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Cost modelling for aircraft design optimization

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This paper summarizes work that has been carried out to date on the Implied Cost Evaluation System (ICES) research project. This is an EPSRC-funded project that is sponsored by BAe (Airbus) and Rolls Royce (Defence Europe). The paper identifies the need for detailed and reliable cost information in order to optimize a product design. This is illustrated with reference to recent cost modelling work carried out in support of preliminary designs for the proposed Airbus A380 600 seat aircraft. The merits of the various alternative approaches are identified and the genealogy of current systems and techniques is briefly outlined. It is argued that current tools lack a number of key features and capabilities. In particular, it is suggested that current cost modelling tools are not able to deal with the multiplicity of levels of abstraction associated with an emerging design. Furthermore, there is no generally accepted method for expressing the uncertainty associated with a cost estimate in a rigorous and systematic way. This paper outlines some of the initial development work on the ICES project. This concerns the development of an object-oriented product data structure that supports multiple levels of abstraction, statistical modelling and decision support constructs.

1. Background

1.1. The design of aerospace products

Aerospace design is largely a functional discipline that lends itself to objective design methods and, in particular, optimization techniques. Most major aerospace design organizations employ computer-based optimization tools, particularly at the early design phase. Typically, the overall objective function used is total life-cycle cost (LCC) of the product. In most aerospace products, one of the major components of LCC is the manufacturing cost of the product.

In the early design phase computer-based optimization methods allow a very broad search of the design space. Thereafter, due to the current limitations of optimization tools, searching is conducted using manual or 'computer assisted' methods and, consequently, the search becomes considerably more expensive and time consuming (Pugh 1996). The search space is narrowed down to a small number of design concepts that are investigated in greater depth. Finally, a single concept will

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be selected and will become fully defined. At each stage of this process, the minimization of LCC remains the overall target.

It is widely acknowledged that very little work has been conducted in the area of conceptual design and that the tools that support this stage from a manufacturing perspective are scarce (Zhou *et al.* 1999). In the early period of a design project, there is considerable difficulty in assessing manufacturability and therefore cost.

1.2. Existing cost modelling techniques

BAe (Airbus) have developed a design optimizer known as TADPOLE (Transport Aircraft Design Programme with Optimisation Logic Executive). This optimizer uses a specially written costing routine known as WAPCO (Whole Aircraft Parametric Cost Estimator) that is restricted to high levels of design abstraction and is currently not capable of costing new processes or techniques.

Similarly, Rolls Royce (Defence Europe) employ a high level optimizer known as GENESIS for conceptual design analysis. They are currently carrying out development work to integrate this with a parametric costing tool.

Essentially, cost models use one of two fundamentally different approaches, parametric or generative costing.

1.2.1. Parametric cost estimating. This approach seeks to identify high-level relationships between cost and one or more design parameters. In the past, such parameters as volume and component mass have been used as high-level costing parameters, particularly for military aerospace products. For well-defined classes of components, this approach has its merits. In particular, it allows optimizers to operate with a highly abstract design definition.

The disadvantages of the parametric approach are as follows.

- A significant volume of historical data is required in order to identify parametric relationships in a statistically meaningful manner.
- Historical cost data has to be carefully normalized to avoid misleading errors. Hence, the cost data must be filtered to remove the effects of inflation, exchange rate fluctuations, and unrepresentative (poor?) manufacturing performance. For assembly operations, it is important that the learning curve position and manufacturing efficiency is recorded with the historical data.
- New manufacturing processes and significant changes to methods can invalidate the parametric relationships.
- Parametric methods have limited resolution and cannot be used beyond the narrow class of components for which they have been validated. Parametric methods cannot reveal the cost implications of subtle changes to the product definition. Hence, a parametric cost estimator based on mass would provide identical cost estimates for parts that weighed the same. One part may, however, have very close tolerance features and would, therefore, cost considerably more.

1.2.2. Generative cost estimating. The generative approach uses the emerging product definition to infer a manufacturing sequence and to estimate individual process times. In most respects, this approach is equivalent to generative process planning and requires the same computational algorithms (Shah 1995). The generative approach can be further subdivided into feature-based and feature-recognition methods.

The feature-recognition approach is required when the product model is expressed in terms of design features (Hill 1994). Conversion algorithms are required to derive a product model that is expressed in terms of manufacturing features.

The manufacturing feature-based approach requires the product definition to be constructed using a predefined set of features that have a direct mapping to manufacturing processes (hence the term manufacturing features) (Hill *et al.* 1995). This avoids the need for expensive feature recognition algorithms but can compromise the flexibility of the design function. For this reason, manufacturing feature-based design systems may not be popular with designers whose responsibility concerns functional design aspects.

The disadvantages of the generative approach are as follows.

- It depends on a rich and detailed design definition.
- The algorithms employed can be computationally expensive and may have narrow applicability.
- This approach does not allow costs to be computed in the early design phase when the design definition is still at a high level of abstraction and a complete set of features or geometry is not available.
- The generative approach requires intimate knowledge of the manufacturing processes concerned. This is not true for the parametric approach where historical costs are treated as 'facts' and the manufacturing detail that underpins the cost is not considered or may even be unknown.

