Assessing the manufacturability of early product designs using aggregate process models

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Abstract: Designers have no way of establishing, and hence controlling, the likely production consequences of design decisions during the early stages of new product introduction. Aggregate process modelling is a newly developed methodology for the identification and manufacturability assessment of production routeings for partially specified product configurations. The novelty of the proposed approach lies in the close integration of process models with existing product and resource information and the provision of feedback regarding manufacturing issues to control downstream design processes. A description of the methods for early estimation of product manufacturability and their potential application in a design support system, able to prevent the progression of design ideas that would be costly, difficult or even impossible to manufacture, is presented in this paper.

Keywords: automated process planning, manufacturability evaluation, conceptual and embodiment design

NOTATION

a_r	activity-based cost rate of current resource (£/min)
c_j	total job cost (£)
c_m	cost of materials (£)
C_p	process capability
d_r	depreciation rate of current resource (£/min)
D	feature depth (mm)
$f(N)$	function relating number of turns to tool
$g(N_e)$	function used to calculate engagement time
H	feature height (mm)
L	length (mm)
M	material removal rate (cm^3/min)
n	number of repetitions
N	number of turns
s	tool feed rate (mm/rev)
t	cycle time of job (min)
t_a	assembly cycle time (min)
t_m	machining cycle time (min)
v	cutting velocity (mm/min)
W	feature width (mm)
$\varnothing$	cutting diameter (mm)

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1 INTRODUCTION

Closer integration of design and process planning is the best way to reduce the overall design lead time and to avoid designing products that are difficult and costly to manufacture [**1**]. The benefits of integration can be significantly increased if feedback of the manufacturing consequences of design decisions can be provided at the conceptual design stage [**2**]. Unfortunately, existing approaches towards integration have tended to concentrate on the development of detailed analysis tools which extract data directly from computer aided design (CAD). Because these tools usually rely on fully specified models of the product and the manufacturing environment, they are unsuitable for evaluating multiple design and process options. As a consequence, many manufacturing companies operate without any tangible feedback from process planning to design [**3**].

Process selection tools [**4**], design-for-X methods [**5**] and process planning systems [**6**] all play a part in controlling product cost and quality. However, very few of these methods have been updated to take advantage of recent approaches to design integration and standardization such as STEP [**7**], the NIST core product model [**8**] and the new process specification language (PSL) [**9**].

Multicriteria design optimization for incomplete designs [**10**] is now an important research topic. The optimization criteria used commonly include design for cost, quality and life-cycle issues, and these should include political considerations. However, the key industrial drivers remain the production of high-quality products under pressure of time and cost; hence, the aggregate process models measure manufacturability in these terms.

It was proposed by Maropoulos [**11**] that the process planning activity can be subdivided into three levels of granularity according to the availability and completeness of design information: aggregate, management and detailed (AMD). In the AMD architecture, aggregate level planning is designed to link the data available during conceptual and embodiment design with methods for the technical evaluation of various production scenarios. To support the aggregate concept, new techniques have been developed for (a) mapping of functional product features to capable processes and, subsequently, the mapping of processes to available resources and (b) the quantitative analysis of the resulting process plans using simplified process models.

Carrying out aggregate process planning within a distributed enterprise means that a previously unavailable process and resource knowledge is now at the disposal of the designer. For example, designers can obtain instant answers to questions such as ‘Can the component I have designed be manufactured on site?’, ‘How much is it likely to cost?’ and ‘If I reduce tolerances can cheaper processes be used?’. Armed with this new knowledge, the designer can choose to carry out more detailed planning, including digital mock-up or discrete event simulations, to obtain full confidence in the planning of problematic components.

2 THE AGGREGATE MODELLING APPROACH

2.1 Principles of aggregate modelling

Fundamental to the concept of aggregate planning is an intelligent process planning engine, which operates early in the design cycle and which is designed to automatically select the most appropriate process and resource alternatives for a feature-based design and provide a method of measuring the manufacturability of the product. To operate such a system, three manufacturing models are required to store descriptions of the product, the available resources and generic process knowledge. The linkages between these models are shown in Fig. 1. While the product and resource models are simply repositories for information, the process models must contain procedural knowledge and methods for constraint checking and manufacturability evaluation. The main principles for creating aggregate process models are thus:

1. Limited input data requirements. In order to balance the amount of data required with the accuracy of the system, process models should isolate the key factors that contribute to the manufacturability of a product and should be configured to function using the minimum amount of data. The basic elements of a design,

