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IMPROVING THE CONCEPTUAL DESIGN OF TURBINE ROTOR BLADE COOLING SYSTEMS

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1 Introduction

This paper describes the process used to design aero-engine turbine blade internal cooling systems. It considers a simplified example, obtained during a case-study with a UK-based gas turbine company. It examines the 2D aspects of the design methodology, and identifies how and where changes to the design process would improve the conceptual design phase.

The turbine operating temperature forms one of the primary influences on the performance of a gas turbine. Improved cooling system conceptual designs are desirable, permitting higher temperature operation using reduced amounts of coolant. The cooling system design process is challenging: cooling is one of several highly integrated systems that together constitute a turbine blade, and the response of an aerofoil to its cooling system can be difficult to predict without a significant amount of modelling work. Incremental design changes are often favoured, because of the strong culture of safety throughout the industry.

Market competition is compelling designers to improve the performance, efficiency and cost of engines and influential components. Certain design drivers are becoming more influential (e.g. design robustness, reduced component numbers, enhanced environmental protection and product life cycle issues). Maintaining a competitive edge will depend on establishing new design trade-offs as well as increasing component and design process efficiencies. The prize for succeeding in the market can be large - the future civil aero-engine market is estimated at \$510 billion until 2022, approximately 94,000 engines [1].

The literature contains a wealth of suggestions to improve system designs. Most effort is concentrated upon optimising specific characteristics of particular system styles, typically by modifying cooling passage shapes or changing the choice and layout of internal features. Notable examples demonstrate an increased creep life for a cooled blade [2] and reduced internal stress levels [3]. Others used inverse design to produce new variants of existing concepts [4]. Much related work has been done to optimise cooling duty and engine cycle choices [5]. Little has been reported that specifically improves the cooling system design process and helps designers identify innovative, feasible systems more rapidly. Many generic methods consider self-contained mechanical problems or the use of libraries of design embodiments and behaviours [6, 7]. They do not easily extend to the most complex design tasks, and may lead to innovative arrangements of known elements rather than to entirely new concepts.

2 Turbine blade cooling background

High-pressure aero-engine turbine blades operate under arduous conditions: they are enveloped by a hot corrosive gas mixture, and subjected to vibration, thermal stresses and intense rotational forces. The turbine entry temperature has been increased by an average of 10°C each year for the past 50 years to improve engine performance and thermodynamic cycle efficiency. The turbine gas temperature can now substantially exceed the blade material melting point during parts of the flight cycle. A service life of many tens of thousands of hours is achieved by manufacturing blades from heat-resistant superalloys and using internal air cooling. Compressor bleed air is passed through intricate networks of passages cast and machined in the blade (Figure 1). Passage surfaces carry carefully selected and positioned features that enhance the level of convective heat-transfer and control the coolant flow structure. Cooling air is exhausted from passages through small holes, forming cool protective films on the blade exterior.

