Expert Assisted Conceptual Design
An Application To Fibre Reinforced Composite Panels

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1. ABSTRACT

An artificially intelligent approach to conceptual design, from initial problem specification to the generation of a good concept, is presented and applied to thin-walled fibre reinforced composite panels for aerospace structures. Conceptual design is a creative and multi-disciplinary process for which numerical computer aided design tools are not sufficient. Specifications comprise both quantitative and qualitative objectives and limitations. Due to the diversity in application of a design system, specifications, and in experience and preference of designers, there is not a predefined procedure for this design process. However, three consecutive design tasks are distinguished.

The first task is to propagate the specifications to limit the design space. Constraint-based reasoning is used to assemble prototype concepts for the specifications on qualitative behavioural relations. The second task is to find the region of optimal and practical designs. Case-based reasoning is used to retrieve exemplar concepts for the prototypes. The third task is to heuristically optimise retrieved concepts for the current specifications. Rule-based reasoning within the concept of Expert Governed Numerical Optimisation (EGNOP) is used to modify the concepts according to explicit heuristic rules. Once a good initial concept is obtained and quantified that satisfies all the qualitative specifications, existing numerical design tools can be applied.

The approach is developed as a supporting tool for the designer, that performs more routine-like reasoning and suggests decisions to the designer. The approach enables multiple knowledge representation techniques and multiple inferencing techniques to more adequately model the domain knowledge and design process.

2. CONCEPTUAL DESIGN OF FIBRE REINFORCED COMPOSITE PANELS

Over the last decade, the role of computers in design has evolved from performing numerical calculations, to integrating several software packages and providing adequate user interfaces. This role of computers relieved the user from certain more computer science related tasks not directly related to the application. 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 well-balanced design have to be initiated by the designer, including the interpretation of the numerical analysis results, evaluation of the design and modification of the concept.

Advanced structural analysis and optimisation tools already exist and are continuously being improved. Sapano, developed by (Van Bladel 1995), is for example a conceptual design tool for thin-walled fibre reinforced composite sandwich panels for application in aerospace structures. Similar tools have been developed for other types of panels as well. These tools are entirely based on the numerical analysis of panel structural behaviour and are very well suited for discrete numerical optimisation of a good initial panel design. Once an optimal panel is obtained with one of these tools, further detailed design and analysis can be performed by means of more extensive tools, such as finite element analysis systems.

Numerical conceptual design tools are only applicable for a specific type of panel and can only evaluate a limited set of behavioural constraints, such as the strength and stiffness. The specifications, however, comprise more than the requirements for structural behaviour. Comparison of different types of panels for the given specifications can be done afterwards, when different panel concepts have been designed to some extend. Only experienced designers could make an initial comparison between different panel concepts for different specifications beforehand.

The behavioural phenomena of panels cannot always be formulated numerically. More practical operational requirements for example, are typically specifications that can only be evaluated in a more qualitative manner, but are as important for success of the final product as the numerically formulated structural requirements for strength and stiffness. Many of these practical specifications should be considered during the development of a concept for the initial panel design.

In practice however, these more practical objections on the concept of the panel design are frequently discovered after preliminary analysis or optimisation of the design, or even later in the design process. During the design process, additional choices are made on specific designs that can be added to the set of specifications. In a new iteration, the concept for the panel has to be adjusted for the extended set of specifications, and the analysis and optimisation have to be repeated.

On top of the iterative loops of design for the numerically formulated behavioural constraints of the types of panels, an additional iterative loop is used to evaluate the different panel types with respect to all specifications. This upper level iterative process is to recover from previous shortcomings in the panel concepts or in the specifications. This iterative process is currently performed entirely by the human designer without support of computer tools. The resulting concept therefore depends heavily on the skills of the designer or design team.

Many of the qualitative considerations are well-known and could have been foreseen if the designer had thought about it. An artificially intelligent computer aided conceptual design system is needed to notify these well-known preliminary considerations to a designer before the numerical design phase is entered.

