Applying Artificial Intelligence for Intelligent Design

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1. Introduction

Design activities are usually characterised by an iterative process in which designers set up a framework for their design and make several consecutive designs, taking into account problems or shortcomings of the previous designs. Computers are often used to perform the calculations. This iterative process has as main goal to improve the design and recover from earlier errors.

Over the last decade, the use of computers in design has evolved from performing problem analysis computations, to integrating several software packages and providing user interfaces. This changed role of computers relieved the user from several computer science related tasks, which are not directly related to the design domain.

In current design practice, however, the designer still has to keep track of the whole design process. All the steps involved to come to a proper well-balanced design have to be initiated by the designer, who will also interpret the results of certain calculations or evaluate the design.

With the current mature state of artificial intelligence techniques, a next step can be taken in which computers will assist designers in the actual design tasks. This again leads to a changing role of computers in design. The advantage of this development can be found in those situations where large and complex designs are created, when it becomes very hard for the designer to keep track of the whole design process.

Primary goal for designing is to be able to focus on the more intelligent and creative design issues of his design problem, rather than having to manage the computer aided design tools. Artificial intelligence will not be used to perform the design tasks autonomously, but in a supporting role to handle more routine tasks of the design process, such as non-procedural reasoning about the design, reasoning about examples, generating a preliminary design, evaluating qualitative and quantitative constraints, etc.

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Incorporating artificial intelligence techniques in design activities may lead to drastic changes in industrial environments. The design time will be used more efficiently, leading to a reduction in design time and a more cost effective approach to design to manufacturing.

2. Current Design Practice

A typical design process follows several steps (see Netten et al. 1993). In a first step, the designer identifies feasible concepts by recalling designs from experience that (partially) fulfil the set of initial specifications, which consist of both strict numerical and more imprecisely described requirements. While evaluating designs, all specifications are treated as qualitative relations with respect to design decisions. In the following steps, the qualitative description of the design is to be translated into a (quantitative) numerical formulation. First an initial design is modified for the current specifications, which are verified with numerical analysis routines. In the next steps numerical optimisation routines are applied to improve the consecutive designs.

In the final step, the resulting design is evaluated for its applicability in the following life cycle, from which additional questions arise. It is impossible for a designer to oversee all consequences of choices made for the qualitative model of the design in the first steps. The outcome of the optimisation might not be what was expected. Obviously the specifications were incomplete and a reformulation of the qualitative model of the solution may be necessary. Even more, as the designer's knowledge is restricted to only a few domains, other problems might be found during the following detailed design and production stages. The design has to be changed again, which can usually only be done at high costs. Most design problems are only noticed after optimisation, but could have been foreseen in a qualitative evaluation beforehand.

Numerical optimisation routines in general cannot guarantee to locate global optimal solutions. This applies for the optimisation of sub-components as well as for the entire design. To avoid the enormous computations involved in numerical optimisation, usually a heuristic approach is followed in which the designer improves the design gradually, based on his knowledge and experience.

3. Artificial Intelligence and Design

Although artificial intelligence has been in the spotlight since the 1950's, it was only during the 1980's that such progress was achieved that it became feasible to apply these techniques to engineering problems, such as fault monitoring and diagnosis, process control and design. Expert systems, emulating reasoning processes, form the most well known result of artificial intelligence research. When implemented in a proper manner, these systems can even outgrow certain aspects of human performance, because computers can handle larger amounts of information faster and more consistent than humans. Moreover,

knowledge from several experts can be added to an expert system and used to the advantage of the reasoning process.

Artificial intelligence has left the laboratory stages and has become available for mature engineering applications. However, many in the technical world see artificial intelligence as a variety of techniques used for a wide range of small practical or academic applications, without any apparent coherence between application domain and techniques used. It is almost impossible to model any real-life application into one single technique. Implementation and maintenance of the knowledge then become complicated. Achieving completeness and maintaining consistency of the knowledge base pose additional problems. As a consequence, selection of and familiarisation with the most suitable techniques become unnecessarily penalised, resulting in denial of artificial intelligence for engineering applications in general. The artificial intelligence academic world tends to focus on dedicated topics and simplified example problems. Real-life problems of integration with existing software and knowledge representation tend to get less attention. It is only since recently that hybrid artificial intelligence systems receive more attention.

