INTELLIGENT ANALYTICAL AIDS IN DESIGN
Decision Support to Engineering Analysis Process

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Abstract: Analytical aids represent a group of the most widely applied intelligent computer systems for supporting design process. Such systems capture the expertise of a specialist in the application of a design technique – for instance in the development of an analytical model, in the forming of assumptions or in the interpretation of results. An example discussed here is an "expert" aid to be applied within structural analysis using finite element method. The system is constituted from three modules, one for finite element selection, the other for finite element mesh design and the third one for results' interpretation.

1 INTRODUCTION

Analysis-based design optimisation is an integrated part of the design process for many components. Moreover, computer aided structural analyses are so extensively applied within design process that analysts are no longer the only specialists dealing with this issue. Designers have to carry out different types of analyses very frequently themselves.

However, the existing conventional computer aided design (CAD) tools are not adequate as a proper aid to be used by designer in the process of analysing a new product. Instead of being oriented particularly in mathematical aspects of the analysis, they should provide a continual stream of advice and information to assist in decision-making. For example, CAD system can be used as a powerful computer graphic tool for developing an idealised model for the analysis, but it would give no advice on what type or density of idealisation is appropriate for the particular design case. For this reason, the quality, effectiveness and reliability of the structural analysis-based design optimisation still depends mostly on the level of designers' knowledge and experience.

The way in which it is hoped to get more intelligent computer support to structural analyses-based design optimisation is to increase the intelligence of the existing CAD systems. In order to do that, some intelligent modules need to be developed and integrated into the analysis process. Analytical aids represent a group of the most widely applied intelligent computer systems for supporting design process.

Such systems capture the expertise of a specialist in the application of a design technique – for instance in the development of an analytical model, in the forming of assumptions or in the interpretation of results.

An example discussed here is an "expert" aid to be applied within structural analysis using finite element method. The system is constituted from three modules, one for finite element selection, the other for finite element mesh design and the third one for results' interpretation.

2 ANALYSIS-BASED DESIGN OPTIMISATION

The purpose of structural design analysis is to simulate and verify the conditions in the structure, as they will appear during its operational life. Physical and mathematical modelling simulations are computationally intensive but offer immense insight into developing product. The results of structural engineering analysis are often basic parameters for design optimisation process.

The analysis' results can confirm the design candidate, but this is very rare at the first attempt. Mostly, the results show that the structure is under-

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or over-dimensioned. An under-dimensioned design needs to be improved and changed, because it will most certainly break. On the other hand, design changes are unnecessary for over-dimensioned structures, although they should be carried out unless the improvement / optimisation process is financially unsound, costing more money than the customers are prepared to pay. In that case, the calculated displacements and stresses in the structure simply need to be within the allowable limits. Where design improvement is needed, certain design changes should be applied, such as the use of another material or geometry modification.

Nowadays, the results of the structural analyses are usually very-well presented. The analysing software is very helpful at this point, as it offers adequate computer-graphic support in terms of reasonably clear pictures showing the distribution of unknown parameters (for example: stresses, deformations, temperatures) inside the body of the structure.

The definition of the design material also defines the allowable values for stresses / deformations / temperatures, which should be specified by the materials' supplier. When the computed values exceed the allowable limits in some critical areas, design improvement is necessary. Thus, when the analysis is concluded many questions need to be answered in order to come to the correct decisions.

However, a lot of knowledge and experience is needed, first to prepare the correct idealised model for numerical analysis, and second to be able to understand the results of the analysis and to choose necessary design optimisation steps (Ong and Keane, 2002).

Young inexperienced engineers often do not understand basic principles of the structural design analysis and make wrong conclusions quite frequently. They even have problem to see whether the results are within expected limits considering the original problem. In most of such cases, the existing software cannot help them, as the support provided by geometry-based CAD systems is limited, mainly because of the wide semantic gap between geometry's expressive power and the abstract features of a product (Mili, Shen, Martinez, Noel, Ram and Zouras, 2001).

Thus, very extensive, time consuming and expensive analysis often become meaningless. Moreover, as a consequence of wrong problem definition or miss-interpretation of the results of the analysis, the structure may even break down during its exploitation. The experiences gained by many design iterations are of crucial importance. When considering this, an intelligent support is needed in this phase of the design process. In order to provide this support, the knowledge and experiences need to be encoded in an intelligent advisory system to help the designer to perform analysis-based design optimisation process.