3. REVIEWING CONCEPTUAL DESIGN

Typically, the first goal in a design process is to obtain a prototype for a panel concept; an abstracted description in terms of classes of design elements, e.g. the type of panel structure, the type of laminate lay-up and the type of composite materials used in the outer and inner layers of the laminate (see Figure 1).

Obtaining a good initial concept for a panel is largely decisive for a number of critical decisions in the following design phases and the final panel. The type of concept also determines what tools are to be used for further design. The "goodness" of the initial concept therefore determines the convergence and the number of required analysis for optimisation. Especially for discrete numerical optimisation, the initial design is largely decisive for the obtained result, because usually the global convergence cannot be guaranteed.

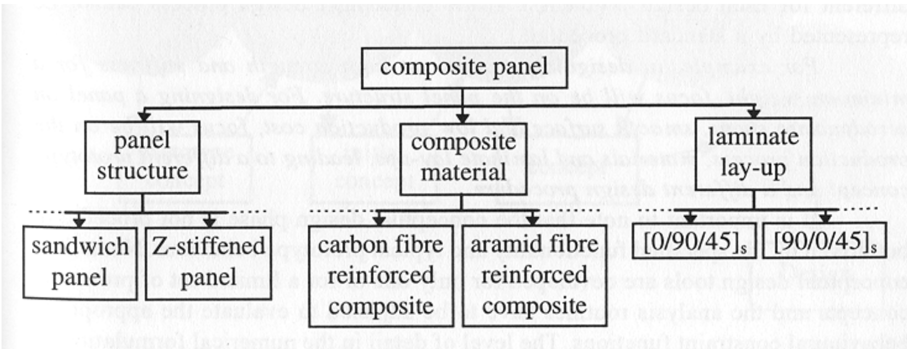

Figure 1: **Breakdown of a panel prototype in design elements**

The designer has to evaluate the specifications; the set of design objectives, hard and soft functional requirements for behavioural constraints, predefined design parameters and bounds on design parameters. The specifications define the required functionality of the panel.

For composite panels for example, many different design objectives can be defined with respect to weight, flutter, impact resistance, maintainability, etc. One of the most important functional requirements concerns the loadcases to be applied on the panel during different operational phases. Different environmental conditions could apply for the operational phases with consequences for material behaviour.

In the context of composite structural design, the term structure is confusing with the terminology of *function - behaviour - structure* as used in functional modelling. In this paper, the term concept or design represents the *structure*, the specifications describe the required *functionality*, and the design elements show typical *behaviour*.

Variation in the specifications is expected to be large as a result of the wide applicability of composite panels. The designer tends to focus on the most stringent specifications (constraints and objectives) to make a first selection for the best prototype concept. The designer assembles a prototype for a panel concept by selecting design elements and qualitatively evaluating the combinations of the elements with respect to the specifications. Less stringent specifications merely serve to fine-tune the prototype. The specified functionality determines the hierarchical ordering of the goals for the current conceptual design procedure.

Design elements are described by a typical subset of the design parameters and can be characterised by a typical behaviour with respect to the design objectives and functional requirements. The relevance of design parameters depends on the panel types, constraints and objectives. The dependency of design parameters is different for each design problem, and the conceptual design process cannot be represented by a standard procedure.

For example, in designing a panel on high strength and stiffness for a minimum weight, focus will be on the panel structure. For designing a panel on aerodynamic shape, smooth surface and low production cost, focus will be on the production process, materials and laminate lay-ups, leading to a different prototype concept and a different design procedure.

It is important to note that the conceptual design phase is not procedural, but driven by the specified functionality and typical prototype behaviour. Numerical conceptual design tools are developed for only one or for a limited set of prototype concepts and the analysis routines have to be adjusted to evaluate the appropriate behavioural constraint functions. The level of detail in the numerical formulation of a design in such tools is too high for the first stages of conceptual design. In practice this implies that different design tools are to be used for different prototype concepts. In every design process, the designer iteratively "learns" where and how to find good and practical solutions. The empirical knowledge that can be acquired from design experts and other sources, is therefore declarative, inconsistent and incomplete.