The preliminary design involves handling both qualitative and quantitative specifications and constraints. Solving design problems numerically consequently involves a quantification of the qualitative relations. These quantifications are only valid in a limited area of the design space and have to be adjusted occasionally based on the results of previous numerical analyses. Due to this highly qualitative character, the design problem cannot be solved using numerical methods only. These qualitative aspects may turn out to be equally important for the final solution as the quantitative constraints. Nevertheless, only numerical design and analysis software has reached a high level of development and is widely used. Qualitative knowledge of different design and life cycle stages is available through literature or the experience of domain experts and can be made available for optimisation. By comparing these experiences, a better founded initial solution can be generated in the conceptual design phase.

A designer recalls solutions and uses rules-of-the-thumb to create and improve designs. Both historical solutions (design cases) and rules are inherently discrete in nature. Cases and simple rules represent occasional solutions (shallow knowledge). Deeper knowledge and analogies are represented in rules and numerical functions (simple theoretical models or approximation methods). The required design knowledge can be obtained from different sources, all of which offer information from a particular point of view, but none of them providing a complete overview on one subject. Due to the diversity in which knowledge is available, no unique form of representation can be used.

- Specifications or constraints can be represented numerically in functions, or else in rules or tables.
- Experience can be either expressed explicitly in rules or functions, or implicitly as individual solutions in form of cases.
- Test results from reports can be either expressed in empirical formula's or as individual exemplar cases.

Most applications in literature address only one design sub-task for which only one artificial intelligence technique is used. The use of separate software tools offers only a limited aid to the designer, who remains responsible for developing the design strategy, including relevant information and judging the relevance of the results at each stage. Integration of all domain information is proposed in concurrent engineering (Ramana Reddy et al. 1993). An important item in concurrent engineering is information sharing, which addresses three major problems of hardware integration, commonality in data representation, and integration of foreign information systems. Assuming all these problems would be solved, much of the required information would become available from which the designer can abstract the relevant knowledge.

Experience, heuristics, and theoretical methods differ in every design task. For each task, abstractions of knowledge have to be made for the data as well as for the relations and a different strategy with specific methods should be build. The knowledge should be made available to all other design tasks as well, to compensate for the lack of knowledge in any of the individual tasks. A new general design strategy should be developed in which different inference techniques and knowledge representations can be used for specific design tasks.

4. A general framework for expert assisted design

A general framework is presented for engineering design incorporating artificial intelligence techniques. The three different techniques that lie at the basis of the approach will be briefly introduced below, to stress the specific functionality of each.

Constraint-Based Reasoning

Reasoning over relations, or constraint-based reasoning (Guesgen and Hertzberg 1993), can be applied to evaluate the possibilities for design decisions for qualitative and quantitative relations. The design variables within constraint-based reasoning can take values from a set, which can have either numerical or linguistic values. Within constraint-based reasoning several different techniques exist to reduce the set of possible values per design variable. The values of the variables drive the reasoning and determine the feasible solution space, therewith simplifying the remaining problem. The power of applying constraint-based reasoning lies in making implicit information from the specifications explicit, without performing large numerical design analyses.

Case-Based Reasoning

Case-based reasoning (Riesbeck and Schank 1992) uses previous experiences to guide the problem solving. It allows to focus on features of the specifications, which were experienced as important in solving a similar type of design problem before. Cases with similar features to the current problem are

retrieved from memory; the best cases are selected and modified for the new specifications. The essence of case-based reasoning is that implicit design knowledge can be used directly for the design process.