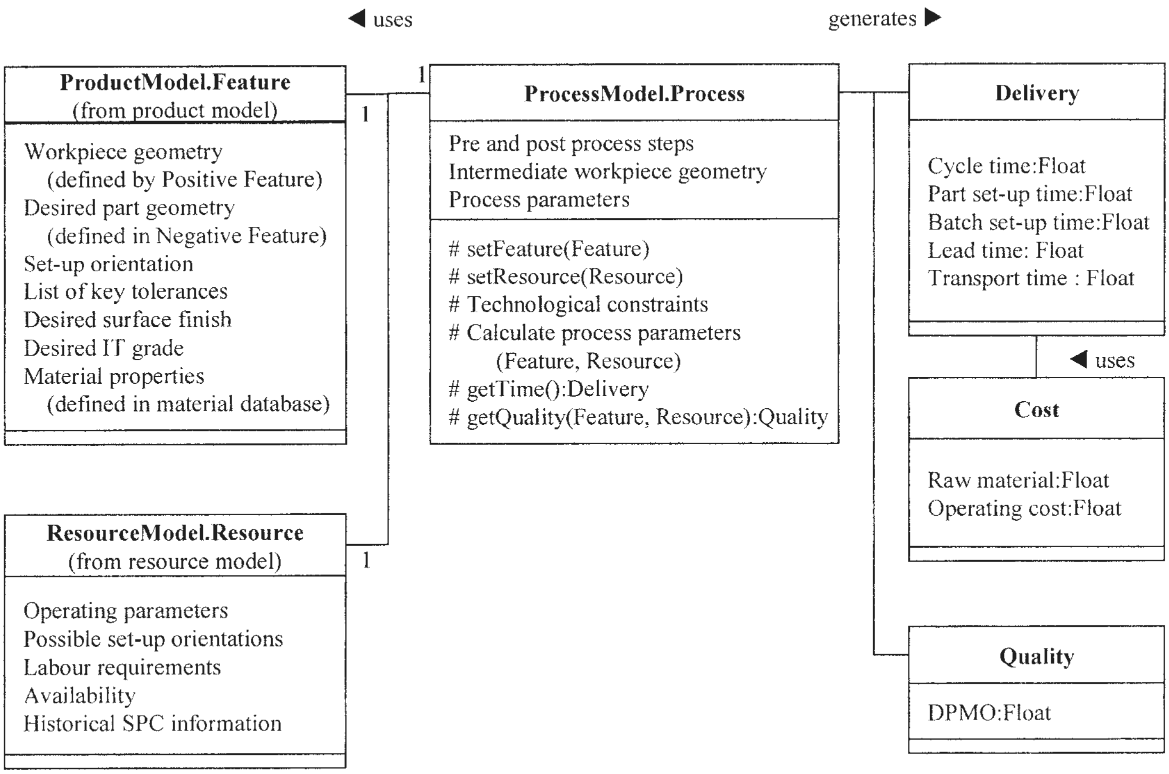

Fig. 1 Process model data flows

such as structure and overall dimensions, should be available to the process models, but exact geometry, tolerance levels and feature locations can often be left undefined until the detailed design. Similarly, the amount of information required to model the available resources within the supply chain should be kept to a minimum. This low information requirement is critical in enabling the real-time technical evaluation of production requirements of multiple conceptual design configurations.

2. Controlled simplification of detailed process models. Through simplification of detailed physical and empirical models, aggregate process models should function with the limited amount of product and resource information available at the concept design stage. The most significant feature characteristics and operating parameters relating to process performance should be used to drive process models. Core capability checks must also be made in order to eliminate infeasible combinations due to mismatches in geometrical or material limitations.
3. Data output requirements. The function of aggregate process models is the automatic computation of estimates for the manufacturability indicators of quality, cost and delivery. Once calculated, these values form the input to the objective function of the process planning engine.

2.2 Aggregate process planning functionality

In the aggregate process planning engine, a simulated annealing algorithm [**12**], not discussed in this paper, is used to find near-optimal combinations of processes and resources to manufacture the features of the product model. The ideal solution is the one that satisfies a multicriteria objective function that includes quality, cost and delivery elements. The focus of this paper is to describe the aggregate representation of features, processes and resources and the mechanism by which valid combinations are chosen and assessed for manufacturability. The functionality described thus represents the generation of a valid 'search space' that the optimization can explore.

3 AGGREGATE ENTERPRISE MODELLING

3.1 Capturing manufacturing information in the aggregate product model

The first stage of aggregate planning is the translation of functional requirements into a feature-based aggregate product model, which must represent the design in a format suitable for early manufacturability analysis. Thus, a hierarchical structure of features and components (which are defined using a minimum amount of production-related data) is the input to the process planning engine.

A *component* is a mechanical part that is composed of a number of aggregate features. To model assemblies a component object may have subcomponents added to it. The precedence relationships of components within the product model hierarchy give rise to the sequence of operations required to construct the top-level component. Hence, the planning results are dependent on the model structure, but because the system does not require detailed product information, multiple product structures can be worked on simultaneously to achieve the optimum design configuration.

An aggregate *feature* represents an entity to be made using a manufacturing process. The feature classes encapsulate the high-level information required to drive the process model equations. Typically, a feature defines the material, shape including key dimensions and a set of process-related information. For example, machining features such as milled pockets, faces and drilled holes contain attributes for the required surface finish and interval of tolerance (IT) grade. Unrelated tolerances, such as diameters for shafts and holes, which are critical for assembly of the components, are added to features so that machine-specific process capability can be calculated by the process models.