3 FINITE ELEMENT ANALYSIS

Finite element method is the most frequently used numerical method to analyse stresses and deformations in physical structures (Zienkiewicz, Taylor and Shu, 2005). Finite element analysis (FEA) is divided into three phases:

- pre-processing phase of the analysis
- matrix calculation
- post-processing phase of the analysis

Usually, FEA software is divided into three modules, each dedicated to one phase of the analysis. The reliability and accuracy of the results are strongly related to the overall quality of the analysis process. Thus, every phase of the analysis is important and has to be performed carefully and consistently.

3.1 Pre-processing Phase of the Analysis

In the pre-processing phase of the analysis, the real structure has to be idealized with the appropriate mesh model that ensures low approximation errors and avoids unnecessary computational overheads. For that purpose, the correct finite elements need to be selected for the analysis and the appropriate density of the mesh needs to be defined.

Whilst many FEA pre-processors will automatically create the finite element mesh, such automatic creation still requires data, such as the type of the elements, the mesh density and the position and type of loads and boundary conditions to be applied.

The selection of finite elements is strongly related with the meshing task. The quality of the results derived by using inadequate type of element for a certain problem is usually very poor. The main differences between the elements are related to the basic polynomial approach and to the geometry of an element (Rieg and Koch, 2001)

3.2 Matrix Computation

After setting up the loads and boundary conditions, the matrix computation is performed to solve a system of linear algebraic equations determining displacements (and stresses) in the nodal points of the computational model. This phase of the analysis is the most optimised and the most user independent.

3.3 Post-processing Phase of the Analysis

In the post-processing phase of the analysis, numerical results have to be examined and correctly interpreted. Post-processing phase represents a synthesis of the whole analysis and is therefore of special importance. It concludes with the final report of the analysis, where the results are quantified and evaluated with respect to the next design steps that have to follow FEA in order to find an optimal design solution.

In spite the fact that the results are pretty well ordered, the numerical figures are hard to be followed in case of complex real-life problem, when the data file is usually both, complex and extensive. FEA software offers an adequate computer graphics support in terms of reasonably clear pictures showing a distribution of unknown parameters inside the body of the structure. However, the user still has to answer many questions and solve many dilemmas in order to conclude the analysis successfully.

4 INTELLIGENT SUPPORT TO DESIGN PROCESS

The application of artificial intelligence (AI) to design is generally concerned with studying how designers apply human intelligence to design, and with trying to make computer aids to design more knowledgeable. The part of AI that is particularly concerned with the development of such representations is known as decision support intelligent systems (Turban, Aronson and Liang, 2004).

Although the AI technology is still a subject of extensive research, many successful AI applications in real–life domains already proved the usefulness of these technologies when dealing with problems that are nondeterministic and as such cannot be treated adequately by using conventional approaches, unless the user is possessed of special skills and experience. It is becoming increasingly evident that adding the intelligence to the existing computer aids, such as CAD systems, leads to significant improvements of the effectiveness and reliability in performing various engineering tasks, including design. In this context, structural analyses are of special importance, representing a crucial part of the modern design optimisation cycle.

Actually, AI applications to design improvement process are reality and subject of intensive development and implementations. Proceedings of the international scientific conferences “AI in Design”, edited by J.S. Gero, constitute a good collection of papers related to this area (Gero, 2002), and some more recent developments can also be found in (Clarkson and Eckert, 2005).

Intelligent computer support to design may be classified into four broad groups, as follows:

- guiding inexperienced users;
- ‘automated’ design of particular products;
- intelligent analytical aids;
- intelligent “design for X”.

In this paper, our interest is oriented in the intelligent analytical aids for supporting FEA process.

5 INTELLIGENT FEA-BASED DESIGN OPTIMISATION

It order to support the designer in overcoming three major FEA bottlenecks (finite elements selection, finite element mesh design, and results interpretation) three separate stand-alone intelligent analytical aids (one for each task) are being developed in our laboratory.

First two KB modules are meant to be applied in the pre-processing phase of the analysis, when mesh parameters need to be set. The third KB module should support the post-processing phase of the analysis.

In continuation, basic architecture of the KB modules that should provide intelligent aid to FEA-based design optimisation process is presented.

5.1 Intelligent FE Type Selection

Nowadays FEA software tools offer to the user a wide range of different, but often also very similar elements. Even the elements that are meant to be used for the same generic type of analysis may have different geometric shape and polynomial function. Thus, selection of the most appropriate type of the elements to be used for certain analysis is a complex task that requires a lot of knowledge and experience.