2. The ACES project

The Affordable Composites Evaluation System (ACES) is a project funded under the DTI-funded AMCAPS (Affordable Manufacture of Composite Aircraft Primary Structures) programme. This work was carried out for British Aerospace (Airbus) in conjunction with a number of other universities.

The ACES work led to the development of a hybrid costing approach illustrated in figure 1. This diagram represents the design space as a triangular area. The vertical dimension represents the depth of product definition, with the upper apex defining the abstract end of the design space. The horizontal dimension represents the breadth or scope of the design space.

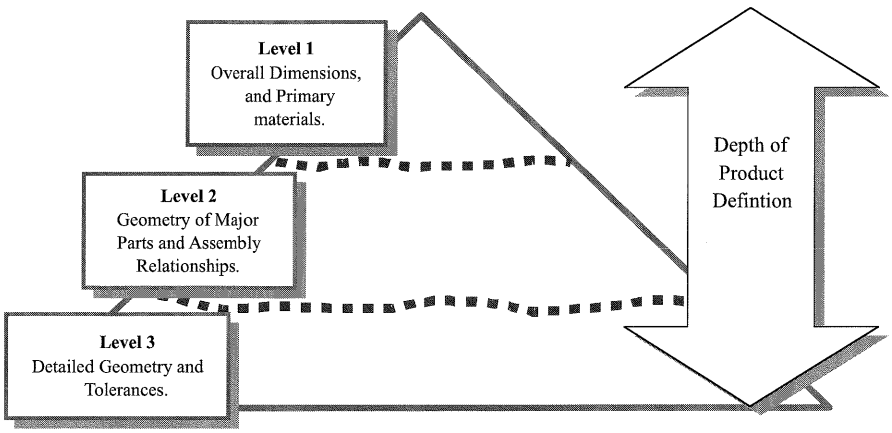

Figure 1. Levels of cost calculation.

- to allow the uncertainty associated with cost estimation to be computed and displayed as a 'cost tolerance';
- to provide multiple levels of cost computation consistent with the incremental emergence of the product model; and
- to provide an experimental environment that will allow designers to gain an understanding of the areas of high cost uncertainty and possible high risk. This will potentially improve the quality of design decision-making.

3.2. Cost exemplars

A key feature of the ICES architecture is the provision of a statistical capability. This allows the entire costing environment to be populated with statistical distributions where there is uncertainty associated with information.

The cost architecture (figure 4) incorporates what have been termed cost 'exemplars', which represent a range of design and manufacturing possibilities for a class of components. The exemplar is a highly detailed and richly populated structure that captures the uncertainty of both the form of the product and the manufacturing possibilities for a class of components.

The exemplar includes a feature-based description that contains default distributions throughout its structure. These express the 'fuzziness' of the class from both a design and manufacturing perspective. This approach provides a seamless transition from the abstract end of the design space to the fully defined product definition. The exemplars avoid the need for discrete and artificially partitioned cost expressions.

In the early design phase, the product definition may contain very little geometrical information. Hence, at this level, the exemplar would return a cost estimate

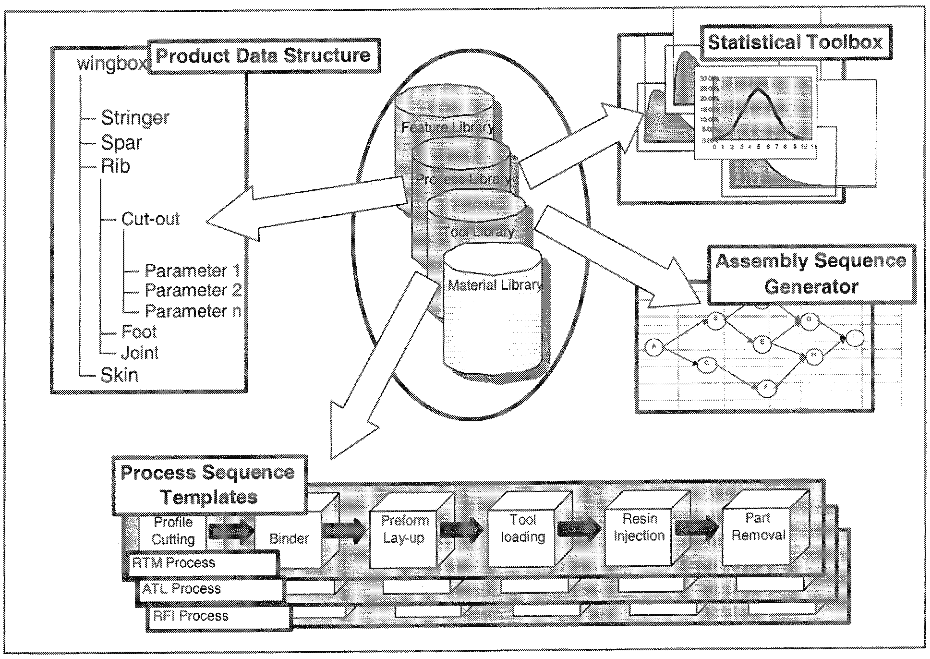

Figure 4. ICES architecture.

based largely on the default distributions. This cost estimate may have a high degree of uncertainty that would be expressed as a distribution with a relatively large standard distribution. This uncertainty will gradually diminish as the product definition matures. At the stage where a full geometric representation becomes defined, the cost estimate will become relatively *certain* but may still contain fuzziness associated with manufacturing uncertainty.