Expert Governed Numerical Optimisation (EGNOP)

The ensurance of a proper convergence in non-linear numerical optimisation often poses problems. At different stages of the optimisation different methods yield an optimal convergence. Also within a specific method, the values of the operational parameters also have to be adjusted frequently for an optimal convergence. This has led to a completely new approach for numerical optimisation (Vingerhoeds et al. 1991; Vingerhoeds 1992). Expert governed numerical optimisation controls the optimisation continuously using a multi-layered rule-based expert system structure. This comprises the choice of a method and the on-line tuning, both depending on the progress of the optimisation. As a result, the optimisation is made more robust, the performance has increased and it allows autonomous operation.

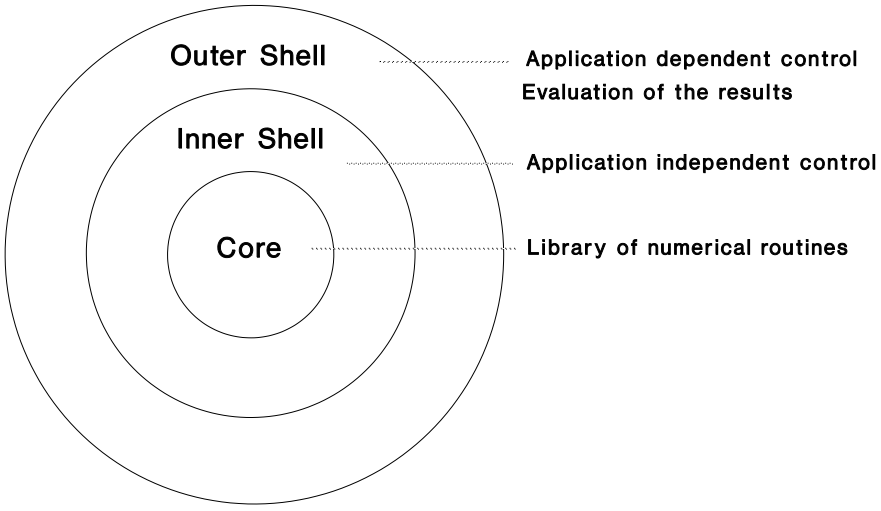

Figure 1 The multi-layered EGNOP structure

The proposed solution does not imply usage of any one of the previously mentioned techniques alone throughout the whole design process, but rather the use of specific techniques for those tasks they are most suited for. The design process comprises three general consecutive phases (see figure 2).

Propagation of specifications to limit the design space.
Starting from a small number of initial specifications, the solution space can be reduced using constraint-based reasoning techniques. The user specifications determine which constraints in the constraint network are relevant. The remaining sets of variables from the constraint network define the feasible and practical design space on a merely qualitative basis.

Find a region of optimal solutions
Within the reduced design space, the area around the optimal design can be distinguished using case-based reasoning techniques. Previous designs and examples, stored in a case-base, can be retrieved based on (partially) matching specifications. Common features of the retrieved cases can be regarded as typical for the optimal solution, while differences in features indicate the yet unresolved design decisions, and alternative solutions should be formulated for each. To satisfy the specifications, retrieved cases will have to be modified in a rule-based system.