Even though a predefined procedural order is not followed, a logical order in design tasks can be recognised (see Netten et al. 1993). Three main tasks in conceptual design, preceding the numerical optimisation and further design, can be distinguished, in function of the incremental development of a conceptual design (see Figure 2):

1 Propagation of the specifications to limit the design space.
2 Finding a region of optimal and practical designs.
3 Heuristic discrete optimisation.

A translation of the specifications onto the design space in terms of prototype concepts must be made first. The prototype concept represents a part of the design space where the (local) optimal design can be expected.

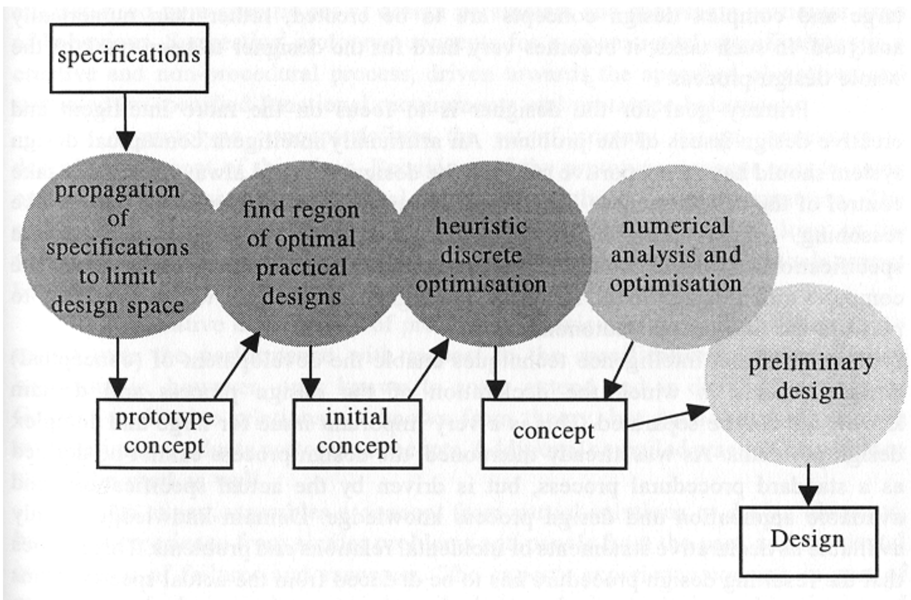

Figure 2: **Conceptual design strategy**

The next task is to provide the designer some insight in this design space and to indicate where to find the best designs within this region. At this stage, there is no information available to represent quantitative relations for the constraints on the discrete design space. However, previous panel designs for similar problems give some indication of possible solutions and problems in this design space.

The third task is to heuristically optimise such example designs for the specifications. At this stage not all specifications can be quantified and only heuristics can be applied to modify the example designs into good initial concepts. Once all parameters of the initial concept are assigned and all qualitative specifications are satisfied, numerical optimisation tools, like Sapano, can be applied.

4. OBJECTIVES FOR ARTIFICIALLY INTELLIGENT CONCEPTUAL DESIGN

With the current state of artificial intelligence techniques, a next step in the evolution of computer assisted design can be taken in which computers will assist designers in the conceptual design tasks. This leads to a changing role of computers in design. The advantage of this development can be found in those situations where large and complex design concepts are to be created, rather than numerically analysed. In such tasks, it becomes very hard for the designer to keep track of the whole design process.

Primary goal for the designer is to focus on the more intelligent and creative design issues of the problem. An artificially intelligent conceptual design system should have a supportive role and the designer should always be able to take control of the design process. The design system should perform more routine-like reasoning, suggest possible design elements and prototype concepts for the specifications, evaluate modifications suggested by the designer, and manage the computer aided design tools. Artificial intelligence techniques will *not* be used to perform the design tasks autonomously.