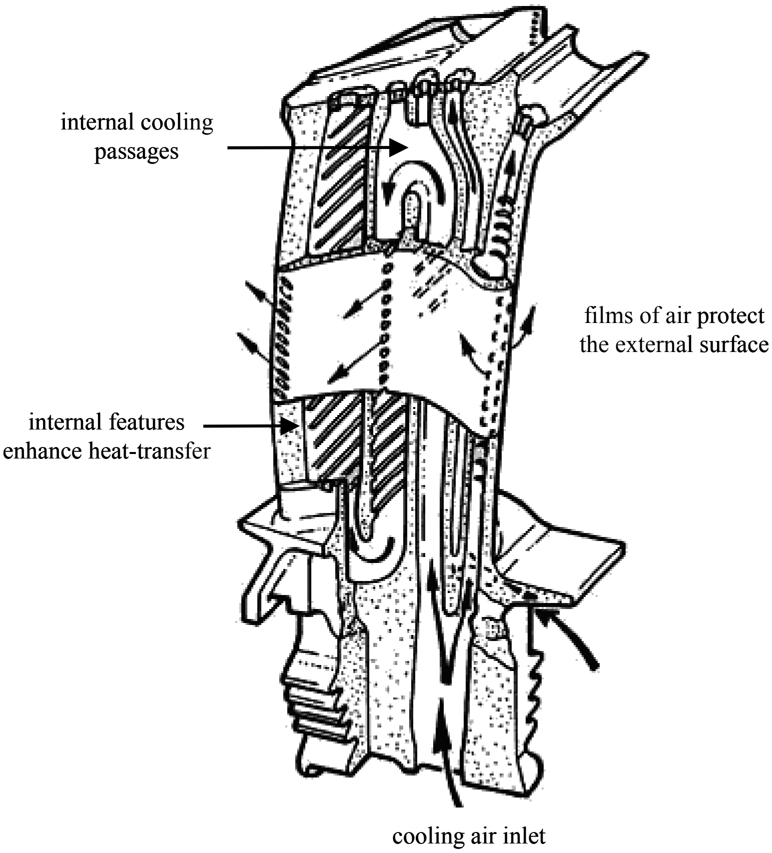

Figure 1. A cut-away view of a turbine blade showing the internal cooling system passages.

Advances in cooling design have been responsible for approximately half of the historic increase in cycle temperature [8]. A cooling system affects an aero-engine at many levels, from the temperature and life of each blade to the overall weight and fuel consumption. The importance of cooling cannot be understated – the life of a turbine blade is sensitive to its temperature, and can be halved by an increase in mean temperature of just 10-15°C.

3 The cooling system design process

3.1 The design funnel

The design process for turbine blade cooling behaves as a funnel, where a number of possible design candidates is reduced to a single choice using a cycle of testing and subsequent acceptance or rejection [9]. For cooling design, the funnel is particularly constricted and the quantity and quality of concepts may not be biased towards the best region of the design space. The number of concepts examinable and the number of changes that can be investigated for each concept are both limited by available time and resources. A wide variation in test fidelity is not practical – although simple tests can reject concepts, only satisfactory predictions of cooled blade life permit concepts to be accepted. The test process contains a significant bottleneck, the requirement for many design choices to be described in detail via a CAD model. Design guidance is not automatically derived from evolving or past concepts, so effort from previous iterations can be wasted.

3.2 The nature of the design process

Cooling design is part of a greater systematic engineering process that uses prescribed working practices and methods to control workflow and quality. The cooling and aerodynamic design processes are connected: cooling choices are influenced by the aerofoil shape, the space available within and by the external conditions around the blade. Engineering and cooling goals are optimised as part of the whole engine using 1D lumped-parameter calculations; these include target blade life and mean blade, hot gas and coolant temperatures [8]. The only necessary description of a cooling system is an efficiency value.

The cooling designer faces a classic design challenge – although an ideal cooling duty and a set of engineering goals can be specified in great detail, no algorithmic method transforms them directly into a feasible design. Whilst cooling has been used for over 50 years, creating new configurations is not yet completely intuitive; compared to other engineering tasks (e.g. automotive design) comparatively few designs have been produced and validated.

Many problems are associated with cooling conceptual design. There is clash of descriptive and prescriptive methodologies, using a mixture of tacit and quantifiable knowledge. The design space is of many dimensions, and the population of feasible solutions sparse. The cooling space can be organised in an infinite variety of ways; only a few will provide sufficient cooling, structural integrity and operating life. The design space topography is non-homogeneous, and responses to design choices can be unpredictable and non-linear. Cooling, aerodynamic and structural behaviour and requirements all influence each other. There are multiple, conflicting objectives. The design is described and influenced by many parameters, and expressing requirements and formulating beneficial trade-offs can be difficult to do.

Cooling system design synthesis is based upon a heuristically guided search. It produces embodiment designs with supporting verification data. The quality of the search directly influences the quality of the solution. The search uses computer model predictions to produce verification data; these are interpreted by the designer to obtain guidance for the continuing search. Verification provides confidence in a configuration, allowing it to be promoted to a higher stage of maturity with the minimum possible risk. The whole cooled aerofoil is considered; a model of an isolated system does not provide sufficient information about the response of an aerofoil to the system or the overall feasibility of a design. Success is measured by the complete cooled aerofoil meeting its requirements. Because simulations require a high degree of modelling detail, it is difficult to make simple, rapid comparisons of competing designs.

3.3 Computer modelling tools

The modelling tools considered here use principles common to the industry. Cooled aerofoils are represented using sections which predict locally-averaged behaviour and whose radial positions track the varying hot gas temperature within the turbine. Each section describes in detail the local layout of cooling passages and the position and type of any secondary features (e.g. film cooling holes and internal ribs). Sections are created using a CAD-based expert system. Abstraction is limited, and a constant level of detail is maintained. Subsequent models cannot use uncertainty or partial descriptions of systems, and they must be fully defined before evaluation takes place.