3.3. Experimental work

The initial experimentation concerns the development of two cost exemplars. The first is for wing ribs for medium to large civil transport aircraft, and the second cost exemplar will be for containment and spacer rings for turbofan engines.

The initial challenge has been to develop an object-oriented representation of the class of part that is sufficiently elegant to capture the design and manufacturing space in a single representation. The structure must be highly polymorphic in order to be able to encompass the wide diversity of instances of part in the class 'wing-rib' or 'engine-ring'. This has to be achieved by incrementally overwriting the default distributions within the structure as the full product definition emerges.

The crucial difference between a conventional product data structure and the cost exemplar is that the exemplar has been designed to incorporate *decision tree* structures. These allow the possibility space to be taken into account when costing the emerging product. It allows incipient decisions to be reflected in a costing *before* they have explicitly been made. It is suggested that this will allow the detailed manufacturing knowledge held in the exemplar data structure to be used even at very high levels of abstraction in the conceptual stage of design. This offers the potential for a common costing system to be used in support of the full range of design activity from initial optimization studies to detailed cost estimation.

The two node types within the structure are shown in figure 5. This shows that

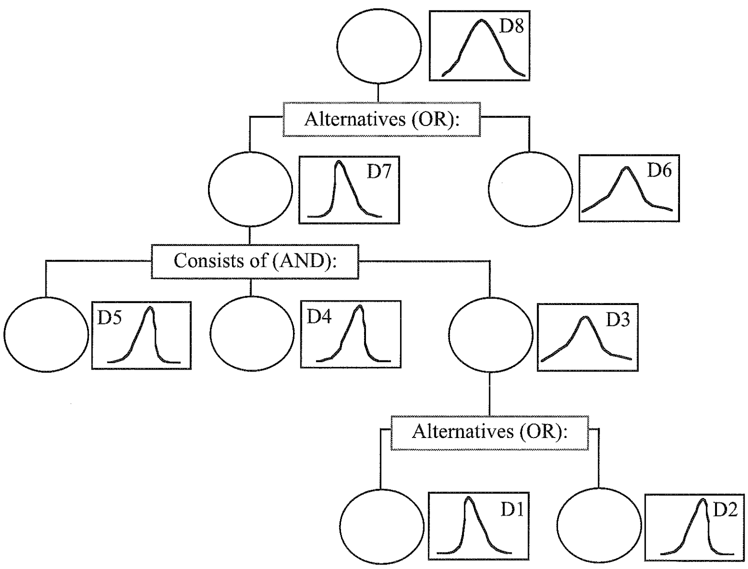

Figure 5. Exemplar structure.

the children of certain nodes are *alternatives* (OR) and this represents a decision point. Prior to an explicit decision emerging, the mean of the child cost distributions is computed. Other nodes represent AND functions where a parent node *consists of* a number of child nodes. In this case, the child distributions are summed.

As the product design emerges, the 'OR' branches will be 'pruned' as decisions are made. Furthermore, as the product data structure is refined, the default distributions held at AND nodes will be overwritten with specific values. Hence, the top-level cost estimate will be continuously refined as the design emerges.

4. Further work

Most of the architectural design issues have been resolved, and the feasibility and utility of the approach will be tested with the two exemplars cited earlier.

4.1. Statistical modelling

A number of matters need to be resolved concerning the generation and processing of statistical data. An analytical approach can be used to aggregate the statistical data for the AND nodes. However, a sampling approach may be required for OR nodes in order to aggregate distributions in a meaningful manner.

The statistical toolkit can model a wide range of distribution types and is hence very flexible. However, it may be that this may make the system less intuitive and easy to use from a user point of view. Trials will assess this issue.

4.2. Assembly sequence generator

The work has so far concentrated largely on detail parts, although some work has been carried out on assembly modelling under the previous ACES project. It is recognized that an assembly build sequence tool will need to be developed and this will be added to the system in order to be able to cost assembly operations.

4.3. Visualization and presentation of cost data

An important objective of the ICES project will be to experiment with ways of presenting cost data in a meaningful way. Some prototyping work has been carried out on a 'cost map', which is intended to illustrate how costs build up from detail parts to final assembly. This could be used, for example, to identify areas of high relative cost or high cost uncertainty.

4.4. Integration

For this work to have direct industrial relevance, it is crucial that the ideas demonstrated in the ICES project can be migrated to the CAD/CAM and business systems used in companies.

A further objective will be to demonstrate how this work can be transferred across proprietary systems that support concept design (such as ICAD from KTI), detail design, and manufacturing planning (such as SAP R3). An important objective will be to show how this approach can lead to pragmatic design decision support tools.

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