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Concurrent engineering design using intelligent agents

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1. Introduction

The last decade has resulted in considerable growth of the availability of Computer Aided Learning (CAL) software systems developed with the intent of improving the educational provision offered by higher educational establishments. Upon examination, many of these systems have been found to be based upon simple "knowledge provision" and rote learning whilst offering the user only a limited capability of employing that knowledge for a useful purpose, an important aspect of engineering education and training. The motivation for the research and systems development discussed in this article came as a result of the changing emphasis of effective product design from those based principally upon functional criteria towards a "life cycle" approach. The resulting interactive multi-media CAL software system developed and marketed under the product name "Design Builder" has two specific learning objectives:

(i) to enable undergraduate engineers to experience working in a concurrent environment without the requirement for direct and specialised teaching staff support; and
(ii) to provide an interactive and intelligent simulation environment from which users may develop a culture that introduces concurrency in the engineering design process.

A manufacturer whose culture encourages personnel to operate within departmental confines, giving rise to insular communications, is unlikely to remain competitive in the longer term. Today's successful companies are seen as those who introduce a strategic approach to their management practices and actively encourage a team approach to their working culture. Our educational provision must meet these requirements sought by manufacturing companies with regard to training for employees that reflect a wide working knowledge of methods and processes, whilst having the skills to communicate and work as active members of an integrated and focussed team. The article identifies the problems associated with making such an educational provision and a means by which they were overcome, utilizing multi-domain knowledge based systems technology incorporated within a virtual multi-media environment.

2. Concurrent engineering design

Engineering design is a complex and ill-defined process requiring the consideration of constraints that may be only vaguely defined but often conflict and which will play a part in determining the success, or

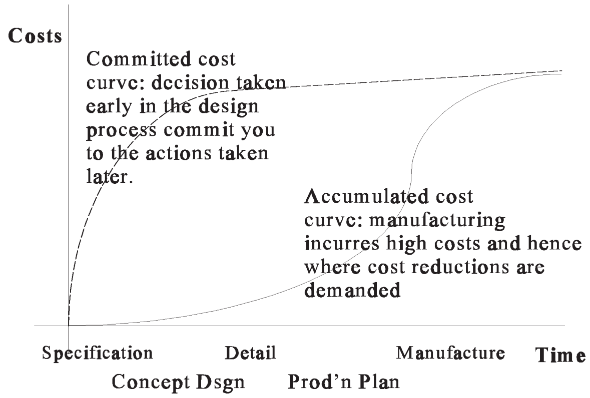

Fig. 1. Cost × time for the design to manufacture process.

other wise, of that product during it's life cycle. Considerations to be made may include those involving decisions regarding the type of manufacturing process to be adopted, assembly procedures, material selection, incurred costs, production quantities, servicing requirements, transportation to the customer, appearance, and many others including material re-cycling upon the product finishing its useful life. A traditional approach to engineering design involves a chain of discrete individuals and departments, each making decisions in isolation and without reference to the design as a whole, nor necessarily to the initial requirements as communicated by the customer. This results in iteration; the developing product design needing to be sent back to previous stages in the process as, for example, its unmanufacturability is discovered at a time when the promised delivery date is fast approaching! This inevitably leads to a delay in the items delivery, the incurring of cost increases and a finished product which may not present the optimum solution to the customer's needs, unforseen modification having to be carried out during iteration of the design process. Hence, successful design implies a knowledge input from a wide variety of different fields, considered with relative merit and enabling the manufacture and production of a product that gives a trouble-free life cycle. Expertise across such wide domains requires a team who's members work in unison to provide feedback on the prevalent issues as outlined by Pugh [1].

Concurrent engineering is a philosophical approach used increasingly by industry as a way of avoiding potentially damaging decisions being taken at the design stage. Improved communications within the design team, and between designer and customer, would help to minimise iteration by pooling all necessary information at the start of the process and raising questions regarding likely problems rather than leaving them to be discovered at some later and more costly stage. Clarification of the design brief is crucial to achieving the required design outcome; understand the problem and all related practicalities and possible implications *before* embarking upon seeking a solution is an important first step towards achieving a "right-first-time" approach.