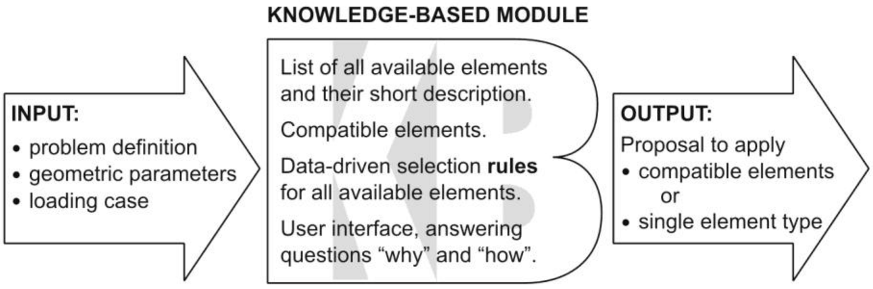

Figure 1: Knowledge-based finite elements selection.

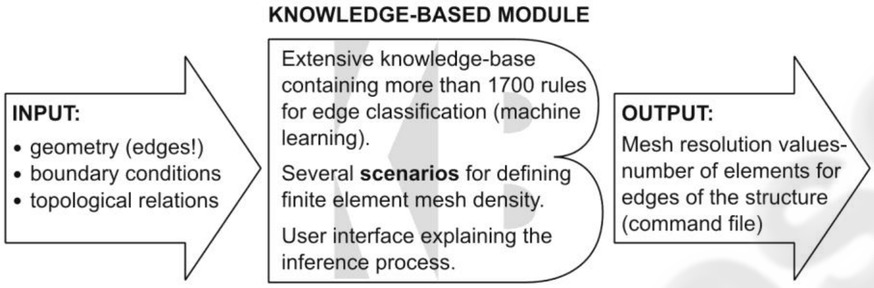

Figure 2: Knowledge-based finite element mesh design.

Most novice designers need advice to select the correct type of elements that ensures quality results at reasonable consumption of computing resources.

Figure 1 presents basic idea for the KB support to the pre-processing phase of the analysis. The proposed scheme has been realised by development of the KB system named Z88FESES (Novak, Rieg, Dolšak and Hackenschmidt, 2006), which is adjusted to the freeware finite element analysis program Z88 (Rieg, 2006).

The knowledge base comprises 24 data-driven production rules that are applied to select the appropriate finite element type out of the list of 20 different types that are available in the current version of Z88 program. The most appropriate type of finite elements is proposed by the system considering problem description given by the user, who needs to answer some questions interactively.

In current version of the system the selection of the most appropriate finite elements type to be used for the analysis is based on the following selection criteria: space dimension, dimension of the structure, cross-section (only for beams), the expected quality of the results, geometry, and loading case complexity. The way of adding the relation between the element type and the mesh density into KB finite element type selection process is still a subject of investigation.

The knowledge base was constructed manually after some interviews of the human experts. The Z88 user manual was also used as a source to construct the rules, as it contains a detail description of all available elements. A thorough presentation of the knowledge base can be found in (Novak, Rieg, Dolšak and Hackenschmidt, 2006).

5.2 Intelligent FE Mesh Design

Within finite element analysis usually a few different mesh models need to be created until the right one is found. The trouble is that each mesh has to be analysed, since the next mesh is generated with respect to the results derived from the previous one.

There is no clear and satisfactory formalisation of the mesh design know-how. Finite element design is still a mixture of art and experience, which is hard to describe explicitly. Defining the appropriate geometric mesh model that ensures low approximation errors and avoids unnecessary computational overheads is still very difficult and time-consuming task.

As alternative to the conventional "trial-and-fail" approach to this problem, we have developed the intelligent computer system named FEMDES (Dolšak, 2002). The system was designed to help the user to define the most appropriate density and pattern for the finite element mesh model. The

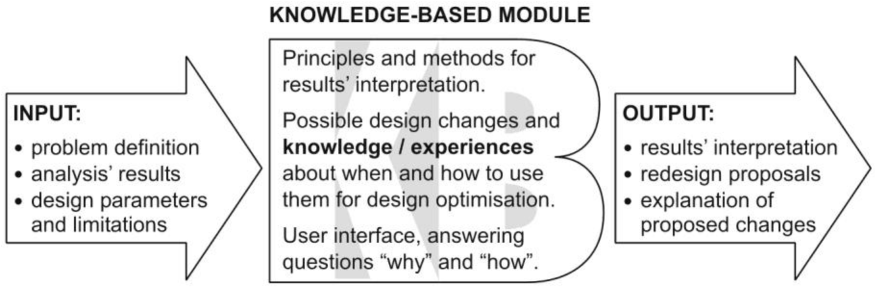

Figure 3: Knowledge-based analysis results' interpretation.

system application enables the designer to conduct the finite element mesh model easier, faster, and more experience independent.