Figure 2 shows the design of a honeycomb panel with a reinforced skin. Two different configurations are possible, which will require different processing capabilities and hence have different process times and costs. Figure 2a shows the component constructed from a single 'SkinA'. In this case, the skin A component must be created by chemical etching of the skin surface to produce the 'DoublerA' feature. In Fig. 2b, the same skin A component is made by joining two components. Because two components are required, the joint feature 'JF1' is added. 'JF1' describes the nature of the joint, i.e. the lap and the key geometrical characteristics such as bond area. This modelling schema can be used to construct complex models of early product designs, such as that shown in Fig. 3. This panel is representative of the complexity of a typical satellite floor panel, constructed using the doubler removal process described above. The panel has six major hole features and a large number of smaller holes, which are required to interface with other elements of the satellite's structure.

3.2 Modelling the available resources

As well as being able to compare production methods, the aggregate planning system is designed to take into account the effect of selecting different resources. A description of the capabilities of available equipment, workcells and labour is stored in the resource model. The resource model, which is again constructed by building a hierarchy of object-oriented classes, represents the

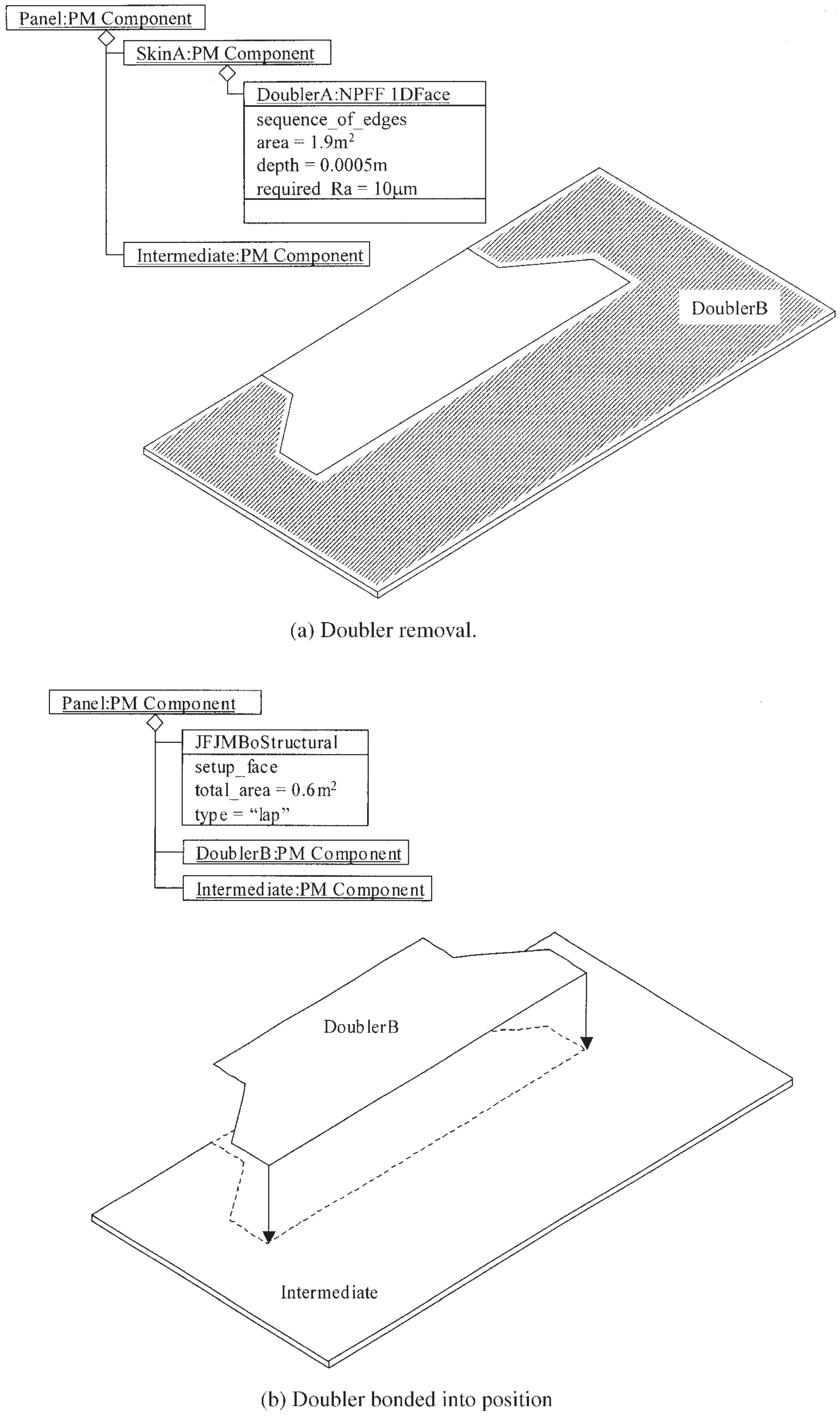

Fig. 2 Alternative product configurations modelled using aggregate features

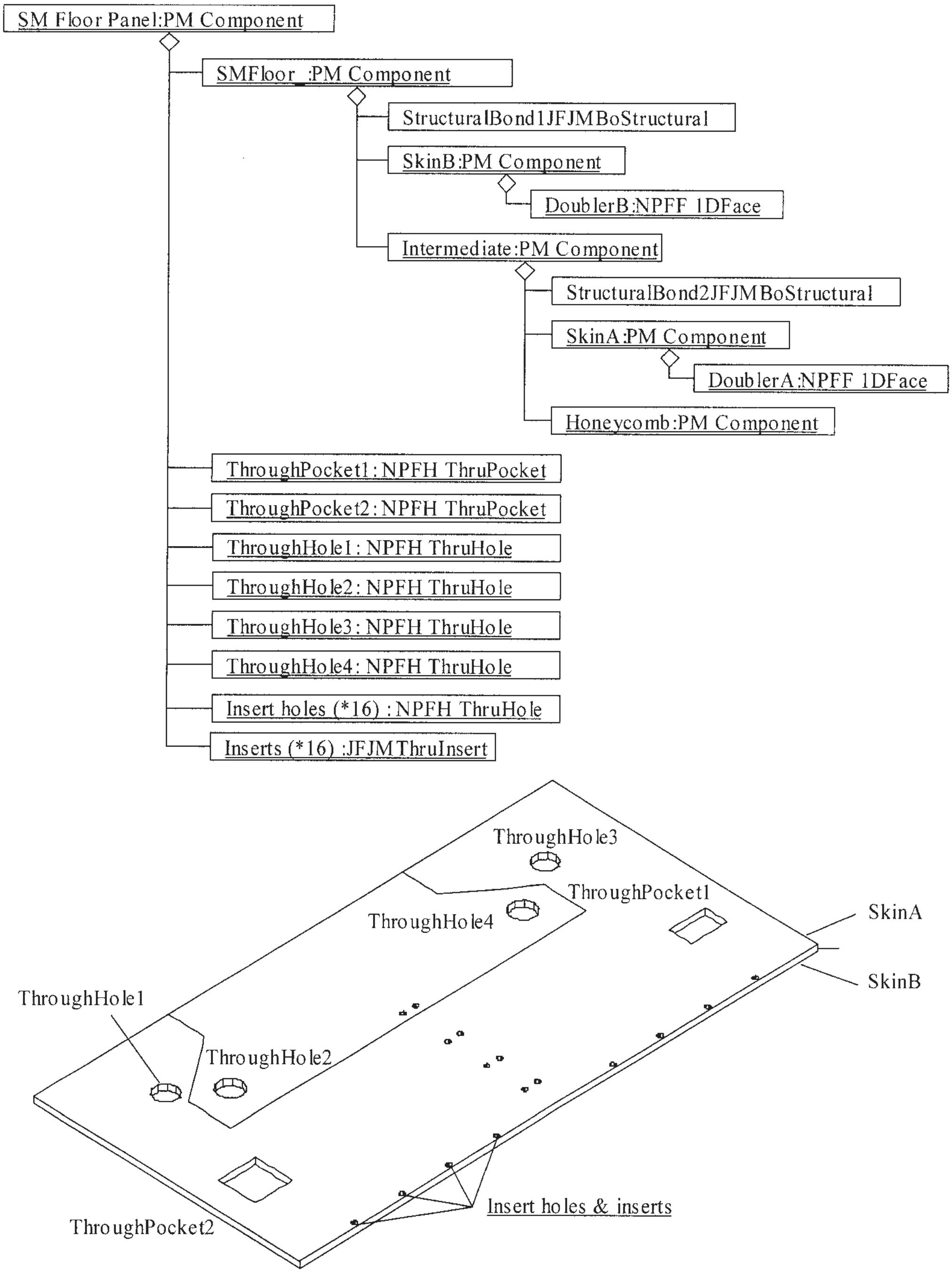

Fig. 3 Product model for a complete 'synthetic' panel

manufacturing system at an aggregate level of detail. The basic information required to add a machine to a resource model includes the footprint, location, maximum operatng conditions, cost and quality data. For the various resource types, carefully determined operating parameters are defined that are essential for executing the simplified process models and performing core technological checks including key attributes. Figure 4 shows a unified modelling language (UML) example of the hierarchy of classes used to create a resource model of a single factory.

3.3 Process model hierarchy

Manufacturing is characterized by two kinds of activities: discrete parts production and the subsequent assembly of these parts to generate the finished product. The hierarchy of process models for discrete parts manufacture broadly follow the classification of Alting and Allen [**13**], which groups processes according to their morphological characteristics. Two broad categories of processes exist within this classification, shape changing and non-shape

