Integration of finite element analysis and expert system for design optimisation in a CAD/CAM environment

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Abstract

This paper reports on the progress of the research currently being undertaken in the Department of Product Design Manufacture of Bournemouth University, aiming at developing a fully integrated design system (Total Design System). The system incorporates solid modelling and Finite Element Analysis (FEA) from a computer aided engineering package with two knowledge based expert systems. The FEA results are used as input data for material selector and manufacturing process adviser. Therefore the reliability and accuracy of the FEA data will determine the quality of the product optimisation performed. The ultimate objective of the Total Design System is to achieve a concurrent engineering environment that is accessible to a far greater number of people by implementing a high degree of compatible data exchange with a wide and varied array of software packages.

1 Introduction

Traditionally the process of the product development cycle involves many iterative stages of design, modelling and testing. With modern tools the design may be carried out much more efficiently and effectively, since many of the stages of analysis and testing can be done much faster and at a much lower cost. It is accepted that concurrent engineering is the solution for competitive product design and development. A very effective way to reduce the product development time is to use new technology to integrate modelling and engineering analysis systems, such as FEA, in a design visualisation environment.

In a production improvement process, it is important to reduce the gap and interactions between the design and the manufacturing tasks. The solution to
this problem is a true integration between these tasks. The rapid progress in the
development of artificial intelligence technology has enabled computers to be
applied to less deterministic design and manufacture processes. These processes
require symbolic manipulation and reasoning instead of routine number
processing. Artificial intelligence uses qualitative reasoning which can be
performed much more quickly than numerical and therefore requires much less
computation time. Furthermore, the mathematical expressions which describe
complex problems are too difficult or impossible to resolve; but with the help of
artificial intelligence they can be transformed and integrated as rules in an
expert system.

This paper will explain how the Total Design System performs the
integration of expert systems and FEA with solid modelling. The analysis part
of the system is discussed in detail with the aim of highlighting the problem of
accuracy and selection of FEA data. The expertise of the system is described as
the optimisation part including a material selector and a manufacturing advisor.
The compatibility of the system with different packages is investigated.

2 The total design system

A simple representation of the Total Design System, is shown in Figure 1. The
system is divided in three distinct parts: Product Design and Analysis, Expert
System for material and manufacturing process selection and Product
Optimisation.

Product design and analysis
The product is designed and analysed using I-DEAS Master Series running on a
workstation. An integrated data management system provides a foundation for
concurrent engineering by maintaining associativity between the solid model,
drawings and finite element models. This allows a designer to provide an early
snapshot of a design to fellow team members, who can begin to perform other
tasks such as simulations and drawings. Meanwhile, concurrently with their
efforts, the designer can continue refining the design. As soon as the final model
is accepted by the team, the solid modelling data and the FEA results are
selected and formatted to be transferred to the expert system.

Solid Modelling  I-DEAS is a user friendly application, thus modelling an
object is not a tedious task. The product is modelled with high performance 3D
design techniques such as precise Non-Uniform Rational B-Spline (NURBS)
geometry. This allows the representation of arcs, conics, and high-degree Bezier
curves without approximation. Therefore the quality obtained from 2D or 3D
models is excellent.
**Finite Element Analysis**  Due to its internal integration, I-DEAS allows the designer to send the CAD model to the FEA environment which provides comprehensive capabilities for building finite element models and reviewing analysis results. It uses the CAD model geometry directly, and includes the fundamental modelling functions of automatic mesh generation, application of boundary conditions and model checking. Post-processing functions allow the recovery of the analysis results and provide extensive graphical and numerical tools for gaining and understanding results.

**Interfaces**  To succeed in today’s business environment the information of the product data must be successfully managed. Various CAD/CAM systems are used extensively, but each system processes the data in its own native format. Then, for better adaptability and compatibility of this system, the designer can choose several options to create CAD or FEA models. As shown in Figure 2, there are different ways to obtain results. With the help of data translators, via IGES (Initial Graphics Exchange Specification), VDA (Verband der Automobilindustrie) or SET (Standard d’Echange et de Transfert) files, interfaces to over twenty modellers or analysis programs are available. The user can import a CAD model from another package into the I-DEAS solid modelling task before FEA, or use a finite element mesh created by an other program and import it to the analysis part of I-DEAS. Basically, custom and third-party applications which utilise this open architecture from I-DEAS, have direct access to wireframe, surface, solid, finite element models and results, and data attributes and descriptions. Thus by the integration of custom and third-party applications the product design and analysis part of the system contributes to the simultaneous philosophy with a large flexibility and compatibility.

**The expert system**
For complex problems, the mathematical expressions which performed the optimisation are too difficult or impossible to resolve. However, current development in artificial intelligence is a potential solution to that problem. The mathematical equations can be transformed and integrated as rules in an expert system. This will form the ‘theoretical optimisation’. Furthermore we can add an ‘expert optimisation’ which is the knowledge gained from a human expert incorporated into the knowledge based system [1].

**Theoretical Optimisation**  The theoretical optimisation is based on mathematical expressions which refer to the engineering science and technology. These equations describe a model with constants, variables, and parameters [2]. If we take the example of a shaft: constants never vary (e.g. \( \pi \)), variables can be changed (radius, length), parameters behave as constants for a particular design, but they can vary from an application to the next (Young’s modulus, torque). Thus if we formulate the problem that desires minimum
weight and maximum stiffness, we obtain two equations or two objectives: one concerning the weight, $f_1(x)$, and the other the stiffness, $f_2(x)$. However, decreasing the weight will decrease stiffness and vice versa, so some combination of the two is required. A simple way to solve these objectives is to assign subjective weightings to each objective, and create a new single objective by summing up all the objectives multiplied by their corresponding weight. Thus for minimum $f_1(x)$ and maximum $f_2(x)$ we may formulate the problem as follows,

$$\min F(x) = w_1f_1(x) + w_2f_2(x)$$

with \( w_1 + w_2 = 1 \)

**Expert Optimisation** The human experience and expertise cannot always be modelled by mathematics, which highlights the importance of an expert optimisation. The knowledge from an individual, usually an expert, in a certain field, is gathered by knowledge elicitation [3]. With that process, the system created attempts to replicate the operation of human intelligence by programming a computer with rules which encapsulate a human expert’s knowledge as a series of interconnected, generalised heuristics (‘rules of thumb’) called the knowledge base. The knowledge base is then searched via a program called an inference engine, to provide optimal judgements to questions input.

