

---

# Chapter 8

## Conclusion

---

This chapter begins with a summary of the extensions that were made to existing methods for integrating manufacturing issues into the structural optimization of composites. Following that, the important results from the research into advanced methodologies is concluded and some comments are made regarding the future developments in these area. Finally, recommendations to other researchers and the CRC-ACS are given.

### 8.1 Extensions to Existing Methods

A number of extensions were made to existing methods of structural optimization to show how problems that involve manufacturing issues can be better addressed. Additionally, improvements to manufacturing cost modeling strategies were investigated with a view to more effectively integrating them into structural optimization. The following sections discuss the results that were obtained during these two avenues of investigation.

#### 8.1.1 Topology Optimization

The work in Chapter 2 was a detailed investigation of the brick-based 3D topology optimization of an aircraft spoiler. This method was a novel application of topology optimization since the optimal 3D topology of spoiler-like thin panel structures has not, to date, been reported in the literature (to the best knowledge of the author). The topology optimization results suggested a rough configuration for an optimal spoiler that was feasible from a manufacturing perspective. The suggested interpretation of the topology into a real design would involve ply drop-offs to form the upper and lower skins, a large central rib and a single interior spar-like member that extending about half of the spoiler's span. An important limitation to the

practicality of this result was the lack of consideration for buckling and non-linear deformations. Further work would be required before such effects could be incorporated into topology optimization problems with this many degrees of freedom.

The ESO topology optimization case study for a plastic milk crate in Chapter 3 presented an approximate method for locating the stiffening members on thin shells subject to buckling. This was a reliable and efficient approach for optimizing the topology of injection moulded plastics that could also be applied to co-cured fiber reinforced composites. For either class of structure, basic control over manufacturing issues could be exercised by using appropriate dimensions for the grid of stiffeners used for the starting design.

Using the shell-based approach of Chapter 3, a two-stage optimization problem could be developed for the spoiler design task. Firstly, the locations of efficient internal structure could be determined with the 3D brick-based method discussed above. Secondly, shell-based topology optimization (such as was used in the milk crate problem) could be used to determine the regions of the spoiler that require extra stiffness for buckling resistance. These regions would most probably be on the large unsupported skin areas that are far from the interior members. Extra interior stiffeners would introduce more weight and manufacturing complexity into the design. However, this level of stiffening may be what is required to provide a near-optimal configuration.

### 8.1.2 Sizing Optimization

Chapter 4 investigated the use of parametric sizing optimization in conceptual design for an aircraft spoiler. An FEA modeling strategy was automated to maximize the usefulness of the ANSYS environment for optimizing arbitrary structural configurations. The various spoiler configurations were each optimized for minimum weight under deflection and buckling constraints.

The comparisons of the different structures resembled common practice by the CRC-ACS and (presumably) other engineering companies where selections are made

from a range of designs with assistance from trade-off tables. The new contribution of this work was in performing buckling-constrained sizing optimization for such a large number of designs. This is often seen a too time consuming since setting up each model is a complex process. Reducing the time to set up the models was a main consideration and the ANSYS Parametric Design Language (APDL) was used to achieve this. It was found that APDL is limited with respect to building optimization models of this type since the topological connectivity between the geometric entities was not known in advance.

### 8.1.3 Metrics for Comparing Structural Optimization Results

Three metrics were introduced in the second chapter to quantify and compare the manufacturing costs of spoiler-like topology optimization results. These were; *surface coverage*, *specific stiffness* and *panel-to-core ratio*. The work in Chapter 4 introduced another metric that was very simple – *the number of uninterrupted internal members*. These metrics do not provide perfect mathematical data about the design's optimality nor are they purely abstract quantities that have no engineering significance. They fit in the middle ground and offer imperfect information to help solve the incomplete, real-world optimization problem.