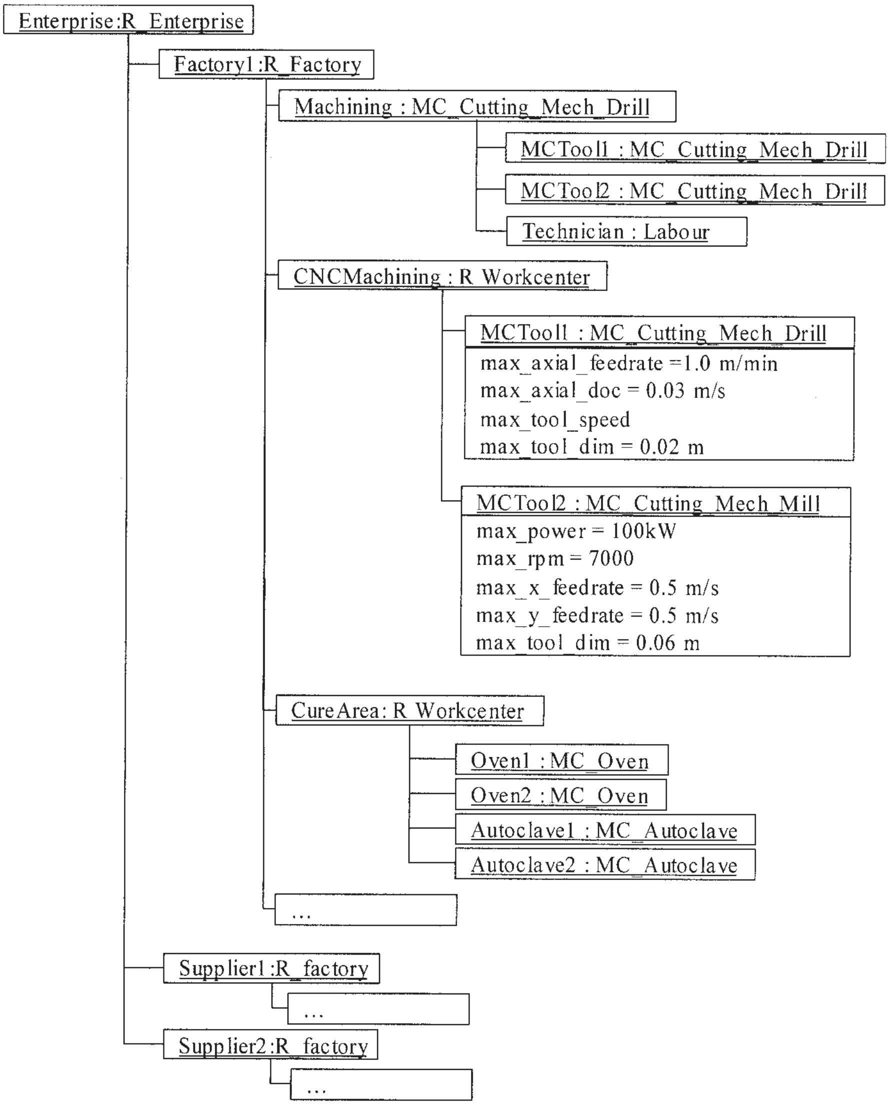

Fig. 4 An example resource model

changing. An object-oriented approach has been adopted to implement the process models, creating a hierarchy of classes (see Fig. 5), which are used to model the different types of process at various levels of abstraction. For each process class that can be instantiated, the aggregate planning system has a set of functions that calculate process times based on the attributes of the selected feature and resource. These functions include subroutines for selecting the most appropriate process parameters, which are outlined in section 4.1.

Assembly processes are fundamental to the manufacture of most products. Assembly operations are further subdivided into two categories: (a) part handling, which defines the orientation and placement of parts, and (b) insertion, fastening and joining, which are the processes used to create the assembly physically. Assembly operations model the joining of multiple parts to form a new subassembly. Assemblies are represented within an aggregate product model through the concept of 'joint features', which link two or more features together [**14**]. The creation of a 'joint' requires a combination of part handling (alignment of the parts) and the physical process of making the joint. The feature-to-process mapping initially selects a method of joining and subsequently the handling requirements are identified based on alignment of the smaller of the two parts to be joined. Process models for mechanical joining processes, such as bolting and riveting, are included in the system as well as adhesive joining processes such as those used to bond the honeycomb-ordered panels, which are found in most satellite bus structures.

3.4 Generating valid process alternatives

Using the assembly structure of the product, alternative production sequences are created. Each type of manufacturing feature in the product model is mapped to one or

