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## Chapter 5

# Cost Modeling for Composite Manufacturing

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In this chapter the methodology and accuracy of existing composites costing models were investigated. The objective was to form an understanding of how manufacturing analysis can be combined with structural analysis during design optimization. To begin with, the important issues in composite manufacturing are discussed, then one particular cost modeling strategy used by the CRC-ACS is investigated in some detail. Finally, a new method for more advanced cost modeling of composites is presented and the CRC-ACS response to this new method is discussed.

### 5.1 Important Issues in Composite Manufacturing

Composite structures have been demonstrated to have better performance and less weight than conventional metallic designs. This effect is most prevalent in the area of aerospace structures (Raju *et al.*, 1995). However, the high cost of manufacturing composites remains an economic barrier to their increased usage. Additionally, the uncertainty regarding both manufacturing difficulties and life-cycle costs presents extra risk that can often discourage the use of composites in applications where they would be most beneficial.

To overcome both the high costs and the uncertainty, better knowledge of composite manufacturing and life cycle issues is needed. Bao & Samareh (2000) explain how finding a balance between cost and structural efficiency requires access to well-integrated resources for composite design, manufacturing, materials and structures technologies.

### 5.1.1 Complexity

In general, composite manufacturing is a complex field. This complexity takes many forms and exists on many levels. The complexity can relate to individual processes or to the interaction between different processes. Also, the complexity of the part being manufactured can have a significant effect on the overall complexity. For instance, installing rivets in a hard to access or hard to see location is far more difficult than a simplistic cost estimation might predict. Therefore, accessibility issues of assembly operations should be considered. Also the time to perform manufacturing processes can be quite variable since the skill level of the operator can introduce large differences in times.

An even more dominant cost in the manufacturing of composites is the complexity of the specialized tooling, e.g. moulds, mandrels, and jigs. Some composite parts cannot be formed using a single-piece mandrel. In such cases, costs related to production, operation and cleaning of multi-piece mandrels often dominate the other costs. It is possible that an intelligent software program could assist in the evaluation of cost by providing automated or semi-automated the design of the mandrel.

The effect of small changes in the design can have a dramatic effect on the manufacturing cost. In particular, increasing the complexity of highly repetitive operations could result in a dramatic increase in the overall time. This is the so called 'knock-on effect'. An example of this is the draping of a laminate's plies over surfaces with complex geometry.

### 5.1.2 Constraints

The concept of manufacturing constraints must be at the heart of any model attempting to deal with the complexity of composite manufacturing. Constraints can take many forms and they can relate to either discrete or continuous attributes of the design. Traditional mathematical optimization methodologies have more success when dealing with continuous constraints since constrained optimization problems

can be formulated. However, discrete constraints pose significant difficulties and are yet to be treated effectively.

Additionally, manufacturing constraints can be rigid or flexible. Rigid means that failure to satisfy the constraint would introduce unacceptably large impediment to the overall manufacturing solution. On the other hand, a flexible constraint may be violated (at a cost) without invalidating the manufacturing approach. When flexible constraints are violated, it may be necessary to shift to other manufacturing options or add another level of complexity to the manufacturing model. Some examples of rigid constraints are the maximum weight that can be lifted by a crane or the maximum allowable working time on uncured prepreg fabrics. An example of a flexible constraint is the maximum weight that can be carried by a human. If this is exceeded by a particular design, mechanical assistance in the form of a crane or trolley could be employed or extra human operators could be utilized.

An important class of constraints is geometric constraints. These relate to physical dimensions of the part, tooling or workshop being used. Geometric constraints are generally discrete. Some examples of simple geometric constraints are the upper limit to the size of a composite part imposed by the size of the autoclave or the locations of manually drilled holes being within length of the human operator.

During design, evaluation of constraints requires prior knowledge of the particular manufacturing issue at hand. For example, determining the constraint on the maximum width of a composite panel requires specific knowledge about the manufacturing method, i.e. the width of the ply rolls. For effective design practice, this type of knowledge must be collected and catalogued by the engineering organisation.

