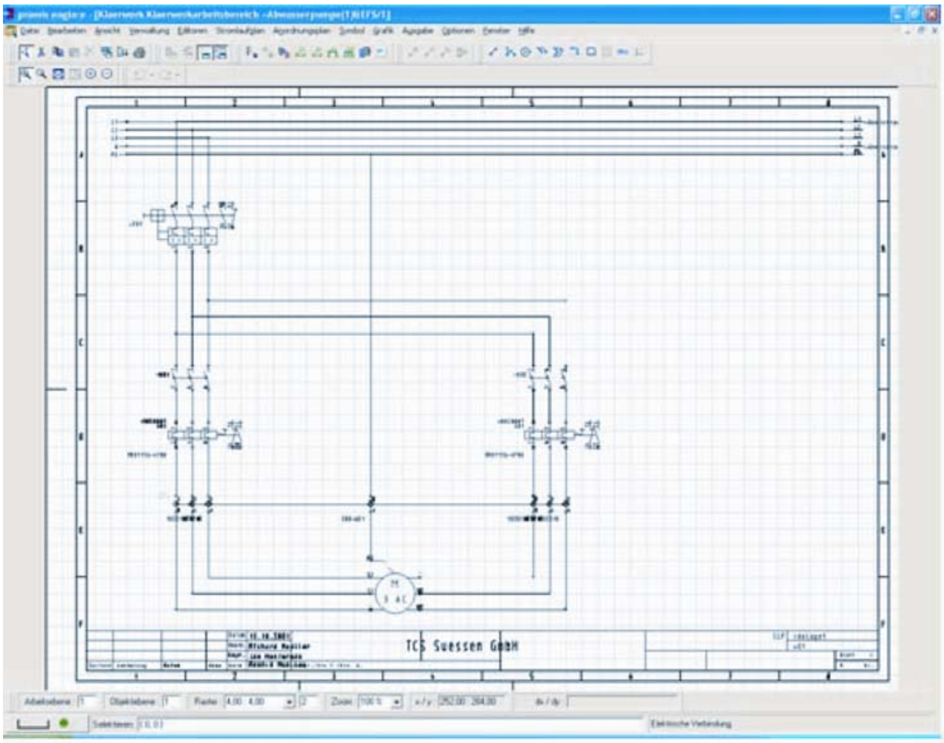
Hence, the steps required for the proposed methodology in the configurator are:

1. Develop an ontology of top level design drivers for ECAD. These can be functionally related to other, for example safety.
2. Develop a case base of previous designs or simple units on which to base the design variant selection system.
3. Manually or automatically develop a system of rules linking design drivers to designs. Constraints can also be expressed as a set of rules between linguistic variables.
4. Establish an empty hierarchical structure governed by design drivers and levels of design detail.
5. Populate the design with previous designs or simpler units using design drivers to fire rules in the expert system. Fuzzy variables for the design drivers allow degrees of fit for previous designs or simpler units. Aggregation of rules through fuzzy operators plays an essential role.

10 Conclusion

The generic approach to automated product variant design technology presented in this paper has been realised as a software prototype. Its applicability has been demonstrated using an industrial problem, and has been found to bear a high potential in respect to cost and time reduction in the area of computer-aided product development. Figure 8 shows an example of a schematic automatically generated using the software prototype of the variant module.

Figure 8 Example of a schematic automatically generated by a variant module



Current work with regard to the approach presented in this paper aims at the development of a top-down approach to rapid component selection and parametric cost estimation in the configurator. Imprecision is levered to facilitate subjective and rapid selection processes. Cost optimisation can be transferred to an objective function or integrated through the use of expert rules and fuzzy optimisation processes in the fuzzy expert system.

References

Amos, G., Bhamra, T., Buttrick, N. and Roy, R. (2002) 'Estimating techniques for decommissioning nuclear facilities', Master Thesis, Cranfield University.

Baker, V., Griggs, T. and Roy, R. (2002) 'Full service supplier cost modelling', Masters Thesis, Cranfield University.

Foussier, P. (2006) *From Product Description to Cost: A Practical Approach: Volume 1: The Parametric Approach*, Springer, ISBN 185233973X.

Guenter, A. and Kuehn, C. (1999) 'Knowledge-based configuration – survey and future directions', in F. Puppe (Ed). *Knowledge Based Systems*, Berlin: Springer, pp.47–66.