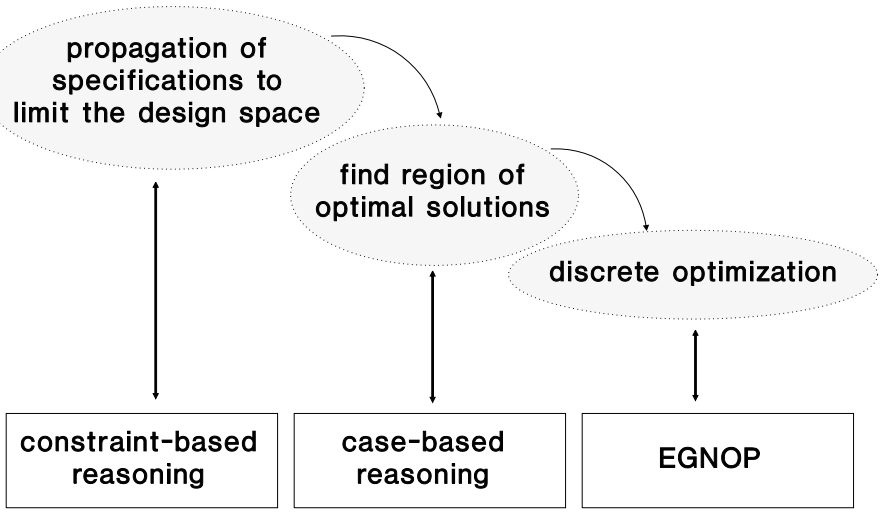

Figure 2 General flow of the concept

Until now, no numerically analysis has been performed. Consequently, no problems were encountered for discrete numerical formulation of the problem. The remaining problem is to optimise the design. This optimisation problem is strictly quantitative in nature.

Discrete optimisation

For the discrete optimisation, the EGNOP-concept is applied. The numerical optimisation problem is formulated from the modified solutions, where features are translated into analysis formulations, constants and design variables. The first task is to select the best solution for further optimisation. The features of the alternative solutions may provide the designer with some insight in the design space around the optimal solution. The selection and the following improvement phases of the design are performed interactively with the designer. Whenever appropriate, the user can stop inference, to examine the previous steps and to suggest improvements. Discrete optimisation should preferably be done by heuristic optimisation. Large numerical analyses should only be applied as verification of the design in the final design phase. Heuristic optimisation consists of 2 steps (see Netten et al. 1993); repair phase to recover from constraint violations and the improvement phase for minimisation within the feasible region.

The proposed concept allows incremental development of a knowledge based system on top of available numerical analysis and discrete optimisation routines. Numerical routines are incorporated within the general EGNOP-structure, while the other knowledge bases are constructed as separate modules within the system, governed by a meta-level strategy. Other artificial intelligence techniques can also be included within the general structure of the system.

The knowledge inhibited in different knowledge bases and numerical routines is complementary. Therefore, it is not necessary to incorporate the complete knowledge about the domain in any of the subsystems. Modelling the knowledge of different sources is no longer restricted to a single representation form. The different techniques described allow new knowledge to be added in any appropriate format.

5. Practical applications of the concepts

Practical applications with EGNOP as optimisation tool

The EGNOP-concept has been applied in several domains.

- In (Vingerhoeds 1992) applications have been described for configuring flight control laws for aircraft.
- In (Netten et al 1992) an in-depth discussion of an application in economic design support is given.
- A structural design application of EGNOP has been realised (Netten et al. 1993), which serves as starting point for the larger design framework. Structural analysis is performed by the Sapano-program (van Bladel 1992).

Expert assisted Design of Aircraft (EDA)

The previously described design framework will be applied on two different domains.

- Design of composite reinforced sandwich panels (Netten 1994). This is a first application of the concept, based on previous work.
- Full-scale application of the concept for generating conceptual designs of aircraft (EDA-project) is described more in detail below.

Designing aircraft is a multi-disciplinary process, including several development stages. From the earliest stages of conceptual design, several aspects have to be taken into account in a well-structured manner. These aspects include flight performance, flight characteristics, operations, manufacturing, maintenance, etc. Based on the design framework, a front-end design system will be developed in co-operation with the Faculty of Aerospace Engineering.

6. Conclusions

The use of artificial intelligence techniques for engineering design allows for a completely new approach to design. In essence, the design procedure is now approached from the opposite side. Many aspects that could only be taken into account after initial designs were generated, are now being used actively from the start to reduce the solution space and to define the conceptual design.

The framework proposed here allows for a search directed towards solutions without using numerical global optimisation techniques. The solutions, which are used for inferencing, are based on all specifications for design, production, maintenance and operation, and are generally accepted as good and practical. Both quantitative and qualitative knowledge is included. Different artificial intelligence techniques are applied to facilitate the representation of knowledge available from different sources and to enable qualitative reasoning and heuristic optimisation prior to numerical optimisation. The artificial intelligence techniques incorporated focus on standard numerical and heuristic tasks, allowing the designer to fully concentrate on the conceptual design.

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