Another issue that relates to manufacturing constraints is the sequencing of manufacturing steps. This can have a very large influence on the manufacturing costs. Discussions with staff from the CRC-ACS suggested that the manufacturing cost for a typical composite part could be reduced by a factor of 2 by rearranging the order of assembly and simplifying the assembly processes.

### 5.1.3 Company-Specific Approaches

Although there are generally many options for manufacturing, a given company will often settle on a standard approach for a variety of reasons. For instance, they may feel confident that a standard type of design can be manufactured if a number of other products have already been manufactured by the same methods. Also, the cost of new equipment or rearranging the shop floor might be prohibitive (especially for small runs) and hence, the company will adopt a standard approach for economic reasons.

In the case of the Australian aerospace manufacturer, Hawker De Havilland (now part of Boeing/Hawker De Havilland), the preliminary design process is actually carried out during the bidding process. This is necessitated since the cost and structural performance must be provided during the bid. After the bid is made, the basic details of the design are often left unchanged. As the typical period of bid formulation is only two or three weeks, it makes sense to stick to company-specific manufacturing processes whenever possible, thereby minimizing the risk of cost ‘blow-outs’.

### 5.1.4 Cost

According to Marapoulos *et al.* (1998), it is widely accepted that a large percentage of the product cost is determined during the conceptual design phase whilst there is relative fluidity of the product configuration and other design decisions. However, a basic shortcoming of many commercial process planning systems is that they are only applicable once the design has been almost completely defined. Hence, it is important to develop cost estimation methodologies that support design activities right from the early stages of product synthesis.

Cost can be defined as the ‘manufacturability’ of a design. Shah *et al.* (1990) defined manufacturability as the quality of a design from the viewpoint of manufacturing feasibility and economics. According to Blair & Hartong (2000), at the early stages of technology development (i.e. whilst innovating) the absolute cost is not

of direct concern. Rather, the relative costs and cost consequences are of importance. Only later, once the general attributes of a design are finalised, does the absolute cost become meaningful in an economic sense.

Cost can be estimated with models of varying complexity, ranging from simplified weight-based parametric models to in-depth time and motion studies. Towards the middle of the complexity spectrum are the Activity Based Cost (ABC) models such as the one proposed by Gutowski *et al.* (1995). By their method, the cost is decomposed into the costs of; materials, labour, assembly, outsourcing, capital investment and other overheads - each of which is evaluated by empirical means.

Another cost modeling system was developed by Northrop Corporation in the 1970's (Lorenzana *et al.*, 1976). They developed a computerized methodology for estimating the recurring costs associated with the fabrication for advanced composite parts of that era. An Industrial Engineering Standards approach was used to formulate time estimations as a function of part geometry. The method included variance equations, support labour cost modeling (i.e. hours for support staff activities) and used power law relationships for the process steps.

An important economic element of cost is the material cost. Although, this cost is relatively easy to estimate, it is often only a small contribution to the overall cost. Bao & Samarech (2000) found that in general, the material cost for advanced composites was only about 5% of the cost of fabrication and assembly.

Perhaps the most important thing to note about manufacturing costing is that the 'devil is in the details' or 'vital few, trivial many'. These statements can be taken to mean that the overall project cost is largely driven by a small subset of the manufacturing processes involved. Once these processes are identified, models can be constructed around these 'cost drivers'. However, their identification is often a difficult task.

Finally, although manufacturing costing is often seen as merely a first order approximation, the calculations can always be correlated with actual data. This contrasts with many of the detailed FEA models that are used in typical design tasks

that can not be directly compared with reality since extensive idealizations are often necessary.

## 5.2 Review of the PCAD Database

As part of the NASA/Boeing Advanced Technology Composite Aircraft Structures (ATCAS) initiative, Gutowski *et al.* (1995) developed an adaptive framework for estimating the fabrication time of advanced composite structures. They introduced a relatively simple model that aimed at ease of updating and providing designers with insight that relates the cost to design decisions. PCAD is a process-based manufacturing and assembly cost modeling tool that can also be used for cost-performance optimization.