The utility of these metrics was to rank design concepts on the basis of manufacturing concerns that are too complex to model in full. It is recommended that similar metrics to these be applied in other topology optimization studies of real-world designs. The flexible Knowledge-Based approach developed in Chapter 7 provides a good framework for using metrics to automate some of the decisions during design selection. For example, a system for optimizing the manufacturing processes of a composite spoiler could be instructed to choose different manufacturing methods depending on the value of the metric from Chapter 4 (*number of uninterrupted internal panels*). Based upon experience with similar structures, the designer could provide the knowledge behind such instructions.

#### 8.1.4 Manufacturing Optimization

In industry, manufacturing optimization is most often done without numerical algorithms due to their non-mathematical nature. Manufacturing optimization problems are incomplete since the optimization variables are not defined at the outset. Rather, the variables are dependent on configurational choices that are made simultaneously with the manufacturing decisions. This contrasts greatly with numerical optimization algorithms that seek to define optimal values to clearly defined sets of variables. The Process Link research in Chapter 5 gave an example of this incompleteness since the number and type of manufacturing processes that made up the models was unknown at the beginning. In these problems, the concept of design variable sensitivities is non-existent since changes to the manufacturing decisions remove or add entire groups of processes, each with their own cost calculations equations. Thus current-day numerical optimization techniques are unable to optimize real-world manufacturing problems.

The most important factor in manufacturing optimization is not the development of new optimization algorithms, rather, it is expanding the designers ability to explore the design space of configurational choices and manufacturing decisions. In the real-world, manufacturing optimization is a process of continuously recognizing and adapting to the constraints on the processes involved. The decision graph presented in Section 7.2.2 presented a method for capturing these constraints in a Knowledge-Based system and using them to navigate the network of decisions involved in manufacturing optimization.

Since topology optimization problems tend to make very few assumptions about the form of the solution, it is very difficult to include manufacturing constraints in topology optimization. It has been suggested<sup>1</sup> that manufacturing cost can become a driver for topology optimization. However, the author is yet to see a practical application of such a method. Hence, in the topology optimization examples covered

---

<sup>1</sup> On going research by K. Wang and D. Kelly from the University of New South Wales, Department of Mechanical and Manufacturing Engineering, is attempting to include some form of manufacturing cost driver in topology optimization of composite structures.

in this thesis, manufacturing considerations were not considered as part of the numerical optimization problem. Rather, these considerations were addressed in the formulation of the problem and in the subsequent comparison of the results.

## **8.2 Research into Advanced Methodologies**

Recognizing the limitations to efficiently linking manufacturing issues directly into structural optimization algorithms, more advanced methods of CAE were researched. The following sections summarise the findings and work on Feature-Based and Knowledge-Based methods, better integrating CAE software and flexible Knowledge-Based systems.

### 8.2.1 Feature-Based and Knowledge-Based Methods

Shah & Mantyla (1995) defined a feature as a physical constituent of a part having engineering significance, predictable properties and as being mappable to a generic shape. Features capture design intent (the utility of particular geometric entities) and allow abstraction in modeling which is useful in conceptual design. Also, features save time for the designer or draftsman because they automate the tedious details of constructing complex models. When a model has a large number of features, a 'feature taxonomy' can be used to show how properties are inherited from higher features. An organisation that uses Feature-Based design most effectively will create a library of features that reflect the properties of commonly occurring designs.

Even if Feature-Based design methods are used, there is a problem in transferring design information between different models. The concept of feature recognition is one solution to this problem. Feature recognition software attempts to assign features to a design automatically from some other representation. If feature recognition is available, the designer can concentrate on defining features at a higher level of abstraction - ignoring the tedious detail design features.

It was found that the distinction between Knowledge-Based and Feature-Based methods is not consistently drawn in the literature. Hence, it was proposed that Feature-Based methods form a subset of Knowledge-Based methods. Under this proposal a Feature-Based method stores and manipulates only ‘features’ as per the definition given at the beginning of Section 6.3.1 whereas Knowledge-Based methods deal with design attributes that are not physical constituents of the product yet still contain engineering relevance (eg. rules, manufacturing sequences, analysis results etc.).