Artificial intelligence techniques enable the development of (conceptual) design systems in which the declaration of the design process and domain knowledge can be separated. This is a very important issue for large and complex design problems. As was already mentioned, the design process cannot be defined as a standard procedural process, but is driven by the actual specifications and available application and design process knowledge. Domain knowledge is only available as declarative statements of incidental relations and problems. This implies that the resulting design procedure has to be deduced from the actual specifications and the available knowledge.

Artificial Intelligence techniques are characterised by different inferencing techniques and by different knowledge representations. The form in which the knowledge can be acquired, determines the representation to be used. The design task, reasoning process and knowledge representation determine what inferencing technique is most appropriate. The proposed solution does not imply usage of any particular AI-technique alone throughout the whole design process, but rather the use of specific techniques for those tasks they are most suited for.

The conceptual design process for this application comprises three general consecutive tasks, performed by three different techniques: constraint-based reasoning, case-based reasoning and Expert Governed Numerical Optimisation (EGNOP). These techniques are embedded in a meta-level rule-based system that controls the design process, data flow and user interaction. The realisation of the three identified design tasks, will be described in the following three chapters.

5. PROPAGATION OF SPECIFICATIONS FINDING A PROTOTYPE CONCEPT

A prototype concept represents a class of conceptual designs and can be characterised by a specific set of design parameters and showing a particular kind of behaviour. Suggesting prototype concepts for a given set of specifications is a creative and non-procedural process, driven towards the specified objectives and restricted by specified functional requirements and prototype behaviour.

A prototype concept defines the set of primary design parameters to describe a concept of this class. Behaviour of the prototype concept can, to some extend, be expressed in numerical functions of these design parameters. The numerical functions are available in the numerical design tools. As long as the values of the design parameters are not assigned, these numerical design tools cannot be used.

Qualitative descriptions of prototype behaviour are therefore necessary to reason over the performance with respect to the specifications. The qualitative behaviour is, however, only known to some extend and is difficult to acquire. General qualitative relations are known from theory, but do not provide enough information to evaluate prototype concepts. Additional compiled practical experience should be used as well.

An expert assembles a concept from partial solutions or design elements, based on experience from similar problems and panels from the past, and incidental occurrences of failures and successes. The expert's experience consists in part of examples of design elements, described by obtained design objectives and restrictions, design parameters and interaction with other design elements. The design element can be regarded is a qualitatively described part of the design space, and behaviour of the design element is this design space. From this experience, subjective and abstracted behavioural relations are built up as heuristics.

For example, sandwich panels are not efficient for high panel loads and relatively high buckling conditions. Aramid fibre reinforced materials are not efficient to carry compressive loads. Here, the efficiency is measured for the objectives, such as a minimum weight.

These heuristics are qualitative declarations of individual behavioural relations of a design element in terms of indicative design parameters or parameter expressions. Qualitative interpretations of the values of these parameter expressions are used to classify the behaviour of the design element with respect to the specifications.

For example, buckling behaviour is a very important criterion for relating specifications to panel structures. Different modes of buckling can be identified for different panel structures. For each mode of buckling and each panel structure, parameter expressions can be identified to indicate buckling behaviour. The expressions for buckling contain parameters such as the panel loads, dimensions and stiffness. Whenever the value of such an expression for the current specifications lies within a certain interval, the panel structure can be applied efficiently for the specific behavioural relation. Other expressions are also important for determining the overall efficiency of a panel, such as the loading index.

These qualitative heuristics can be used a-priori to identify primary design parameters, expressions and behavioural relations for a design element. The parameter expressions can be used to classify qualitative behaviour of panel types in function of the specifications and other design elements. A qualitative behavioural constraint can be compiled from all similar relations for other design elements, stating the applicability of these design elements for this behaviour in function of the actual specifications.