### 5.2.1 Methodology

The PCAD methodology uses a list of sequential manufacturing processes of predefined types. This list is dependant on design attributes such as the materials used, the manufacturing processes or the sub-assemblies that make up the full part. This list of processes forms a manufacturing scenario that is investigated with PCAD in order to estimate the manufacturing time.

The model was originated with the observation that many manual and automated manufacturing processes could be represented as dynamic systems with first-order velocity response to step inputs as per:

$$V = V_0 \left( 1 - e^{-t/\tau} \right), \quad (5.1)$$

where  $V_0$  is the steady-state process velocity,  $\tau$  is the dynamic time constant of the system and  $t$  is the process time.

The model makes the assumption that the process time is driven by a well-defined geometric property of the part being manufactured such as its length, volume or surface area. This property is given the variable name  $\lambda$ . The process velocity,  $V$ , can be equated to the first derivative of  $\lambda$  with respect to time, leading to:

$$\lambda = V_0 \left[ t - \tau(1 - e^{-t/\tau}) \right]. \quad (5.2)$$

As  $t$  is not explicit in this equation, two approximations can be made depending on the value of  $t$  relative to  $\tau$ . These are:

$$\text{For } t \ll \tau \quad t \cong \sqrt{(2\tau\lambda)/V_0} \quad (5.3)$$

$$\text{For } t \gg \tau \quad t \cong \tau + \lambda/V_0 \quad (5.4)$$

These two approximations can be combined into the following hyperbolic function as follows.

$$t = \sqrt{(\lambda/V_0)^2 + (2\tau\lambda/V_0)} \quad (5.5)$$

In the methodology of PCAD, (5.5) is applied to each of the processes in the model with their respective cost driver and process velocity variables retrieved from a database. The addition of the time taken for all processes then becomes the overall manufacturing time estimate. The process time database contains data for over 200 process types including those relating to; mandrel preparation, lay-up, curing, part extraction, installation of fasteners, secondary bonding and non-destructive inspection. An important issue in this research was assisting the designer to select the appropriate processes from this wide range.

### 5.2.2 CRC-ACS Utilization of PCAD

In collaboration with the CRC-ACS, Surpuram & Kathrotiya (2000) from the Royal Melbourne Institute of Technology (RMIT) did work to add an interface to the PCAD database using graphical programming tools that are part of the Microsoft Access Relational Database software package. The CRC-ACS performed trial evaluations of the RMIT implementation of the PCAD database but found that the controls were non-intuitive and restrictive (Raju, 1999 a). As a result, in subsequent design tasks, a more straightforward application of the PCAD data was realized by manual manipulation of the process data in a spreadsheet program.

It was noted that the most significant step yet to be automated was the linking of manufacturing processes from purely geometric data about the design. This step is not straightforward since it involves manually querying a geometric model stored on a CAD system and entering this data into the cost estimation program. Furthermore, the existing approach did not have any intelligence regarding what processes are suitable for particular geometric arrangements.

To achieve a faster turn-around, the CRC-ACS was interested in automating some of the activity in the above-mentioned stage. This led to the following research by the author into methodologies for more advanced cost modeling.

## 5.3 Advanced Cost Modeling

### 5.3.1 Computer Aided Process Planning

Computer Aided Process Planning (CAPP) methods commonly occur in advanced cost modeling. These approaches seek to automatically or semi-automatically define the list of processes required during manufacturing. Once process lists are available, a variety of methods can be used to calculate cost estimates.

Joshi *et al.* (1987) integrated the design of machined components with automated process planning using Artificial Intelligence (AI) techniques. Their approach used

automated feature recognition from CAD models. An expert system was used for process planning and it was interfaced to a solid modeler for fast extraction of geometric design information. Similarly, Chep & Tricarico (1999) used a Generative Computer Aided Process Planning (GAAPP) system to generate the machining process sequence automatically. Primary features of the design were extracted automatically from a CAD model in CATIA (Dassault Systemes).