The sections are used to generate coupled analysis models that predict the behaviour of the cooling system and the cooled aerofoil (Figure 2). The models use Computational Fluid Dynamics (CFD), Finite-Element Analysis (FEA) and heat transfer and pressure loss correlations to predict the section temperatures. Additional FEA models consider the effects of the rotational and pressure forces on each section. Temperature and stress fields are combined with knowledge of the material properties and used to predict the blade operating life and the mode and position of failure. The computational time required to iterate and converge the models is negligible when compared to that required to define the system.

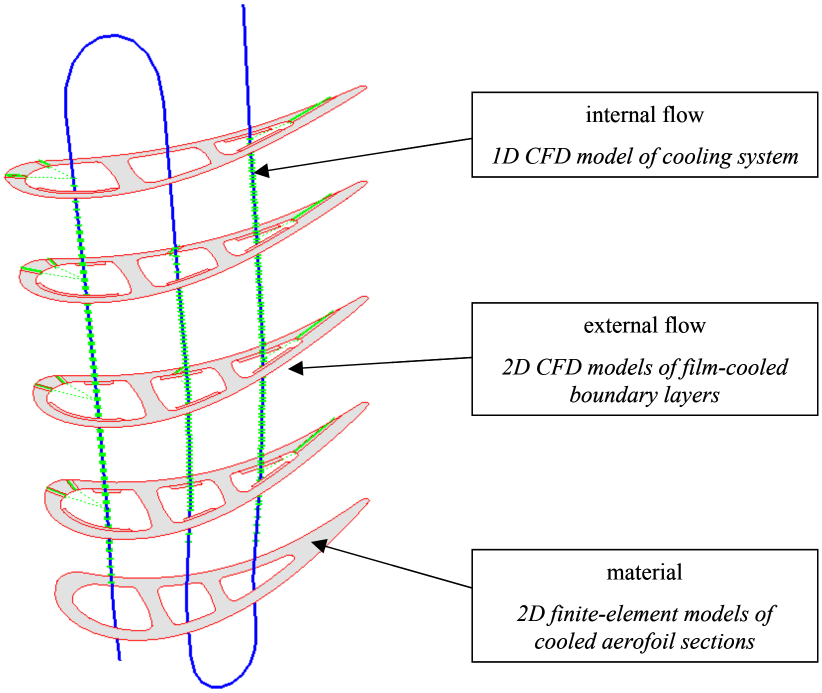

Figure 2. A representation of a cooled aerofoil used by the computer tools during the design process.

3.4 Searching the design space

The search uses a cycle of synthesis, analysis and evaluation [10]. It treats parameters such as life as design objectives, because of the difficulty in using them to constrain the designer's choices. Without using machine learning or AI to harvest the verification information, each iteration represents a cost rather than an investment in finding a better solution.

Typically, a number of points in the design space will be investigated, using local searches to refine promising designs (Figure 3). The design process usually stops because of constraints to design time and resources, when requirements have been met with an acceptable level of engineering risk. Regardless of modelling fidelity, solutions tend to be sub-optimal; additionally the degree of sub-optimality remains unknown to the designer. The success of a search may depend upon finding cooling capacity undiscovered by a truncated earlier search. When it becomes impossible to find, a new concept must be sought.

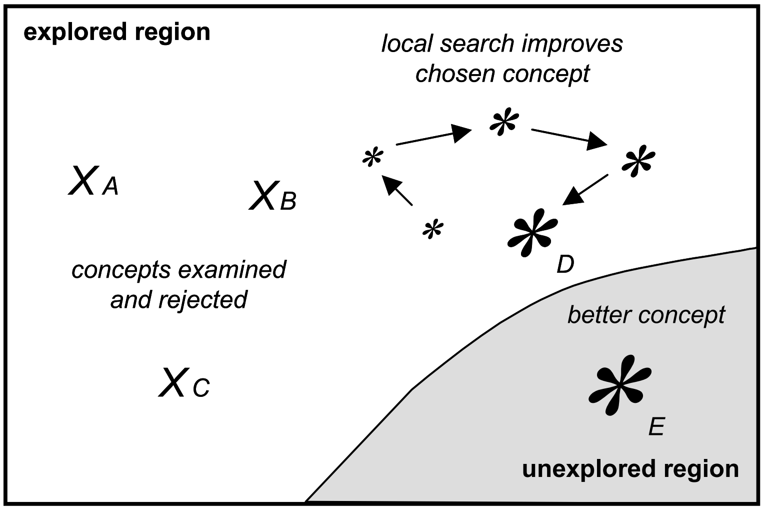

Figure 3. Exploring the design space using a search-based process can find sub-optimal solutions.