An expert searches for design elements for which the typical behaviour best resembles the most stringent specifications. These specifications are regarded as constraints on and objectives for the design space. Each design element represents part of this design space that is further constrained by the element's typical behaviour. Wherever possible, the constraints of a design element are fitted to the current specifications. Undesired behaviour has to be corrected by adding other design elements. The mutual interaction and overall behaviour are to be fitted to the current specifications. The prototype concept can then be assembled from the best fitting design elements.

The functional requirements of the actual problem should be posed onto the constraint relations as the required behaviour of design elements in the prototype concept. In other words, the specifications determine the qualitative values of the parameter expressions in the behavioural constraints, and thus the relevance of the design elements with respect to the current design problem.

The design elements are the variables in the process of assembling a prototype concept, and therefore the variables in the constraint relations. Design elements are expressed in the primary design parameters. As parameters may appear in different expressions and behavioural constraints, the design elements also appear as variables in different behavioural constraints. A constraint network results, for which prototype concepts can be obtained by applying constraint-based reasoning techniques (see Guesghen and Hertzberg 1992).

For a given design problem, the feasible region in the design space is determined by the constraints in the network for the given specifications. The design elements are "pushed" through the network of behavioural constraints, and will result in the set of "feasible" prototype concepts as the tuples of feasible design elements.

Domain knowledge is stated in the constraints as declarations of heuristics and qualitative behavioural relations. The network structure results from the dependencies of the constraints on primary design parameters. The actual specifications determine the actual dependencies, and the design procedure is generated at run-time by following the dependency links in the network structure. The design process knowledge for this phase is not declared explicitly, but can be deduced from the domain knowledge.

The "feasibility" of the prototype concepts depends on the accuracy of the qualitative constraints and is only regarded as an indication for the efficiency of prototype concepts. Note that only a rough approximation of the behaviour is expressed in these constraints. The purpose of these constraints is only to provide a means of indicating which design element can be applied best in a prototype concept, and not necessarily to exclude other design elements. Qualitative behaviour of design elements and prototype concepts is not exclusive, only further detailed analysis can provide a solid motivation for the behaviour.

In conceptual design, it is likely that only a limited number of the primary design parameters is initially specified. Missing parameters can be prompted to the user for further specification, otherwise all possible design elements are maintained. It may occur that specified design parameters are conflicting with previously obtained "feasible" design elements. Trade-offs or relaxation of the constraints then becomes necessary. Alternatively, the user might adjust some of the specifications.

The domain knowledge contained in the constraints is not expected to be complete and fully consistent and therefore, the designer is expected to make final decisions. In conceptual design different approaches and preferences can be recognised among experts. Incompleteness of constraint declarations prohibits the restriction of certain design elements from prototype concepts. This may result in the generation of too many prototype concepts, that have to be eliminated during later stages of conceptual design or by the designer. Inconsistency is difficult to detect, as the constraints are rough approximations of the physical relations and their validity largely depends on the current problem. Inconsistencies are most likely detected during operation and from feed-back of results during later design tasks.

The generated prototype concepts are by no means restrictive, but only serve as an indication for good possible solutions. The designer should always be able to suggest new prototype concepts to be evaluated by the system. Complementary knowledge acquired from other sources following design tasks can be added to the existing knowledge bases.

6. FIND A REGION OF OPTIMAL DESIGNS OR FINDING AN INITIAL CONCEPT FOR A PROTOTYPE CONCEPT

In the first step, one or more prototype concepts have been suggested that are expected to provide the best concept for a panel design for the current set of specifications. Each prototype in itself, still represents a considerable part of the design space, and the next step for the designer is to find a good initial concept.

The design space for a prototype concept is described by the assembly of design elements, primary design parameters and the qualitative behaviour. The primary design parameters for the design elements are to be assigned in this second design step.

Primary design parameters for a panel, for example, can be the bending stiffness coefficients of the panel, and the orientation and materials of the plies in the laminates.

The primary parameters in the behavioural relations are highly interdependent and there are no direct and accurate relations to compute optimal values for these parameters in function of the specifications. In numerical routines, the relations are formulated in the opposite direction, to analyse behaviour for a given design. This design problem appears to be solvable only from practical experience.