However, a traditional educational environment is not conducive to operating such concurrency in its teaching practices. There are physical limitations upon individuals – both with regard to academic staff and the students they teach – and these along with burdening cost and resource restrictions generally prevent such experimentation. Engineering design pools a vast range of knowledge and expertise from across a wide variety of fields both of a technical and non-technical nature. Any one individual cannot realistically master such a breadth of knowledge to the required depth of understanding needed to support all likely areas in which questions need answering. A team-teaching approach is one possible alternative but the incurred costs and time needed to prepare generally make such approaches unviable. Students themselves often exhibit poor team working capabilities due primarily to a lack in communication and time management skills which prove antipathetic to an atmosphere of concurrency. To a certain extent it is a chicken and egg argument: which comes first – the poor communication skills, or the difficulty in creating a concurrent environment? Integration of "Design Builder" [2] and "Blueprint" into the educational experience will create the atmosphere of concurrency, enabling interaction between system and user, demonstrating the advantages of a parallel interaction between colleagues and with the customer – and therefore encouraging students to employ similar interaction in their own projects. Creating the right culture is as important as teaching a process with regard to engineering design.

3. Simulating a concurrent design environment

A large number of CAL packages currently available effectively adopt a format that could be referred to as "book-on-screen", combining text and various graphics to convey information. The use of technology for technologies sake will not, however, result in the objectives originally established by the development team being met. The use of books is still both a valuable and effective means of communication; they use a natural language format almost generally understood by the human operating system, they are easy to read and not affected by ambient lighting conditions, they are highly portable needing no external power source or ancillary devices, indexes enable quick location of the required subject matter and, perhaps significantly, they do not crash leaving the user with mid-session frustration. The capable learning experience is also underdeveloped through a failure to exploit the high degree of interaction possible with current developments in user interface and knowledge based systems technology. Soloway et al. [3] suggested that a computer based learning environment should enable the student to "learn by doing" and not by simply telling. The advances made in computer technology, particularly with respect to increased processing speeds, cheaper memory devices including RAM and hard disk drives has enabled development of valuable multi-media teaching and learning aids to support and aid student learning. User interactivity required in operating such systems can significantly aid understanding and hence improve learning. Encouraging the user to make reasoned decisions ands act upon them does considerably broaden the abilities of pupils when related to vocational requirements. This is a philosophy that has been strongly adopted in developing both the "Design Builder" and "Blueprint" CAL systems. Both of these systems use a highly interactive environment as a means by which pupils may experience and learn regarding the problems associated with organising and managing design decision making in a realistic world as reflected by the virtual industrial environment built into these systems. The user of both of these systems assumes the role of a designer working in companies who have adopted a concurrent philosophy in developing and manufacturing defined products. An objective of both software systems is to enable the user to learn good practice in terms of the "process" of design which is generic and easily adopted in any future design situation confronted with.

4. A model for the design process

Although no generally accepted model exists for engineering design, widely used models are based upon Pahl and Beitz [4] and Hubka [5] which assumes that the designer proceeds by developing a specification, produces a number of concepts to satisfy the developed specification and then detailing the

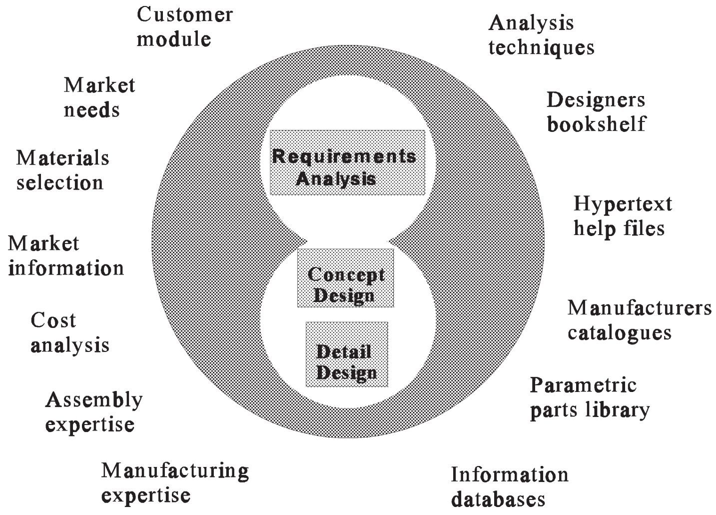

Fig. 2. The system structure used in developing the Design Builder CAL system.

most suitable concept in order to arrive at the final detailed design. Chandrasekaran [6] believes that the method of design adopted by many design teams use is a process of:

propose – critique – modify.

This suggests that a design is initially proposed as a possible solution to an identified problem, it is then critiqued by people other than the originator with the intention of outlining any conflicting constraints and then the necessary modification is carried out to overcome those identified conflicts. This, like any other iterative process, could result in unnecessary expenditure being incurred as the significance of the conflicts increases. The objective is to minimise both the lead-time for design and the costs involved whilst producing a product that satisfies the initially identified needs and at a competitive price.