4 Mapping the design process

A process map is required in order to improve the design process, clarifying how the transition is made from a set of requirements to a suitable design. As well as showing information flow through the various stages and decision points, the map had to indicate the types of activity undertaken, the interactions with linked engineering groups and the types of design information being processed. Particular prominence was given to the CAD-related tasks, which were known from the outset to be significant. A single repeated process is used during all design phases, and is outlined below in simplified form (Figure 4). The map shows the strong "design-by-analysis" character of the overall process and the likelihood of large amounts of change-related CAD work.

The map was not readily available and was constructed from various disconnected parts of an overall process. The parts were collated and connected together; some were obtained from documented procedures, others from computer training systems. Cooling designers and aerodynamicists were interviewed informally to gather heuristic knowledge supporting each of the different parts of the process. The first author has previously worked as a turbine cooling engineer with the company whose design process is being studied; this experience was used to assist the research and the gathering of information from the engineering team. Additional heuristic knowledge binding the overall process together was acquired by learning to use the complete set of computer programs for making thermal, stress and life predictions. Doing this identified aspects of the process that were not described either by formal descriptions or by expert instruction.

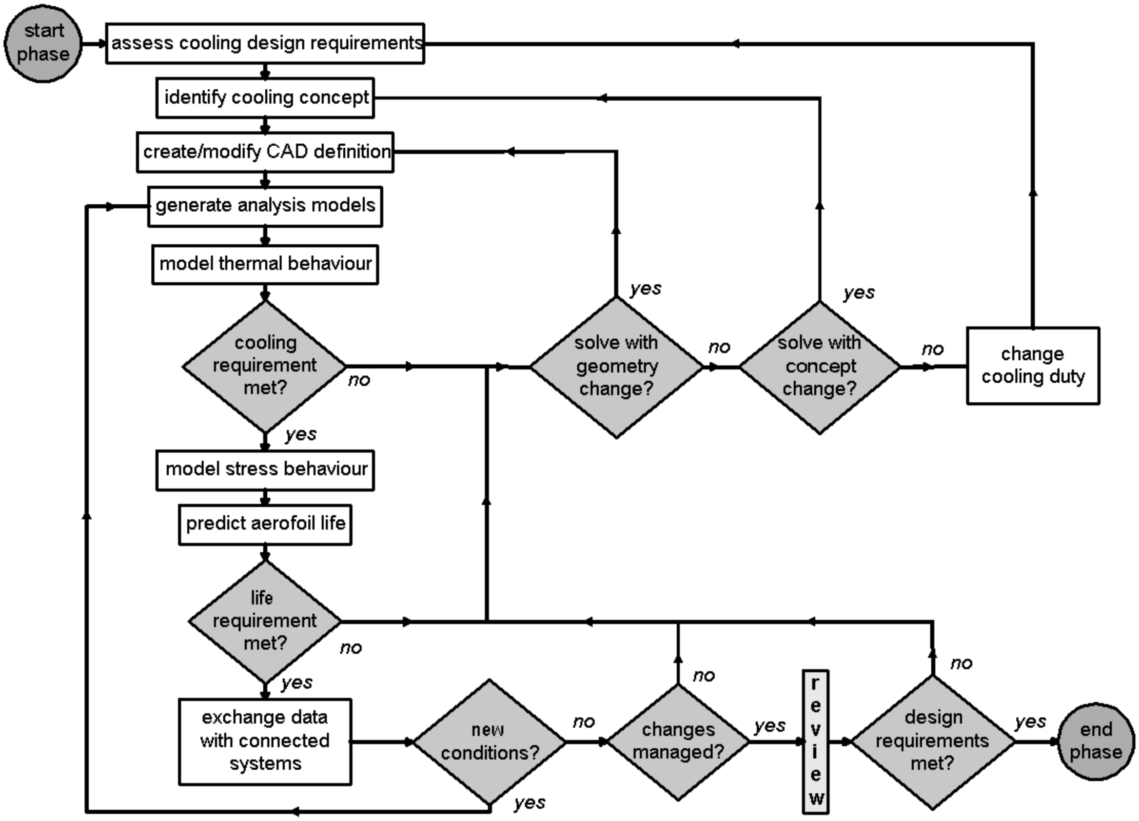

Figure 4. A simplified process map for creating and verifying concepts using 2D modelling tools.