It was suggested that Knowledge-Based systems should be defined as methods that allow integrated control of the following types of knowledge; highly organized data, loosely organized data, hierarchical data, procedures and algorithms. To best store this knowledge, the following key aspects of a Knowledge-Based CAE system were suggested; knowledge entities (with engineering significance), user-defined algorithms, a graphical user interface and file transfer utilities. Knowledge-Based systems are of little use unless the knowledge of the designer is progressively captured, thus flexibility is a key issue in designing or choosing such a system.

### 8.2.2 Better Integration

Chapter 6 discussed interfacing issues for CAE software and uncovered a dichotomy between analytical models and CAD-type models that shed some light on the limitations of current CAE methods. The limitations to the types of knowledge that can be stored in CAD systems were an inability for FEA systems to handle features and a general inability to customize algorithms or data types for arbitrary models. The customization issues are most important during innovative design where it can be advantageous to break the rules regarding how things are normally done.

The discussion on data sharing issues in engineering design explained the ISO project known as STEP that is attempting to integrate data from different CAE applications. Two particularly beneficial aspects of the STEP project were found to be the Application Protocols (APs) and the EXPRESS language. The benefits of the APs

are in making product information more portable between systems. The EXPRESS language developments have led to a language (EXPRESS-2) that is suitable for modeling a range of engineering systems that is impossible with existing methods. Also, the language is designed to be readable by humans and computers, thus maximizing the speed of this critical link in the flow of knowledge during design activities. In this thesis, it was demonstrated how EXPRESS-2 can form the basis for a flexible Knowledge-Based system.

### 8.2.3 Flexible Knowledge-Based CAE

Solutions to real-world composite structural optimization problems are not in the form of one particular optimization algorithm or idealization since such methods cannot capture a sufficiently broad amount of information about the design. When real-world problems are being solved there are always issues arising that lie outside of the model – either because they are too complex for the model or because the designer has not needed to include them yet. It was suggested that the only way to reliably solve the optimization problems occurring in composites design is by allowing considerations to be progressively incorporated into the knowledge base. These considerations can be in the form of data or algorithms operating on that data. Integral in this process is the construction of a knowledge library. This is an investment of the engineering organisations time that pays off in the long term once the customization of designs using pre-existing features and knowledge becomes trivial. A further benefit is that the designers become free to concentrate on the more abstract and esoteric issues in the design problem, thus adding more value to the products they develop.

A new framework was proposed for integrating manufacturing concerns into a concurrent engineering environment that used EXPRESS-2 and integrated geometric modeling. To demonstrate this concept, a prototype Knowledge-Based system for composite structural optimization was developed. In Chapter 7 this system was used for the concurrent design of a composite wing rib. To achieve this, a preliminary knowledge library for model for laminated composite structures was created. This modeling showed how algorithms of almost any type could be included into the

system and how both existing and new optimization methodologies could be applied. The results from this research presented the opportunity to explore the trade-off between structural efficiency and manufacturing cost with unprecedented levels of thoroughness, efficiency and flexibility.

### **8.3 Future Directions**

#### 8.3.1 Top-Down vs Bottom-Up

There is an important distinction between the approaches to real-world optimization problems that deal with complex issues such as manufacturing. These methods can be loosely classified as one of two types – top-down or bottom-up. In top-down structural optimization methods, the configuration of the design (i.e. topological connectivity of the design’s features) is decided before the optimization problem is formulated. Thus, the solutions solve a sub-problem that is strongly influenced by the decisions made earlier. Sizing optimization can be considered as a top-down approach since the design variables are linked to already existing features such as beams cross-sections and panel thicknesses. Shape optimization (not covered in this thesis) has a similar nature since the topology of the design is fixed in advance, and the available perturbations to the shape are often limited.