Maropoulos *et al.* (1998) defined a new time-based process planning software architecture consisting of three levels corresponding to aggregate, management and detailed planning. Their system was tested in close collaboration with an industrial partner and they successfully modeled a number of machined components, in addition to the factory and tooling used to manufacture them. The objective was to rapidly convert early product specifications into manufacturing and assembly process requirements. The concept of time based process planning was found to be an important factor in effectively dealing with issues during integrated product development.

Chang & Tang (2000) designed a system for computer integrated manufacturing of die-cast or machined parts. Their system used smoothed topology optimization results to create a CAD model that was then investigated with virtual manufacturing techniques to determine if the part could be produced at a reasonable cost. They report that the narrow range of manufacturing processes under consideration limited the practicality of the system.

In all of the above-mentioned approaches, the structures under investigation were solid machined parts. There are fundamental differences in the analysis, design, manufacturing and usage of such parts when compared with thin panel structures that are the subject of this research (as discussed in Section 1.4). Hence, the above approaches serve only as a broad guide for how process planning can be automated for advanced composite manufacturing. There is also some limited work appearing recently in the area of aerospace composites.

Zaki & Daud (2000) developed a method for costing aerospace composite structures that used a framework commonly applied in business software to support

decisions relating to advanced composite manufacturing. They developed a system to search a production planning database for similar products in the past experience of the design organisation. Their system retrieves data on all the processes that were used in similar products previously designed by the organisation. Then the designer interacts with the system to create a new, fully developed process plan. One limitation to this approach may be its lack of support for geometric data. As such, their approach is similar but slightly more automated than the CRC-ACS usage of the PCAD data discussed in Section 5.2.2.

Blair & Hartong (2000) adopted a general purpose design modeling environment to address affordability issues during conceptual and preliminary design. Their approach was demonstrated on the design synthesis of a hot-structure, high speed, lifting surface. A geometric modeler was integrated into the system and Activity Based Costing (ABC) models were created in a semi-automated manner. This approach bears close similarity to the research reported later in this chapter.

### 5.3.2 Non-Discrete Methods

In some specific cases, the design search space can be simplified to contain only continuous design variables. In these cases, simple manufacturing cost models can be directly linked to existing structural optimization software and subsequently, multi-criteria optimization problems can be formulated and solved. These methods do not deal explicitly with the manufacturing processes to be applied and hence fall into a different category to the cost modeling methods discussed in the previous section.

Edwards *et al.* (1998) integrated the VICONOPT structural analysis software for prismatic anisotropic plates subjected to buckling constraints to costing estimation formulae. Least-cost design examples for prismatic assemblies of composite panels with regularly spaced stiffeners were demonstrated. Similarly, Henderson *et al.* (1999) integrated manufacturing considerations into the design optimization of blade-stiffened composite panels manufactured by the Resin Film Infusion (RFI) method. A structural optimization problem of minimizing the mass under buckling constraints was combined with a manufacturing problem to minimize the resin infiltration time.

Whilst the above examples are essentially sizing optimization approaches, topological or shape optimization approaches to manufacturing optimization are also possible. Wang *et al.* (2000) optimized the skin thickness distribution for an aircraft wing under manufacturing and strength constraints. In that work, smoothness constraints were used to guide the design away from overly complex configurations.

The above mentioned non-discrete cost models involve purely continuous design variables and cannot capture the complexity of arbitrary manufacturing scenarios for arbitrary structural designs. Hence, these methods are most suitable in specific cases where discrete design decisions can be ignored.

### 5.3.3 Feature-Based Methods

Salomans (1995) discussed the use of a Feature-Based design methodology for modeling the manufacturing of machined solids. He examined the linkage between CAD design features and manufacturing features. It was observed that the link from manufacturing features to process steps could be defined by decision tables or rules.

An alternative architecture for Feature-Based, vertical integration of tooling considerations during preliminary design of machined components was presented by Baker & Maropoulos (2000). It was noted that process planning activities within CAD environments must consider the lack of hard data available to construct a detailed product model during the early stages of design. In their work, the selection of cutting tools was as essential step for linking the Feature-Based design of machined parts to process planning models. Also, their work included was a limited survey of the industrial requirements of intelligent manufacturing software tools. The survey received 38 useful responses from various manufacturing sectors including small and large firms, tool manufacturers, aerospace, shipbuilding and general batch manufacturing. It was found that just under half of the firms used Feature-Based methods in their design activities.