Gutowski, T.G. (1998) *Advanced Composite Manufacturing*, John Wiley and Sons.

Hicks, B.K., Culley, S.J. and Mullineux, G. (2002) 'Cost estimation for standard components and systems in the early phases of the design process', *Journal of Engineering Design*, Vol. 13, No. 4, pp.271–292.

Jang, J-S.R., Sun, C-T. and Mizutani, E. (1997) *Neuro-Fuzzy and Soft Computing, a Computational Approach to Learning and Machine Intelligence*, Prentice Hall, ISBN 0-13-261066-3.

Mendel, J.M. (2001) *Uncertain Rule-Based Fuzzy Logic Systems*, Prentice Hall, ISBN 0-13-040969-3.

Mendel, J. and John, R.I. (2002) 'Type-2 fuzzy sets made simple', *IEEE Transactions on Fuzzy Systems*, Vol. 10, No. 2, pp.177–127.

Mešina, M. and Roller, D. (2004) 'Configuration management using standard tools', in X-T. Yan, C-Y. Jiang and N.P. Juster (Eds). *Perspectives From Europe and Asia on Engineering Design and Manufacture*, Kluwer Academic Publishers, pp.645–658.

Mink, U. and Roller, D. (1997) 'New ECAD systems technology', in D. Roller and P. Brunet (Eds). *CAD Systems Development: Tools and Methods*, Springer, ISBN 354062535-6, pp.41–54.

Roller, D. (1995) *CAD- Effiziente Anpassungs- und Variantenkonstruktion*, Springer-Verlag.

Roller, D., Dettlaff, B. and Richert, U, (1996) 'Rationalization in the electrical engineering process', in D. Roller (Ed). *Mechatronics – Advanced Development Methods and Systems for Automotive Products, ISATA Proceedings*, Automotive Automation Ltd., Croydon, England, pp.279–284.

Roller, D. and Schaefer, D. (2000) 'Variant design in electrical engineering – an extension of parametric modelling', in P. Brunet, C. Hoffmann and D. Roller (Eds). *CAD – Tools and Algorithms for Product Design*, Berlin: Springer, ISBN 3540662049, pp.233–250.

Ross, T.J. (1995) *Fuzzy Logic with Engineering Applications*, McGraw Hill, ISBN 0-07-053917-0.

Rush, C. and Roy, R. (2001) 'Expert judgement in cost estimating: modelling the reasoning process', *Concurrent Engineering: Research and Applications*, Vol. 9, No. 4, pp.271–284.

Scanlan, J., Hill, T., Marsh, R., Bru, C., Dunkley, M. and Cleevely, P. (2002) 'Cost modelling for aircraft design optimisation', *Journal of Engineering Design*, Vol. 13, No. 3, pp.261–269.

Schaefer, D. (2003) 'Variantentechnologie unter besonderer Beruecksichtigung von Elektrotechnik CAD' (in German language, translated title: 'Variational design with respect to Electrical Engineering Computer Aided Design', Aachen, Shaker, PhD Dissertation, ISBN 3832219013.

Schaefer, D. (2004) 'A new method for variant design technology in ECAD', in P.G. Maropoulos and D. Schaefer (Eds). *ECAD/ECAE2004 – Proceedings of the 1st International Conference on Electrical/Electromechanical Computer-Aided Design and Engineering*. Durham, UK, 15–16 November, ISBN 09535558-36, pp.46–49.

Skonnard, A. and Gudgin, M. (2001) *Essential XML Quick Reference – A Programmer's Reference to XML, XPATH, XSLT, XML Schema, Soap and More*, Addison Wesley, ISBN 0201740958.

Tan, K.H., Lim, C.P., Platts, K. and Koay, H.S. (2006) 'Managing manufacturing technology investments: an intelligent learning system approach', *International Journal of Computer Integrated Manufacturing*, Vol. 19, No. 1, pp.4–13.

Vercher, E., Bermudez, J.D. and Segura, J.V. (2007) 'Fuzzy portfolio optimization under downside risk measures', *Fuzzy Sets and Systems*, Vol. 158, pp.769–782.

Zadeh, L. (1965) 'Fuzzy set', *Information and Control*, Vol. 8, pp.338–353.

Zangwill, W.I. and Kantor, P.B. (1998) 'Toward a theory of continuous improvement and the learning curve', *Management Science*, Vol. 44, No. 7, pp.910–920.