Topology optimization methods fall into the category of bottom-up approaches since relatively few assumptions are made about the attributes of the solution (i.e. the various features that make up the design). Hence, topology optimization is probably most useful during earlier stages of the design process where the overall efficiency of the structure is of primary interest.

Manufacturing optimization problems can also be examined from either top-down or bottom-up frameworks however top-down approaches tend to dominate. For example, the process modeling work outlined in Chapter 5 was clearly a top-down approach since there were predefined procedures for choosing the manufacturing steps. On the other hand, the decision graph concept presented in Section 7.2.2 represents one possible method for including bottom-up knowledge to evaluate

manufacturing costs. In that methodology, the designer's role is to specify the numerous but simple constraints that exist between the decisions (switches). When a multitude of these switches are considered as a network of interacting entities, the true complexity of the problem is realized from the bottom upwards.

The Object-Oriented nature of Knowledge-Based systems means they are able to capture the large number of interactions in complex bottom-up approaches with the same effectiveness as they can capture the top-down hierarchical relations between the features of a design. Arguably, there is currently a slow shift from old-fashioned engineering design techniques that rely on a top-down division of the design problem to new computational methods that utilize bottom-up models<sup>2</sup>. The growing adoption of concurrent engineering also represents a shift towards bottom-up approaches since the multidisciplinary design teams are intended to eliminate the need for the top-down problem solving approaches of traditional engineering design.

It is suggested here that the best approach to solving integrated structural optimization problems is to utilize mixed models that apply both top-down and bottom-up approaches. For instance, the spoiler sizing optimization of Chapter 4 attempted to work around the top-down nature of sizing optimization by optimizing a large number of configurations. This approach shows promise but requires extensive computational time. With flexible Knowledge-Based systems (such as discussed in Chapters 6 and 7) it should be possible to rapidly construct a wide variety of mixed models for effectively integrating manufacturing issues in structural optimization. These models could utilize the best of both worlds – top-down modeling for complex abstract issues and bottom-up modeling to deal with large collections of inter-dependent data.

---

<sup>2</sup> Evidence for this can be seen in the literature where methods such as Genetic Algorithms, Simulated Annealing and neural networks and constraint-based systems are becoming increasingly prevalent.

### 8.3.2 Roles of Humans and Computers

With current technology, humans are still an essential link in the design optimization loop. They give a reality check to the results, suggest avenues to explore and formulate models to perform the exploration. If or when true Artificial Intelligence is realized, design could proceed without human intervention. However, in the near term humans will still be responsible for the most important design decisions.

Regarding the nearer future, a number of optimistic and pessimistic predictions can be made. Optimistically speaking, the responsibilities of the human designers will change from tedious assignment of design details to more rewarding work where their creativity and vision are expressed in the configurational decisions made in a design. Pessimistically, humans will be forced to become increasingly adept at manipulating data stored on computer and will be even more tied to the computer terminal than we are today. In this pessimistic prediction, humans will be tasked with linking the aspects of the design together that computers are unable to do through their linear, deterministic programming.

To avoid the pessimistic case and encourage the optimistic one, effort should be focussed on more seamless interaction between the knowledge stored in the designer's brain and that stored on the computer. To this end intuitive GUI's, 3D models, efficient data retrieval and rapid design exploration are important issues. This dictated the characteristics of the flexible Knowledge-Based system that was proposed in this research.

### 8.3.3 High Volume Knowledge-Based Systems

In the near term, Genetic Algorithms (Goldberg, 1989) may be the best solution to the problem of searching for optimal design solutions through the combinatorial explosion of decisions in real-world design tasks. They can be applied to problems in which the number and type of the design variables are not known, also they can deal with multiple optima. If such approaches are embraced, the designer will be the

controller of the environment in which the Genetic Algorithms (GAs) evolve, and human knowledge will be captured in Knowledge-Based systems that the GA can explore. As computers become faster, the evaluation of the fitness functions for these GA can become more complex. In the not too distant future, it is foreseeable that an entire design with the complexity of the rib or spoiler models investigated in this work could be built from a set of decisions (in the form of a GA chromosome) in a matter of seconds. Already FEA for simplified models such as the rib in Figure 7.10 can be analysed in this time frame. The development of flexible knowledge systems is an important step to realizing an environment where GAs and similar methods can be applied to concurrent engineering problems.