Feature-Based methods have also been proposed in a concurrent engineering context to better integrate the diverse team of experts involved in a complex design task. Here, a major limitation to the use of the multifunctional teams is that the engineers often come from different backgrounds. Feature-Based methods have been proposed to facilitate interdisciplinary communication and learning. Such issues are of particular importance when it comes to the interaction of manufacturing engineers and structural analysis engineers since these two types of engineers frequently have weak understanding of each other's field.

In this work, only a Feature-Based philosophy was judged to be sophisticated enough to provide a significant improvement to the utility of manufacturing models during structural optimization. Hence, the Section 5.4 details some specific research into Feature-Based cost modeling for aerospace composites that was undertaken by the author.

#### 5.3.4 Highly Integrated Production Modeling Applications

With increasing access to computational power, software products to support the entire cycle of product development and manufacturing planning are emerging. One example is a suite of software packages by DELMIA (part of Dassault Systemes) that is devoted specifically to eManufacturing. In addition to industry standard CAD applications, the suite also includes some advanced tools for simulating the operating sequences in production and for integrated product/process planning. These are known as 'ERGOMan' and 'ERGOPro' respectively and some information from the DELMIA website ([www.delmia.com](http://www.delmia.com)) is summarised below.

ERGOMan focuses on the human element in manufacturing process design. A variety of tools and algorithms are used for analysing and optimizing the layout of manual workstations in a manufacturing environment. The system takes into account a wide range of ergonomic factors such as body postures, movement, dynamic strains and time-motion analysis. This provides an effective tool for designing the workplace but apparently does not consider the ergonomic effects of product configuration

choices. Hence, the methodology may not be applicable to the design of the products themselves.

ERGOPro is an elaborate system that supports all computerized aspects of preliminary planning, Target Costing and Digital Mock-Up for high volume manufacturing. The system is designed to deal with assembly lines and automates many calculations for plant layout, line layout and logistics. Systematic Target Costing is used to control the costs for every component involved in the product's manufacturing.

The DELMIA software suite provides a valid model for highly integrated production modeling that is particularly suited to the manufacturing in the automotive industry. It seems unlikely that the user can customize the system to be equally applicable to the manufacturing of aerospace composites. However, as composite manufacturing technologies mature in the future, similar systems specializing in this area will no doubt arise.

#### **5.4 The Process Link Program**

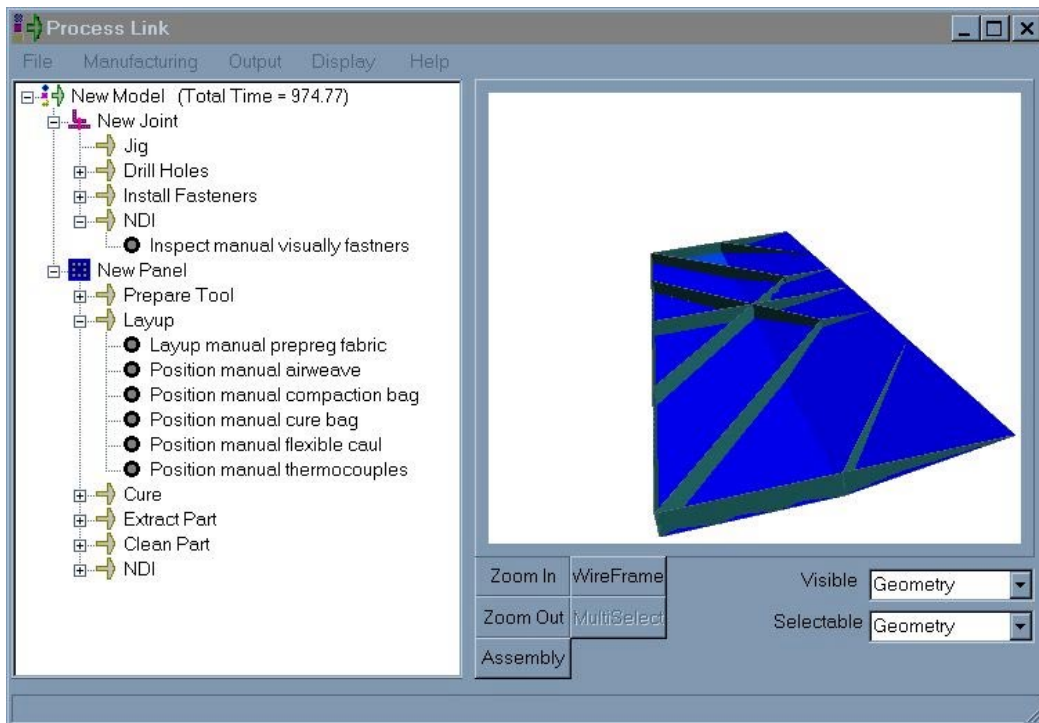
A prototype program called Process Link was developed by the author to demonstrate the potential of Feature-Based methods in composite cost modeling. The CRC-ACS was interested in evaluating Process Link methodology in the context of their aircraft spoiler demonstrator study (Raju, 1999 b.). An example application was presented taking an example spoiler design from Chapter 4. The following sections describe this example and summarise feedback from CRC-ACS regarding the applicability of such software.