Development of the CAL software system Design Builder has been influenced by these various and established models for the design process. Consideration was also made to a number of case studies that have been undertaken analysing design processes associated with different manufacturing organisations. Figure 2 shows a simple flowchart schematic of the resulting design process as formed the base for developing the Design Builder CAL system software.

5. System development considerations

Originally developed for use by undergraduate engineering students as an introduction to engineering design using a concurrent philosophy, the development had a number of constraints as follows:

- (i) The system was to be developed on the Microsoft Windows operating platform using PC-based hardware – generally available in the majority of establishments.
- (ii) In operation, the system should be self contained and requiring no special skills or expertise user.
- (iii) System interface design should be intuitive and user friendly.
- (iv) Multi-media can be used were appropriate to enhance the learning process.

(v) In emulating a design team, the system needs to incorporate expertise from a number of specific domains and represented as knowledge-based structures.
(vi) Whilst interrogation of knowledge bases should be available to a user, the knowledge bases should automatically respond to decisions made by the user during the design process.

The expertise modelling for Design Builder was based upon the approach advocated by the *Common*KADS methodology. This is the accepted European standard methodology for developing knowledge based systems. *Common*KADS advocates a similar approach to other more conventional software development methodologies (e.g., SSADM, Yourdon, etc.), however, it specifically includes for a model of expertise to be incorporated. Such an approach advocates development of modelling expertise in three stages:

1. Analyse static knowledge to build up an initial model for the domain layer.
2. Select and construct an initial task model.
3. Construct the expertise model, using the initial task model to act as a catalyst for further knowledge acquisition. This refers to the process of communicating with an "expert" in order to try and model their expertise.

An analysis of the static knowledge within several of the different domains modelled in the system reveals the following:

(a) *Marketing*: expertise is mainly heuristic in nature and fits a rule based format.
(b) *Materials*: the expertise in this domain needs more sophisticated techniques for modelling. Materials fit a classic hierarchical frame type structure as illustrated in Fig. 3. Material selection for a component would then be carried out using two approaches. An "off the cuff" approach would initially be used to select a suitable material for the purpose defined. This appears to be based upon a "heuristic" approach or knowledge of similar past cases the expert had experienced previously. If this failed, the expert would adopt a more systematic search approach by successively ruling out classes of different material on the basis of their properties and thus eventually refining the choice down to one considered most suitable. This approximated to a "breadth first" search pattern with domain knowledge dictating selection at each branching stage.

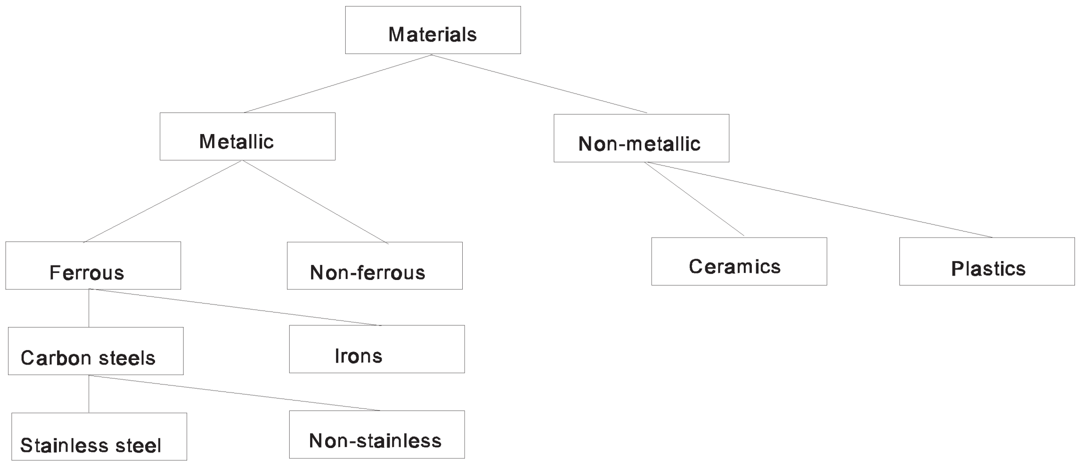

Fig. 3. Hierarchical frame structure used for materials selection.

(c) *Assembly*: assembly knowledge is concerned with different components and their spatial relationships and interconnections with adjacent components. The objects and their interrelationships were mostly suitably represented using an object orientated hierarchical structure.