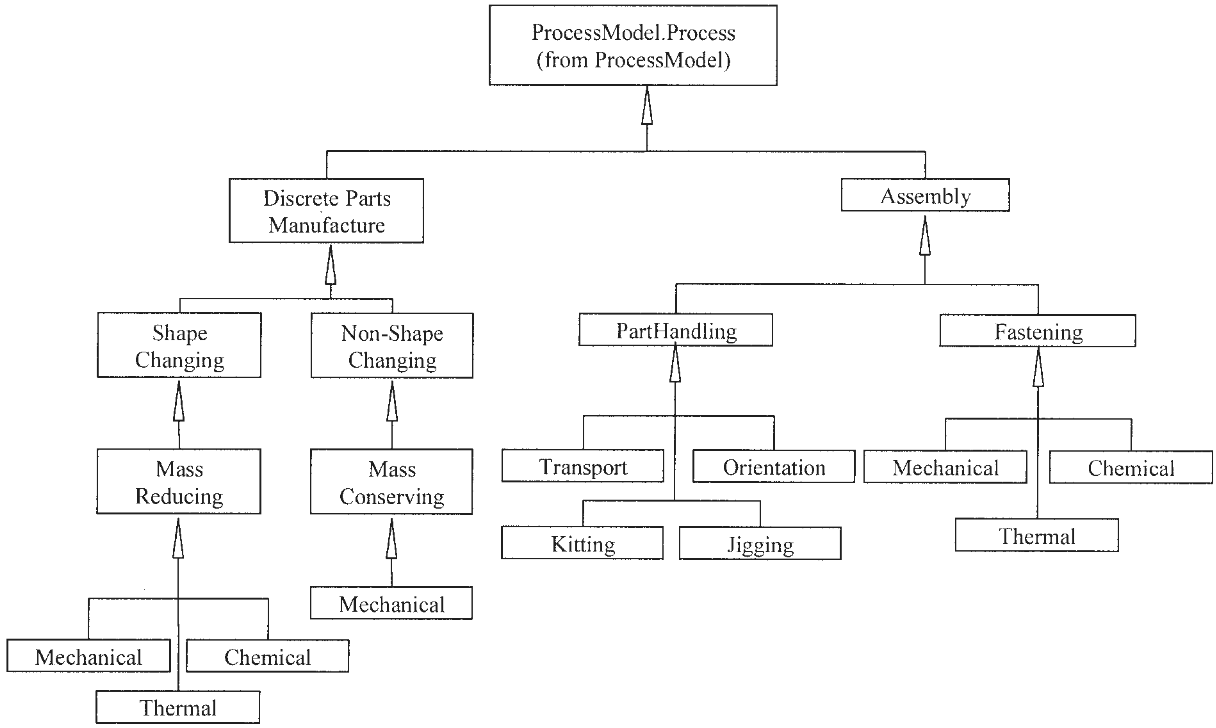

Fig. 5 The process model taxonomy

more feasible production methods in the process model via a compatibility matrix. This matrix encodes the feature (shape)-producing capability of each process model. At this stage, preliminary checks are made to ensure feature-to-process compatibility.

Just as each feature has many process alternatives, each process can be executed on multiple resources in the enterprise model. A mapping of processes to resources is also required. However, the supply network is dynamic and hence the mapping is done at run time. To facilitate this, each resource in the resource model maintains a list of the processes that it can perform. For each process selected in the previous stage, random resources are returned from this mapping. A second set of resource-dependent technological constraints are applied to ensure that the resource is capable of making the required feature object using the identified processes.

4 ANALYSING MANUFACTURABILITY DURING EARLY PLANNING

During early design it is not possible, or indeed desirable, to create detailed plans for a product's manufacture, as the data required may not be available. Additionally, there is a high probability of engineering change, frequently resulting in the need to re-plan. However, during new product introduction decisions revolve around controlling three key metrics: quality, cost and delivery (QCD). Clearly, it would be of great benefit if these metrics could be estimated early in the design cycle. Thus, the aggregate process models are designed to utilize the simplified product and resource models to generate estimates of QCD, which are representative of the final production values. To ensure accuracy when constructing aggregate process models, it is suggested that simplifications are only made where the result will not deviate more than 10 per cent from detailed model outputs. As with any system, continuous monitoring of its performance will be necessary to keep the system up to date. From experience, this 10 per cent target value is realistically achievable and gives sufficiently accurate results to evaluate the viability of a product design and to perform comparisons between alternative production methods; however, the actual accuracy requirement is to be determined by the user.

The functionality required from the process model is, firstly, to check that a process is capable of producing the aggregate feature, as designed. After the initial process selection, based on the shape producing ability, the technological checks are made by the process model to reject any processes incompatible with the feature geometry or surface roughness criteria. As an example, for drilling operations, these technological constraints include geometrical limits such as the maximum drillable diameter, the minimum ratio of length to diameter and the surface finish and interval of tolerance limits of the process [**15**]. Secondly, the process models contain the analytical methods for QCD calculation. For every process, a time-based process model, obtained from the simplification of

Table 1 Calculation of machining times

Process category	Characteristic equation	Parameter selection strategy
Turning	$t_m = \frac{L\pi\varnothing}{1000vs}$	1. Find v, s from machine tool limits/recommended data. 2. Calculate depth of cut (i.e. number of passes required) using maximum machine tool power.
Milling	$t_m = \frac{HWD}{M}$	1. Calculate M for machine tool power. 2. Calculate M according to feature geometry. 3. Select appropriate processing rate.
Drilling	$t_m = \frac{H}{v}$	1. Select v from either recommended data or machine tool limits.

detailed physical models or quantitative analysis, is required. The calculation for delivery time is unique to each process, unlike the cost and quality calculations, which are common to all processes.

4.1 Delivery

The multicriteria optimization functions, which are used to evaluate process plans during the optimization stages, break delivery time down into three major components: set-up times (for both parts and batches), transportation times between resources and cycle time, which is calculated by the process model. At the aggregate level, cycle time calculations for shape-changing process models are based on the assumption that a theoretical maximum process rate, such as the material removal rate, can be calculated. This is based initially on look-up tables giving maximum feeds and speeds suitable for cutting a particular material. These suggested parameters are modified to take into account the capability (available power, table feed rates, etc.) of the chosen machine tools. The geometry of the workpiece is also an important consideration and heuristic methods are applied to determine: (a) the number of set-ups required and (b) the number of passes of a 'generic' cutting tool with default geometry used to estimate the volume of material to be removed in each pass. For parts that have large set-up times (in comparison to their cycle time), the number of set-ups is determined by matching possible set-up faces specified in the product model to tool approach directions specified in the resource model.

Detailed process optimization considerations such as tool life balancing and work-holding forces are omitted. Table 1 shows the characteristic equations and parameter selection strategies implemented for the calculation of cycle time for common machining processes.