##### 5.4.1 Methodology

The Process Link software links CAD data generated within the ANSYS environment to the PCAD process modeling database. The user specifies the manufacturing features used for a design and automated querying of an external

database is used for costing calculations. All of these activities were integrated with a Graphical User Interface (GUI) to assist rapid manipulation of the model's data.

This is a step up in efficiency over the CAPPs methods discussed in Section 5.3.1 since manufacturing decisions can be made with a better understanding of the geometric issues influencing the design. Furthermore, the geometric measurements that are fed into the PCAD process model are automatically extracted from the CAD model. This saves time and potential errors associated with manually transferring these quantities from design drawings or a CAD program to a separate process-modeling environment. Figure 5.1 shows a screen shot of the Process Link GUI.



**Figure 5.1,** A spoiler manufacturing process model in Process Link

For the purpose of demonstration, the 'D1' spoiler configuration from Figure 4.4 was loaded into the program. At this stage, some assumptions were made regarding the manufacturing approach to investigate. It could be assumed that the top skin and all of the ribs and spars were to be co-cured with the Resin Transfer Moulding (RTM) method. This would reduce the part count (reduce the assembly costs) yet add to the complexity of the mould (increase the mould costs). The bottom skin could not be

included in the same mould since the finished spoiler needed to have an entirely closed (torsion box-like) structure. Hence, the bottom skin could be cured as a separate structure.

A typical assumption would be that the bottom skin should be a single pre-impregnated CFRP panel. This decision is possible since the bottom skin is very nearly flat. It could be mechanically fastened to the co-cured remainder of the spoiler structure with bolts or rivets. With this design approach, the manufacturing processes would result in a spoiler with a smooth top skin - important for it to function as an aerodynamic surface on the top of the wing.

Once the Feature-Based model was finalized, Process Link was instructed to build the process model. This involved associating each sub-component of the design with its corresponding manufacturing processes, extracting the cost driver variables from the geometry and evaluating all of the individual process time equations. The software took approximately 20 seconds to build models with the complexity of the example described above on a 133 MHz PC. The interactive definition of the features took around 5 minutes in the first instance but small modifications to the features were quicker. These fast turn around times for process model generation and cost estimation demonstrate the potential for rapid searches for cheaper manufacturing options.

Each of the manufacturing decisions was applied to the Process Link model using the 3D geometric display that forms part of the GUI. The full range of manufacturing feature options that were included in the Process Link software prototype is detailed in Table 5.1.