The process information is organised into standardised packages of data. They connect geometric descriptions of cooling systems with important parameters (e.g. local hot gas temperature or heat flux). The packages have been designed specifically to support automated model creation and an iterative multi-domain analysis process.

As the design develops, the output forms the starting point for the next more concrete configuration. The emphasis of the process changes for each phase, and because of this some small variations occur. Both the first phase (conceptual design) and the second (design verification) result in verified embodiment designs. They differ in the degree of concreteness of the configuration and the known influences. Additional forms of analysis support the design verification phase; this is because the risk of significant further change occurring is low and the effort is likely to be useful. Later phases (development, production) provide validation data which is applied to the verification models, transforming them from predictions into records. Some minor configuration changes are usually made, reflecting any modifications necessary to improve manufacturing or engine operations.

5 Conceptual design process observations

Although difficult to avoid, the use of detailed representations during conceptual design tends to go against well-established design principles [11, 12]. Creating design embodiments has been united, by necessity, with the means of producing models and interpreting verification data. High-resolution descriptions have become necessary to set up even 1D models, and little of a system can be modified purely by changing descriptive parameters. Late design rejection can occur because of changes created by other engineering activities; the frequent exchange of developing design information helps to mitigate this problem.

Everything, apart from the creation or modification of CAD models, is controlled by prescriptive processes. The CAD work and supporting decisions form a strongly descriptive process, akin to skilled craftwork. It is multi-disciplinary (considering aerodynamics, thermodynamics, structures and manufacturing) and needs understanding of many heuristic design rules. Small changes of configuration (e.g. repositioning or re-specifying internal ribs and film cooling holes) can be made simply, though laboriously. Many can be required for each design iteration. Larger changes (e.g. to passage shapes or the system topology) tend to require significant amounts of re-work, wasting previous CAD modelling effort. The map contains decision points that indicate design changes are necessary, but the underlying activities do not feed the process with information or guidance about the nature of beneficial changes. Since implementing almost any change requires the designer to directly or indirectly revert to CAD modelling, the process is forced to pass through its slowest stage for most design iterations.

Put simply, the lack of guidance when making design choices and the cost of setting up and changing simulation models limits the ability of the designer to explore the design space.

6 Proposed solution

6.1 Improve design funnelling

The currently constricted design funnel must be opened up. The descriptive nature of geometry creation and design verification must be properly supported; the nature of the problem will continue to frustrate purely algorithmic approaches. Rather than minimise designer interactions, the process must support human decision-making and steer the search towards favourable concepts. This is a departure from the automated, design-optimisation principles that have directed much cooling system design improvement work to date.

6.2 The form of the solution

A new computer prototyping tool is required, a design “wizard” based upon a model of the prescriptive *and* the descriptive processes to define and assess cooling system configurations. The tool will provide decision support absent from the current process, and will sit alongside the existing, validated design system. The search process has been likened to a hunt for buried treasure, an extreme example of a sparse population of feasible solutions [12]. The wizard will organise the design process and the collection and presentation of information. It is not intended to be an expert system that accelerates the design of previously known classes of system. The wizard will not replace the search, but use the verification data to build a guide map to assist exploration of the design space. By identifying suitable characteristics, the design funnel will be charged with a better initial selection of concepts. Design feedback will direct changes and allow faster rejection/retention of designs. Designs will be passed further down the funnel in less time, by developing them more directly into a state where they can be judged.

Too few concepts and their variations are currently investigated, and the quantity and quality of modelling work cannot easily be reduced. Because reduced model fidelity is difficult to implement, the time to produce or change models must be decreased so that unsatisfactory solutions are rejected faster. The nature of the modelling process makes it almost impossible to eliminate CAD work. What can be done is to reduce its impact when making small and intermediate design changes that preserve the topology of the cooling passages (e.g. moving cooling hole positions and modifying passage shapes). Introducing greater abstraction and lowering modelling resolution will allow designers to create and judge between competing designs more rapidly. By concentrating effort upon investigation rather than describing form, the designer will be able to pass more concepts through the funnel in the available time (Figure 5).