**Expert Systems** In The Total Design System, the artificial intelligence is divided into two expert systems based on a personal computer and designed with the help of the Crystal knowledge based system.

The first one is a knowledge based system which aids the designer in the difficult process of material selection. The system offers the option to search through the database to find the adequate material required for an application. By answering a series of questions relating to the application of the material, the user is presented with a short list of selected materials and then has the option to select the properties which are most important to the required application.

The second system is a manufacturing adviser. It has been developed in order to assist the designer and the engineer in the selection of the manufacturing methods (for a given application), at the design stage. The role of the user is restricted to answering the questions by selecting an option from a question menu. The system contains the manufacturing processes of both categories of materials: plastics and metals. It also includes all four major categories of manufacturing processes related to metals: casting, metal forming, powder metallurgy and machining [4] & [5].
Product Optimisation
The expert systems usually have several acceptable solutions and one of them may be selected as the optimal. The set of values for the design variables satisfying all constraints is called the feasible domain. To choose the best feasible solution from the domain we use a statistical formulae where a comparative method is employed. The various properties are weighted according to their significance and candidate solutions are evaluated on a scale of 1 to 10 relative to each property. A rating number is computed by multiplying the property rating by its rating significance and summing the results. Potential solutions can be compared in a uniform, unbiased manner. Moreover, the method can be computerised and run with a large database of information.

3 The analysis
In FEA, the primary goal is to determine how a component or assembly will respond to a given set of boundary conditions. The results of the analysis can be used to verify the performance, and can also be used to improve and optimise the design. Of course, all of this relies on the assumptions that the design has been correctly modelled, the boundary conditions have been properly defined, and that the FEA software itself performs correctly. Consequently, although sophisticated and user friendly commercial finite element packages are available, the theory of finite elements and the practical (modelling and analysis) aspects of the technique must be clearly understood by the user to develop reliable, valid and accurate FEA. The compatibility of the Total Design System with other FEA software is investigated with the aim of promoting the concurrent engineering philosophy. Furthermore, the large amount of data produced by an analysis should be post-processed to allow a good understanding of the results and the selection of the data required by the expert systems [6].

Reliability
The finite element method is approximate, its accuracy depend on the mathematical assumptions used in the method. This includes the way the interpolation function are set up and derived, and also the way the algorithms are implemented in the software. Nowadays, the size and complexity of FEA packages, such as I-DEAS Model Solution, mean that the essential mathematical routines are quite remote from the user and it becomes difficult for him to keep control of it. Anyway, due to the complexity of the control, it is easier to use an automatic solver which produces reliable results economically.

To perform a program validation and gain confidence in the results, the behaviour of the elements could be tested individually and in an assembly. The usual assessment tests to validate the implementation of a system are the single-element test, the patch test and the benchmark test. I-DEAS produces a
verification manual [7] which shows that the differences in finite element and theoretical results are in the most cases negligible and therefore its solver is reliable and accurate.

Validity and Accuracy
Validity of a model depends on how faithfully the physical problem is represented in the computer, while accuracy depends on how close the resulting solution is to theoretical result. Then both relate to:
- how well the model mathematically mirrors the geometric and material properties of the actual product,
- how close the boundary condition assumptions reflect the real loading,
- how the method of discretization has been implemented.

To prevent these problems, I-DEAS can check the solid properties and the geometry of any combination of element, use an interface which sets up the constraints automatically, run an adaptive meshing.

Selection of Data
Even a simple model can produce a large amount of output data. For example, in a three-dimensional stress analysis, each node of each element will generate a minimum of three displacements (x, y and z) and six stresses components (σ_x, σ_y, σ_z, τ_xy, τ_yz and τ_zx). This data needs to be sorted, selected and converted to be readable as a parameter by the expert system. I-DEAS provides a relational database management system, called the Pearl Data Manager. All data generated by the system is contained in tables to provide a clear, easily manipulated view of the information. The Pearl Data Manager allows the user to manipulate entire tables as well as individual data items. Since this data is sorted and selected, the Pearl system can create a new table of data in ASCII code. This ASCII file contains some of the parameters required by the expert systems to perform their tasks. It will be transferred from the workstation (UNIX environment) to the personal computer (MS-DOS environment) by the actual network [8].

4 Conclusion
In this paper it explained how, with the integration of expert systems and finite element tools, it can be possible to optimise the design of a product by utilising a solid modeller. By allowing artificial intelligence to use qualitative reasoning as opposed to numerical reasoning, tasks can be performed more efficiently and therefore require much less computation time. Expert systems provide a powerful tool for engineering design that allows both novice and experienced designer to operate at a similar level of competence by using qualitative and quantitative support during the design cycle. Furthermore, with the integration of such expert systems with a CAD/CAM/CIM package, a fully integrated
design system can be achieved, following the concurrent engineering philosophy. The Total Design System will hence reduce the interaction between the user and the software to perform an accurate and rapid optimisation of the design and the manufacture.

References


Figure 1: The Total Design System.

Figure 2: Interface and Compatibility.