<i>Feature</i>	<i>Property</i>	<i>Description</i>
<i>Panel</i>	<i>Name</i>	Unique text string
	<i>Material</i>	CFRP prepreg, CFRP RTM or Aluminium
	<i>Laminate</i>	Choice of a range of laminates (CFRP only)
	<i>Match Laminate by Thickness</i>	Tool to automatically select a laminate based on the required panel thickness
	<i>Max. Fastener Spacing</i>	Maximum spacing along attached joints. To avoid inter-fastener buckling (mechanical fasteners only)
	<i>Shear Flow</i>	Approximation used for design calculations
	<i>No. Pilot Holes</i>	These are to be drilled in the panel for assembly
	<i>RTM Lid Perim.</i>	A cost driver for RTM panels
<i>Joint</i>	<i>Name</i>	Unique text string
	<i>Flanges to Panels</i>	Boolean value for each attached panel. Indicates where flanges are used
	<i>Connection Type</i>	Choice of rivets, lock-bolts, torqued bolts, secondary bond, ply continuation or folded (aluminium only)
	<i>Shim Type</i>	Kapton or Liquid (secondary bonded only)
	<i>Template</i>	Drill plate or Mylar (mechanical fasteners only)
	<i>Fasteners by Panel</i>	Boolean option to use panel faster properties.
	<i>Fastener Spacing</i>	(not 'Fasteners By Panel')
<i>Assembly</i>	<i>Fastener Type</i>	Select from library of fasteners
	<i>Name</i>	Unique text string
	<i>Parts</i>	List of panels, joints or assemblies

**Table 5.1,** Manufacturing feature options included in Process Link

#### 5.4.2 CRC-ACS Response to Process Link

In 1999, two workshops were conducted with staff from CRC-ACS industrial partners – Hawker De Havilland in Sydney and Boeing ASTA in Melbourne (both now part of Boeing/HDH). These workshops were used to present a demonstration of

Process Link and obtain feedback on the use of its methodology from an industrial point of view. This feedback took the form of suggested improvements that would be necessary for a methodology like to Process-Link to be applied for practical cost minimization of composite structures.

Firstly, a simple suggestion was to include a bill of materials in the final process model report since every design requires a bill of materials to be defined at some stage. Process Link deals explicitly with that information and hence it would only require small modifications to the software. Another observation was that the Process Link software could be driven by an external program with the intention of providing a 'black box' cost estimator. Although, this would require some expert knowledge to be built into the system to automatically choose from the wide array of manufacturing options.

Implementing either of the above suggestions into Process Link would involve relatively simple modifications. However, a number of crucial issues about its inherent flexibility were also raised. These suggestions relate to the exact process features that are available and to the cost model used. Most importantly, rather than hard-wiring the manufacturing features, process types and cost equations into the system, the user should be able to customize them. Such ability would be quite powerful when new manufacturing methods arise – methods that were not known at the creation of the system. It was suggested that some sort of equation editor be included to store and evaluate the user-defined cost relations.

Finally, it would be useful to apply different cost models to the same design, e.g. any of the model types discussed in Section 5.1.4. This would allow different levels of detail and different manufacturing requirements that can be tailored to different customers. Furthermore, it would provide a natural progression from simple and quick cost modeling during conceptual designs to highly accurate cost models used in subsequent detailed design.

## 5.5 Conclusion

This chapter highlighted the need for integrated resources for composite design and complexity, constraints and costs were shown to be particularly important issues in composite manufacturing. Feature-Based methods were judged to be able to provide the most significant improvement to the utility of manufacturing models during structural optimization.

From the CRC-ACS feedback on the Process Link program and methodology it was concluded that its biggest weakness was its lack of flexibility. The modeling capabilities of the system were effectively fixed in the software. Efforts to incorporate more flexibility into manufacturing cost estimation software led to the work discussed in the following chapter.

One final point to note about the Process Link method described above is that ideally many passes through the feature specification stage would be desirable by the designer before settling on a sensible and efficient manufacturing scenario. This search would also be possible through a discrete optimization method such as random search, genetic algorithms, simulated annealing or even a full search of the design space (if the cost evaluation was fast enough to make this feasible). The option of linking an optimization method in such a way was not considered in this research although it is one potential extension of this work. Alternatively, a Knowledge-Based system could be applied to make the decisions using expert knowledge. Chapters 6 and 7 address this option in some detail.