Knowledge bases incorporated in Design Builder encapsulate expertise in different life cycle perspectives. These enable the system to "critique" the students evolving design specification from a variety of different perspectives as it progresses. Clearly, a number of perspectives are likely to produce conflicting constraints with any one single design process. A cost constraint, for example, is likely to conflict with other perspectives as the quality standard issues selected are increased. In presenting the on going designprocess in such a manner, the student is required to make judgements as to which critique is the most significant given the nature of the particular problem confronted. Expertise in the knowledge bases has been derived from a number of sources and these include:

(i) Academics who are recognised experts in the relevant subject areas;
(ii) Standard engineering literature and text books;
(iii) Manufacturers catalogues and literature;
(iv) Various British and International Standards; and
(v) Professional engineers involved in the design and manufacture of related products.

6. Design Builder's virtual environment

Design Builder simulates a virtual concurrent engineering design environment in which the student, as the system user, takes on the role of the design team leader faced with providing the necessary documentation to enable manufacture of a product that satisfies a system generated customer enquiry. The system models the design process in three integrated phases as follows:

(a) The development of a detailed Product Design Specification or PDS;
(b) The conceptualism and evaluation of a number of concept designs that comply with the previously derived PDS;
(c) The analysis and detail design of the optimum concept including bought-out parts and materials listing.

From the customer enquiry initially derived by the system, the student is first required to construct a detailed Product Design Specification. The importance of this phase cannot be over stated, too often the design process commences without a clear understanding of what exactly is required. As in reality, the customer's request is incompletely specified and needs the student to question experts and the customer to gain a fuller understanding. Advice by the experts enables comprehensive specifications to be assembled which are analysed and finally ranked according to their influence on the impending design.

As previously mentioned, at the core of the Design Builder system are a number of knowledge based systems which encapsulate expertise in a number of diverse areas, including manufacture, assembly, costing, materials properties and selection, marketing and a general technical expert. Through the simulated design process, the student is prompted towards their own unique end result as the system is completely open-ended with no in-built solutions. Decisions made by the user are continuously analysed by the experts who provide a critique of the product developments. Applying such a critique is particularly appropriate for simulating an engineering design environment as the student is left in overall control and hence "manages" the design process being undertaken. This approach is in marked contrast to the way more traditional expert systems are employed to aid problem solving, where the expert system takes over

Fig. 4. The designers virtual office.

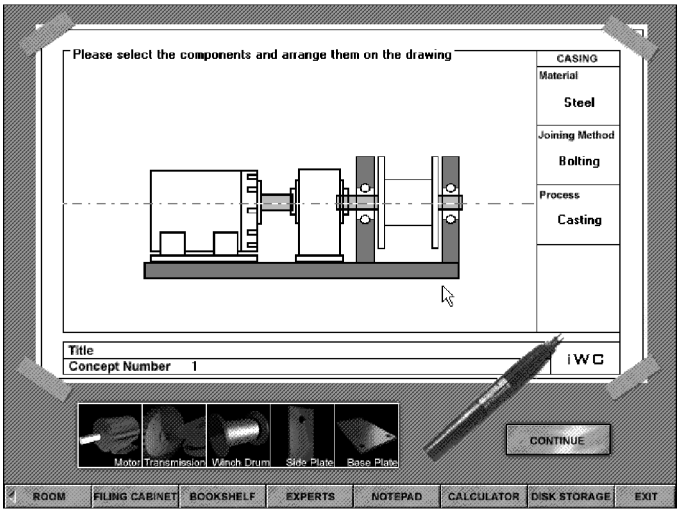

Fig. 5. The concept design tool in Design Builder.

the problem solving role from the users control. This subtle difference between the two approaches is characterised by the system evaluating user-given solutions to problems rather than a more orthodox approach of presenting solutions to user-given problems. Enabling such comprehensive critical evaluation to occur can often provide conflicting advice resulting in the user having to make justified decisions as to which course of action to adopt.

7. Concept to detail design

Upon completion of a suitable PDS, there is a need to create a number of different concept designs to enable an optimum end design to be achieved. This is achieved in Design Builder by a menu driven

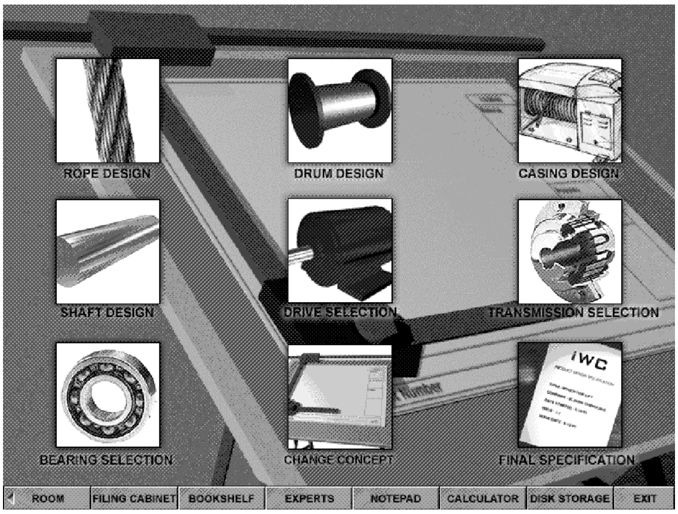

Fig. 6. The detail design tools in Design Builder.

approach, specifying individual components to use in an assembly. A parametric drawing tool enables students to size and assemble the chosen components in a "sensible" manner. This approach implies choosing components to satisfy some functionality and then arrange them in a layout to suit a particular application as detailed in the specification. An example of this approach is illustrated in Fig. 5.