The designers search for initial concepts by recalling previously designed panels for similar problems from the past as an example for the current prototype concept. Previously designed panels can be regarded as example cases, described by features for the design parameters of the panel, design objectives and behaviour. Features can be described in qualitative as well as quantitative values. A number of such cases can be stored in a case-base, which can be searched for this design task. This case-based reasoning approach is used successfully for other domains, see for example (Riesbeck and Schank 1989).

A concept can be obtained for the prototype concept by matching the cases against the specifications. The similarity of each feature with the specification of prototype concept can be measured. The degree of matching of a case depends on the similarity of all features with the current design problem. The method to measure similarity depends on the features, specifications and primary parameters of the prototype concept.

It is unlikely that the actual specifications will fully match an existing panel in the case-base, but several cases will partially match. Matching cases are retrieved from the case-base and an initial concept can be suggested by adapting these retrieved cases to the current specifications. Adaptation implies the inter- or extrapolation of design parameters to cover the differences in specifications. The similarity and the number of retrieved cases determine whether one initial concept can be interpolated from several retrieved cases or that multiple initial concepts are extrapolated for each retrieved case. Adaptation and other modifications are regarded as a heuristic optimisation.

7. HEURISTIC DISCRETE OPTIMISATION OR MODIFYING A CONCEPT

Those features that are common to all retrieved cases can be regarded as typical values for the initial concept, while differences in the features may indicate regions for optimisation. A set of a-priori defined heuristic rules can be applied to adapt the retrieved cases for a number of specifications. Due to the complexity and interdependence of the parameters, it is almost impossible to develop a complete model of the domain in a set of rules. The adaptation rules are therefore restricted to a set of well-known heuristics.

Depending on the similarity of the retrieved cases, one or more adaptations can be suggested, for which the effects on the specified objectives must be estimated. The retrieved cases and adaptations, with predictions on the objectives of the specifications, provide a set of well-motivated design options. From the set of options the most efficient adaptations can be selected and superimposed on the retrieved cases to obtain an initial concept.

The parameters of the initial concept have all values assigned and can be numerically analysed to verify the adaptations and estimated objectives. For numerical analysis, existing programmes can be invoked and the results can be used as feed-back to adjust the adaptation and estimation rules.

Analysis results may indicate that the initial concept can be further modified. If behavioural constraints are violated, the concept has to be repaired. Repair modifications can be suggested for each violated constraint. If the behavioural constraints are all feasible, the concept might be further improved. An improvement can be suggested in function of the margins on the behavioural constraints.

Repairs and improvements are similar to adaptations in that the accompanying modifications to a concept are in essence the same. In the current application, possible modifications are changes in the number, orientation and material of a ply.

Individual rules can be declared to determine possible modifications for each flaw; differences in functional specifications (adaptations), violations of constraints (repairs) or further improvements of design objectives (see Table 1). In such a modification rule for each flaw, any of the possible modifications (j) can be suggested in function of the difference (Δ). Generic rules can be declared to determine the effects of the actual modification (m) on the objective (o).

IF condition	*THEN suggest*
difference in specification $i = \Delta_{s\text{-}i}$ *violation of constraint* $i = \Delta_{c\text{-}i}$ *feasible margin on constraints* $i = \Delta_{m\text{-}i}$	*modification* $j = m_j(\Delta_{s\text{-}i})$ *modification* $j = m_j(\Delta_{c\text{-}i})$ *modification* $j = m_j(\Delta_{m\text{-}i})$
modification $j = m_j$	*estimated objective* $o = o(m_j)$

Table 1: **Generic modification rules in outer shell of EGNOP.**

The advantage of this approach is that all possible modifications are well-known, and the effects of a modification on the objectives can be analysed with numerical analysis routines or estimated from approximate relations. The design experience usually only expresses why, when, what and how to modify for a certain flaw in the concept. This design experience can now be stated in well-known and pre-defined modifications.