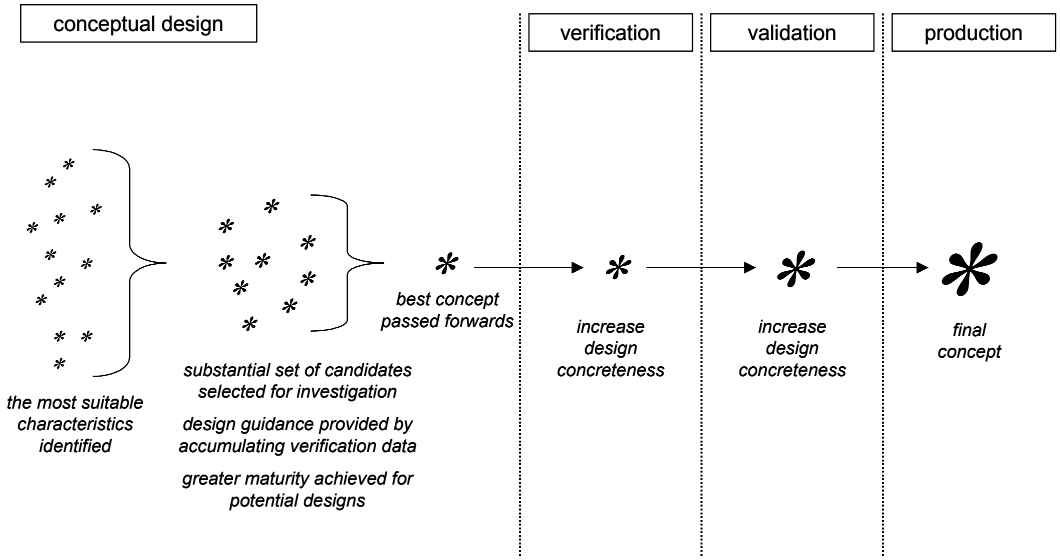

Figure 5. Flow through the design funnel must become less constricted.

6.3 Realising the solution

The key to the design wizard will be the creation of a representative process model. It must accommodate iterative loops, and permit decision-making and interaction with other processes. For this task, using a Design Structure Matrix (DSM) to represent the process would not provide the best illustration of the many iterative loops or of the consequences of design activities failing to produce positive results during an iteration. The "SignPosting" methodology will be used instead, since it can describe and model processes using a network of tasks and parameters, rather than tasks alone [13]. It provides a way to manage the evolving confidence associated with a design and its parameters. Certain developments are of special interest because they deal with complex iterative design processes reliant upon the use of computer models [14, 15]. As well as describing a design task network and the information exchange, a SignPosting model can encode information about *how* cooling conceptual design is done. This is an important extension to the task-based process map shown, which does not record the content of the choice-making processes.

The SignPosting model will be built by researching this necessary extra content. It will provide a more specific description of what cooling designers consider and what detailed actions are taken during conceptual design. The research will be undertaken by working with cooling designers, and will consider both current and historical approaches. There may be different approaches available for the descriptive part of the design task, for characterising designs and making design trade-offs. Identifying the heuristic knowledge used to accept or reject conceptual designs will be important in producing an effective process model. It would be desirable to include the decision processes that experienced engineers use so successfully.

The wider design process must be clarified to identify the important design influences and the information exchanges that take place with stress, lifing and manufacturing engineers. Activities apparently far removed from cooling system behaviour have a part to play during conceptual design (e.g. anticipating investment casting problems that may occur for a particular style of cooling system).

The design wizard will be created as a program that sits alongside and interacts with the existing suite of modelling tools. Specifically, it will be written as a plug-in program to the graphical user-interface that hosts and controls the individual simulation tools. This approach will preserve the familiar design environment and avoid having to re-connect a functioning, validated network of linked programs. Certain changes to the modelling tools will be necessary, though the underlying modelling principles will remain the same.

7 Conclusions

Identifying the best conceptual design for a turbine cooling system is vital to the successful operation of a gas turbine aero-engine over its life-cycle. Creating innovative designs is challenging and resistant to automation. The design process depends on computer simulation, used during the design synthesis activity as part of a heuristically-guided search. The funnelling of candidates to a single choice is frustrated by a CAD-modelling bottleneck and a lack of automated design guidance. The design-by-analysis approach produces satisfactory but sub-optimal conceptual designs, whose sub-optimality is difficult to assess.

The solution to the problem will be the creation of a design "wizard", an additional computer tool based upon a model of the total cooling design process. It will interact with standard modelling tools, organise the process and provide appropriate feedback from the models. It will assist exploration of the design space and provide decision support to the designer, rather than operating as a traditional expert system to assist the creation of known classes of design.

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