A minimum of three concept designs are required by the system, which are individually evaluated using a optimization matrix. Employing this simple method of concept evaluation allows the student to consider the relative merits of each concept design and then make a value judgement as to which is the most suitable for the final design. The optimum concept is then taken on to the detail design phase where a variety of analytical tools and techniques are available, as illustrated in Fig. 6. Design Builder has a considerable wealth of information and data stored on the designers "bookshelf" which has been compiled with the assistance of a number of manufacturing companies. Information regarding components and items listed in the various catalogues may be utilised in the final design specification as would be the case in reality.

8. System evaluation

Engineering design is a co-operative activity involving the communication of information and expertise of both an academic and industrial nature. The work entailed must take into account all aspects of the final product necessary to satisfy the customer's needs, and to achieve this the designer must be prepared to compromise within his/her own field of expertise in order to accommodate the requirements of the other disciplines involved. A system to aid the teaching of engineering design must therefore be broad enough to encompass a variety of concerns and viewpoints, but not so diffuse as to have no practical implications. It is important for students to appreciate from an early stage in their studies those factors in other disciplines likely to impinge on their future role. This should be a common feature of any engineering course, and has a high priority in the design and development work undertaken by the iDer development team working at the University of Hertfordshire. At an early stage of systems development, 55 second year B. Eng (Hons) Engineering undergraduate students were asked to provide information to clarify the desired learning outcome from the teaching of engineering design. The exercise provided some interesting results emphasising a number of important aspects:

(i) most of the students indicated that they had little if any previous engineering design experience;
(ii) prior to their under-graduate studies, only a small number of students, including those with some industrial experience were aware of the philosophy of "concurrent engineering";
(iii) the majority of students had used computer applications at some point previously; and
(iv) a majority of students expressed a desire to use computers for "design" work as against employing them as simple graphics packages.

The results of this survey justified to the iDer development team the need for a system such as Design Builder to aid in the teaching and learning of engineering design from a concurrent approach.

Once developed the system was evaluated both internally and at a number of other institutions. The system has been adopted as a permanent and intrinsic part of the first year undergraduate teaching programme in the Faculty of Engineering and Information Sciences at the University of Hertfordshire. During the current 1997/98 academic year some 445 first year students alone have used Design Builder in their studies at the university. On a more general level, to-date some 80 universities world-wide have adopted Design Builder into their teaching programmes and on going system developments are making continuous use the feedback supplied by the ever growing list of users.

9. Conclusions

The future competitiveness of manufacturing industry relies to a significant extent upon existing undergraduates who will progress to be professional engineers of tomorrow. The importance of our educational provision cannot be over stressed and it has been indicated in this paper that the traditional "solution" driven approach to learning must be complemented by a "problem" orientated, open minded approach to investigating the total problem and its constraints. Students need to be made aware of the necessity and importance of communicating with working colleagues as experts in their particular industrial role. This is difficult to achieve in the conventional educational environment; however, one way in which students can experience this and become active participants in the learning process is by the use of "virtual environments" which simulate the real working environment. Such a system is represented Der Design Builder as described in this article.

The results of various studies carried out by the development team indicate that the learning process is enhanced by employing such approaches. Experience has indicated that, generally, students who use the system both enjoy the experience and found it enhanced the learning process. "Learning by doing" can have considerable benefits whilst being both enjoyable and exciting to those carrying it out: the students keenness in using the system bears witness to this aspect.

Encouraged by the reception of Design Builder, the development team at the University of Hertfordshire have recently been working on a schools version. Due to be released later this year, the student is required to design and build a racing car within a set of regulations provided. Each student is provided with a system defined budget and driver specification and using a similar knowledge based approach to that used by Design Builder, a team approach is used in designing the car. A novel approach is being used to provide feedback on the success of the outcomes: the system allows up to fifteen previously prepared designs to compete in a race simulation and the commentary is provided on progress. Aimed at captivating interest in engineering among pupils at key stages 3 and 4 and those attending GNVQ courses, the system has been christened "Blueprint".

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