#### 8.3.4 Integration of Mixed Models

One of the key benefits of a flexible Knowledge-Based system is the ability to formulate and solve mixed models. For instance, metrics like those developed in Chapters 2 and 4 could be applied in combination with manufacturing process selection procedures. This would better merge the early topological studies into the later design process since manufacturing models could be progressively introduced. The manufacturing models could start with approximate rankings of the various configurations and finish with detailed and high-accuracy manufacturing task breakdowns. In this way, the resolution of the manufacturing costing estimates could be adjusted to suit any stage of the design process.

With future increases in computer power and substantial investment in the Knowledge-Based systems, even more complex mixed models could be attempted. One promising area is 3D, virtual reality, dynamic simulations of the manufacturing activities (for both humans and machines) such as the DELMIA system discussed in Section 5.3.4. Linking a flexible Knowledge-Based system to these kinds of simulations could provide highly accurate process time estimates whereby troublesome 3D constraints could be modeled in full. However, such detailed simulations are of little use unless they also model the uncertainty related to processing steps and or the consequences of failing to complete specific operations.

## 8.4 Recommendations

The recommendations from this research are divided into two categories. Firstly, there are recommendations for other researches interested in integrating manufacturing issues into the structural optimization of thin-panel structures. Also, there are recommendations for the research that is carried out by the CRC-ACS. These recommendations are given in point form below.

### 8.4.1 General Recommendations

For researchers interested in optimizing real-world thin panel structures, the following recommendations are given:

- Formulate topology optimization problems such that the most important constraints are satisfied. For example, many thin-panel structures are required to be non-buckling so all solutions should respect this constraint. Also, manufacturing constraints on stiffener placement should be addressed by specifying their proximity limits in advance.
- If necessary, use two-stage or multi-stage optimization approaches and mixed models when dealing with constraints that relate to opposing sides of the dichotomy identified in Section 6.1.3.
- Use appropriate levels of accuracy for the respective stages of the design process. For instance, don't solve large problems during conceptual design since this is the time for wide ranging experimentation. However, do use complex analysis models when comparing candidate designs with vastly different configuration since simplistic estimates may not suffice.

#### 8.4.2 CRC-ACS Recommendations

For future research in the CRC-ACS relating to structural and manufacturing optimization, the following recommendations are given:

- In future designs for spoiler-type structures consider the topology suggested by Figure 2.7. In these designs, the relatively unsupported upper and lower skins could be stiffened with co-cured or secondary bonded stiffeners.
- When searching for optimal spoiler design configurations, use multiple sizing optimizations that constrain linear buckling and have the locations of interior members fixed. Allowing these members to move when the panel thicknesses are being optimized buckling introduces excessive non-linearity into the search space.
- Use customizable and integrated analysis systems as much as possible and support them in ways that allow maximum reuse in later design tasks, e.g. build feature libraries and knowledge libraries and develop algorithms that are modular and can be applied to multiple types of structures.
- Be aware of over-reliance on top-down optimization formulations that make assumptions about the configuration of the design.
- Expand on the PCAD models to incorporate uncertainty for process times and process failures.
- Consider the level of STEP compliance when purchasing CAE software since this is the emerging standard for engineering data interchange. Most CAE products offer only partial compliant STEP file transfer.

## References

Goldberg, D. E., *Genetic Algorithms in Search, Optimization, and Machine Learning*, Addison-Wesley, Reading, MA, USA, 1989.

Shah J., Mantya M., *Parametric & Feature-Based CAD/CAM*, John Wiley & Sons, N.Y., 1995.