For this system the knowledge base was constructed by using inductive logic programming algorithm Golem (Dolšak, Bratko and Jezernik, 1998). Machine learning techniques were used on numerous examples to develop more than 1700 classification rules.

Figure 2 shows the idea of this KB module application within the pre-processing phase of the analysis. In any case, the user has to define the problem (geometry, loads, and supports). The data about the problem need to be converted from the FEA pre-processor format into symbolic qualitative description to be used by the KB module.

The task of the intelligent system is to determine the appropriate mesh resolution values. A command file for the mesh generator can be constructed according to the results obtained by the intelligent system.

5.3 Intelligent Aid for Analysis Results' Interpretation

When numerical part of the engineering analysis is finished, designer has to be able to judge, whether the results of the analysis are correct and reliable, and decide what kind of design changes are needed, if any.

Most of the users need "intelligent" advice to perform the results interpretation adequately (Pinfold and Chapman, 2004). Unfortunately, this kind of help cannot be expected from the present software. The traditional systems are rather concentrated on numerical aspects of the analysis and are not successful in integrating the numerical parts with human expertise.

In order to support this crucial phase of the analysis-based design optimisation, a prototype of the intelligent consultative system PROPOSE has been developed (Novak and Dolšak, 2006).

PROPOSE provides a list of redesign recommendations that should be considered to optimise a certain critical area within the structure, considering the results of a prior stress/strain or thermal analysis.

As a rule, there are several redesign steps possible for design improvement. The selection of one or more redesign steps that should be performed in a certain case depends on the requirements, possibilities and on requests.

Figure 3 presents a basic idea for the KB analysis results' interpretation. The user has to define design problem and present the results of the engineering analysis. In addition, critical areas within the structure need to be qualitatively described to the system. These input data are then compared with the rules in the knowledge base and the most appropriate redesign changes are determined and recommended to the user.

The qualitative description of the problem area should be as common as possible to cover the majority of the problem areas, instead of addressing only very specific products. In cases when the problem area can be described to the system in different ways, it is advisable to run the system several times, every time with different description. Thus, the system will be able to propose more design actions, at the expense of only a few more minutes at the console.

At the end, the user can get the explanation how the proposed redesign changes were selected as well as some further guidelines how to implement a certain redesign proposal.

The knowledge base of the PROPOSE system is quite complex and was constructed by using different approaches for knowledge acquisition, including experts' interviews, study of literature and some project elaborations, etc. Development of the knowledge base is described in detail in (Novak and Dolšak, 2006).

6 CONCLUSIONS

Structural analysis-based design optimisation is a part of development process for almost every new product. Thus, it has very important role in nowadays high-tech world, where only optimal solutions can win the game on the market. However, development of the optimal analysis proven design solutions is very complex domain, which cannot be treated adequately by using the conventional CAD tools, unless the user is possessed of special skills and experience. The main reason for that lies in the fact that the present CAD tools are still mainly mathematically oriented and are not able to provide an adequate expert advice when some crucial decisions in product development process need to be made.

On the other hand, advanced computing applications are changing the way in which designers interact with computers. Knowledge representation formalisms and advanced reasoning techniques are no longer the sole territory of AI community. New approaches have earned acceptance in design sphere and have started to emerge in commercial software.

For this reason, many research activities are oriented in making analysis-based design optimisation process more intelligent and less experience-dependent (Chapman and Pinfold, 2001). Many experts share the opinion that it can be done by supplementing the existing CAD systems with some intelligent modules that will provide advice when needed.

The intelligent modules discussed here represent some crucial parts of the overall design optimisation cycle, where in addition to the structural analysis, some other design aspects, such as for example the ergonomics and aesthetics of the product (Kaljun and Dolšak, 2006) also play an important role.

The intelligent analytical aids in design that are presented in this paper have already proved to be very useful in the university education as well as in engineering practice. Some practical examples demonstrating the use of intelligent decision support in FEA-based design optimisation process are presented in references that are listed for each intelligent module discussed in this paper.

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