## References

Baker, R. P., Maropolous, P. G., 'An Architecture for the Vertical Integration of Tooling Considerations from Detailed Design to Process Planning', *Robotics and Comp. Integ. Maufact.*, 16, pp. 121-131, 2000.

Bao, H. P., Samareh, J. A., "Affordable Design: A Methodology to Implement Process-Based Manufacturing Cost Models Into the Traditional Performance-Focused Multidisciplinary Design Optimization", *AIAA-2000*, 4839, 2000.

Blair M., Hartong A., "Multidisciplinary Design Tools for Affordability", *AIAA-2000-1378*, 2000.

Chang K., Tang P., "Incorporation of Computer Integrated Manufacturing for Structural Shape Optimization", *8'th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization*, Long Beach, CA, A00-40151, *AIAA-2000-4910*, 2000.

Chep A., Tricario L., "Object-Oriented Analysis and Design of a Manufacturing Feature Representation", *Int. J. Prod. Res.*, Vol. 37, No. 10, pp 2349-76, 1999.

Edwards D. A., Williams F. W., Kennedy D., "Cost Optimization of Stiffened Panels Using VICONOPT", *AIAA Journal*, No. 2, February 1998.

Gutowski T. G., Neoh E., T., Polgar K., C., "Adaptive Framework for Estimating Fabrication Time of Advanced Composite Manufacturing Processes", *Technical Report, Laboratory for Manufacturing and Productivity, MIT, 1995*.

Henerson J. L., Guerdal Z., Loos A. C., "Combined Structural and Manufacturing Optimization of Stiffened Composite Panels", *Journal of Aircraft*, Vol 36, No. 1, January-February, 1999.

Joshi S., Vissa N. N., Chang T., "Expert Process Planning System with Solid Model Interface", *J. Prod. Res.*, 20, No 5, pp 863-883, 1987.

Lorenzana, J., Kokawa, A., Bettner, T., Timson, F., Proctor, J., Behrens, H. J., Lyle, L., Woo, M., Bernhardt, L., "Advanced Composite Cost Estimating Manual", *Technical Report AFFDL-TR-76-87*, Northrop Grumman Corporation, Hawthorne, California, USA, 1976.

- Maropoulos, P. G., Bradley, H. D., Yao, Z., 'CAPABLE: an Aggregate Process Planning System for Integrated Product Development', *Jnl. Materials Processing Tech.*, 76, pp. 16-22, 1998.
- Raju, J., Cale, N., Salmon, J., Kanavas, T., Wells, T., Katzos, T., "Final Report: Co-Cured Aileron Manufacturing Development and Final Assembly", *CRC-AS Control Surface Demonstrator Program*, CRC-AS TM95018, 1995.
- Raju, J., 'CRC-ACS Experience with Computer Based Costing Models', *CRC-ACS Design Optimization Workshop*, Sydney/Melbourne, Australia, 1999 a.
- Raju, J., "Feasibility Study for an Aircraft Spoiler", *Proceedings IAC*, Adelaide, Australia, 1999 b.
- Shah J. J., Rogers M. T., Sreevalsan P. C., Hsiao D., Mathew A., Bhatnag A., Liou B., Miller D. W., "The ASU Features Testbed: An overview", *ASME Computers in Engineering Conference (CIE)*, 233-241, Boston, USA, 1990.
- Salomons, O. W., 'Computer Support in the Design of Mechanical Products', *Ph.D. thesis, University of Twente*, Holland, 1995.
- Surpuram, S., Kathrotiya, J., 'Computer Based System for Determining the Cost/Time of Manufacturing Composite Components', *M.Sc. thesis, RMIT University*, Australia, 2000.
- Wang L., Williams A. F., Llamas R., "Aircraft Wing Structural Optimization with Manufacturing Considerations", *8<sup>th</sup> AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization*, Long Beach, CA, A00-40099, AIAA-2000-4842, 2000.
- Zaki, N. M., Daud, N., 'A Decision Support System for Advanced Composite Manufacturing Cost Estimation', *Journal of Theoretics*, Vol. 2, No. 3, 2000.