The method of generating process models for assembly operations makes use of recent work on assembly planning [**16**, **17**] in which data from Boothroyd *et al.* [**18**] were analysed to determine the relationships between assembly feature connection (AFC) variables on the product model and assembly cycle times. Example equations for calculating the assembly time for common fastening operations are given in Table 2.

4.2 Cost

The main costs in manufacturing are direct labour, machine time required and the raw materials cost. However, it is the configuration of a design that most influences the choice of processing technology and resources which in turn have a large bearing on final product cost [**19**]. Since the aim of the aggregate process planning system is to consider the effect of design decisions and equipment choice on product cost, the operating costs of machines and labour must be apportioned to individual jobs. The two cost rates that have been programmed into the aggregate costing calculation are depreciation and operating cost, which are important for assessing make-or-buy decisions and the evaluation of purchasing new equipment. The standard method for calculating the activity-based cost rate for a resource, a_r, is to divide the

Table 2 Example equations for calculation of assembly time

Process category	Characteristic equation	Operation sequence
Bolt and nut systems (BN1)	$t_a = [(4 + 6n) \times 2.78^{\times 1}] + nf(N)$	1. Collect a handful of bolts. 2. Insert a single bolt and repeat n times. 3. Collect a single nut, tighten and repeat n times.
Screwing systems (SCR2)	$t_a = 8n \times 2.78^{\times 1} + n[f(N) + g(N_e)]$	1. Collect a handful of screws. 2. Engage a single screw and repeat n times. 3. Fasten a single screw with the desired tool and repeat n times.
Riveting systems (RIV3)	$t_a = (10n + 11) \times 2.78^{\times 1}$	1. Collect a single rivet and insert into a predrilled hole. 2. Apply the riveting tool and actuate. Repeat n times.

overall cost of running a resource for a year by the total production time during that period.

The cost of purchasing new equipment is spread over its useful life cycle. In order to include depreciation costs during early planning it is necessary to obtain the cost *per product* so that the yearly depreciation is turned into an hourly cost rate based on an estimate for the resource utilization.

Once the system delivery time for a job has been determined, a cost is calculated according to

$$c_{\mathrm{j}} = c_{\mathrm{m}} + t\sum a_{\mathrm{r}} + t\sum d_{\mathrm{r}} \tag{1}$$

where a resource-dependent activity-based cost rate and a depreciation cost rate are applied. The cost equation includes the cost rates for all resource objects involved in the process; e.g. the cost of processing on a manual lathe would include both a cost rate for the machine and a cost rate for the operator.

4.3 Quality

Quality is measured by estimating the number of defective features produced per million opportunities that will not meet the specified tolerance criteria. Unrelated tolerance information from the product model and the historical capability of a resource (when making similar features) are processed to determine the likely failure rate, $p(fail)$. The cost of the job is dependent on whether the failure requires the part to be scrapped or whether rework is possible. Cost calculations for the two alternatives are

$$q = \begin{cases} p(fail)\sum c_{\mathrm{j}} & \text{for scrap} \\ p(fail).c & \text{for rework} \end{cases} \tag{2}$$

The quality calculation routines are designed to be compatible with both existing quality systems and the aggregate planning paradigm. They work on the premise that, when a new feature with a tolerance is process-planned, historical or expected performance of a resource producing similar features can be used to estimate the likely quality of the new design.

4.3.1 Aggregate product model tolerancing

Geometric dimensioning and tolerancing (G,D&T) refers to the application of dimensions and tolerances to a product model, giving the limits of acceptable deviation of the product's dimensions/geometry from nominal values. Tolerances are usually the last part of a design to be specified. However, since tolerances should relate to the interrelationships between key features, it should be possible, and desirable, to specify them during early design. Another requirement is to deal with product redesign that may contain fully toleranced subassemblies. Hence, the aggregate product model supports the definition of related and unrelated tolerances that are used for discrete part process capability calculations and assembly tolerance analysis using tolerance management systems.

4.3.2 Storing statistical process control (SPC) data in the aggregate resource model

Process capability (C_{p}) metrics are used to measure observed product quality. The most commonly used form of process capability, C_{pk}, defines the relationship between the design specification (i.e. tolerances in the product model) and the quality output of the manufacturing process. C_{p} is closely related to the rate of defects per million opportunities (DPMO). DPMO is calculated as the probability (normalized to one million opportunities) that a process will produce a part that exceeds the tolerance limits. The historical quality performance of a process can be represented as a normal distribution having a mean and a variance, and (for each type of feature) this information is stored within the resource model.

4.3.3 Estimation of DPMO by the process model

Since the dimensions of features in the aggregate product model will not necessarily be exact matches with the stored data, the SPC data in the resource model is queried to find the closest possible equivalent using a case-based similarity algorithm. Once the quality measurement has been retrieved from the resource for a feature/process combination, the DPMO for the new tolerance can be calculated by adjusting the mean value (if necessary) and calculating the area of the distribution (using Simpson's rule), which lies outside the upper and lower specification limits specified by the feature's tolerance. The number of defects for a job is calculated by summing the DPMO for each tolerance on the feature.