Another point of commonality in the three types of modifications is the method of suggesting all possible modifications to the designer and in making a selection. There is a natural hierarchy in the modifications. Adaptations are to be performed before repairs, and finally, if the concept is already feasible, it can be further improved. There exist several selection criteria for modifications, such as the severity of a flaw, the gain in design objectives and the number of flaws that can be solved with only one modification.

Several prototype concepts can result from the first design task. For each prototype concept one or more cases can be retrieved and for each retrieved case one or more adaptations can be superimposed. Each concept then can be repaired or improved with one or more modifications. In this way, the number of alternative solutions increases rapidly. Although autonomous heuristic rules can be applied to make selections in each of these situations, or to control a search process through these alternatives, the authors feel that for most decisions the designer is to be consulted to make the final selection.

All modifications so far are based on heuristic rules and for this application concern only discrete design parameters. The heuristics are used extensively to obtain the “best” initial concept before turning to numerical optimisation. The current status of the application is that existing numerical analysis and optimisation programmes are used.

In the future it is foreseen to implement the concept of EGNOP to govern the numerical optimisations (see Vingerhoeds 1992 and Vingerhoeds et al. 1991, 1992). The EGNOP concept consists of three layers, or shells: the outer layer consists of the heuristic modification rules, the inner layer consists of application independent rules to govern the numerical optimisation routines, that are contained in the library in the core of EGNOP.

Whenever the concept has been improved to the extend that no further heuristics can be suggested, a local numerical optimisation can be performed by the inner layer of EGNOP. The objective of the inner layer is to continuously control the convergence of the numerical optimisation process. The inner layer rules contain knowledge about the numerical optimisation routines, their typical application behaviour and limitations. The inner layer selects the most suitable numerical optimisation routine for the current characteristics of the design space. If the convergence of the selected routine decays, the inner layer detects the phenomenon that caused the delay, adjust the operational parameters of the optimisation routine, or selects another routine better suitable for the changed situation.

The core of EGNOP momentarily consists only of numerical optimisation routines for continuous design parameters. For the current application, discrete optimisation methods are to be added to the library, and additional governing rules added in the inner layer.

8. CONCLUSIONS

Conceptual design of panels is a multi-disciplinary and creative process, that is currently not supported by advanced computer aided design tools. The reasoning process is complex, non-procedural and strongly driven by a diversity of specifications, and by the designer's skills, experience and preference. An approach for an artificially intelligent conceptual design system is presented that supports the designer in more routine-like reasoning tasks, managing the design process and suggesting design decisions.

The knowledge required for the application and for the design process is available in different forms and from different sources. Integration of different knowledge sources is necessary but cannot be represented in only one format or inferenced with only one reasoning technique.

For conceptual design, three tasks have been identified by which the initial specifications are translated via qualitative analyses into a quantitative description of a good initial concept for further numerical design. The design is incrementally build-up from design elements, via prototypes into concepts.

The design process is driven by goals that result from the specifications, for which multiple reasoning techniques are used: constraint-based reasoning, case-based reasoning and rule-based reasoning. The domain knowledge is declared in multiple representations: qualitative behavioural constraints, example designs, heuristic modification rules and numerical behavioural relations.

The approach to model the domain and process knowledge separately and in different representations also provides the flexibility to inference the appropriate design process for a diversity in specifications.

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10. ACKNOWLEDGEMENTS

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In the EDA project, and intelligent conceptual aircraft design environment is developed, together with a visualisation system to provide the input for the Aircraft Design and Analysis System (ADAS) system. ADAS is a computer aided design environment to perform the numerical analysis and optimisation in the conceptual and preliminary design phase and has been developed at the Faculty of Aerospace Engineering, see Bil (1988) and Middel (1992). The input for the ADAS system is an initial conceptual design, in the form of two-dimensional drawings and primary design parameters. Once the initial conceptual design has been created by EDA, ADAS offers suitable analysis tools for further development and optimisation.