The two main advantages of carrying out systematic calculation of DPMO are seen as:

1. Specifications of new products will be automatically checked.
2. The data produced can be used as a basis of making improvements to the manufacturing system.

5 TESTING OF THE EARLY DECISION SUPPORT METHODS

The work described in this paper has been extensively tested as part of the CAPABLE space program [**20**]. The prototype software has been used successfully to process-plan both simple parts and the distributed production of complex satellite bus structures. The creation of process models has been heavily biased towards the space industry; however, a sufficient number of generic process classes have been developed to allow the system to be used with a broad range of product models.

Table 3 Product model data

Prismatic feature	x (m)	y (m)	z (m)	Volume (m^3)	Tolerance T	
					+	×
Positive	0.128	0.104	0.012	0.000 160	–	–
BlindPocket1	0.025	0.100	0.010	0.000 025	0.000 100	0.000 100
BlindPocket2	0.085	0.049	0.010	0.000 042	0.000 150	0.000 150
BlindPocket3	0.020	0.049	0.010	0.000 010	0.000 120	0.000 120
BlindPocket4	0.063	0.049	0.010	0.000 031	0.000 110	0.000 110
BlindPocket5	0.010	0.100	0.010	0.000 010	0.000 090	0.000 090

Table 4 Resource model data

Resource	Type	Power (kW)	r/min	Feed (mm/min)			Quality	
				X	Y	Z	Mean	Variance
H-S VK45-II	M/C centre	11.2	8000	0.16	0.16	0.16	0.1	$3.05 \times 10^{\times 5}$
H-S HG400-III	M/C centre	26.1	12 000	0.25	0.25	0.25	0.1	$2.08 \times 10^{\times 5}$

For preliminary validation of the process models, the heuristics and equations shown in Table 1 were used to generate quality, cost and delivery data for an amplifier chassis component, constructed from a single billet of aluminium and having only pocket and hole features. The product model used for this test is summarized in Table 3. To test the methods for quality estimation, each of the pocket features was given a tolerance (on its z dimension), T. The resource model for this test consisted of two machines, one having better historical process capability (again on the z dimension) than the other, as shown in Table 4. Finally, data from various sources, including tooling manufacturers' catalogues, was aggregated to provide recommended tool feed rates and speeds for this type of aluminium component. Process limits were also identified; e.g. the drilling process was given the following technological constraints: IT grade 11–13, surface roughness R_a, 5–80 μm. Using these data models, processes were selected and routes generated for the part. The results, presented in Table 5, show the QCD values that have been calculated for each job in the process plan, which ultimately form the input to the objective function of the optimizing process planner.

To test the system under more realistic conditions, the system was also used to generate several, alternative, process plans for the 'synthetic' panel of Fig. 3. This panel represents a relatively common panel structure, having doubler removal features on both panel skins. There are six large manufacturing features on the panel, two square pockets and four through holes. A number of small-diameter holes, required for the assembly of the panel to the satellite, were also present. For reasons of confidentiality, the geometry of the product model has been altered and relative values are given to obfuscate sensitive information from the resulting process plan. An enterprise model, which consisted of a main site and three suppliers, was also created.

Several scenarios were run for the satellite example, changing the ratings of QCD in the objective function of the simulated annealing algorithm. The resultant plans, consisting of around 80 jobs, were compared to actual production routeings for similar products and found to have viable sequences of production processes. The stability of the multicriteria optimization process is governed by that of the underlying control algorithms **[21]**. In this case, no problems were observed and multiple runs of the planning engine resulted in virtually identical plans (<5 per cent deviation in QCD), giving confidence in the stability of the simulated annealing algorithm and the repeatability of the system. Several

Table 5 Results of the piece part example

Feature	Process	Resource	Quality (DPMO)	Cost (£)	Cycle time (min)
BlindPocket1	Cavity Mill	HG400III	3.08	1.29	1.20
BlindPocket2	Cavity Mill	HG400III	0.00	1.93	2.04
BlindPocket3	Cavity Mill	HG400III	0.02	0.74	0.48
BlindPocket4	Cavity Mill	HG400III	0.27	1.53	1.51
BlindPocket5	Cavity Mill	HG400III	27.79	1.34	0.48
Positive	Grasp Easy	Labour1	0.00	0.20	2.00

production scenarios were evaluated by changing the weightings of QCD in the objective function of the simulated annealing algorithm. Planning for minimum delivery resulted in cost and quality of components that were 6 and 14 per cent respectively higher than the minimum values. These possible savings were significant given that the critical path of the panel build sequence is in the order of 7000 min.

6 CONCLUSIONS

The main driver for this work was the need to balance product cost considerations against quality and delivery, during the early phases of product and production process design. A solution has been developed for assessing the early manufacturability of individual jobs by relating feature geometry to knowledge about processes and resource operating parameters to estimate process quality, cost and delivery. These methods form part of a larger project, which performs optimization of production routes using these QCD data. The main beneficiaries of such a pilot software system will be companies who integrate high-complexity products and who have large supply chains in which subcontracting decisions need to be evaluated on a more rapid and scientific basis than is currently available.

Very few planning decisions are made purely on the basis of quantitative production metrics. In fact, it is often the experience and intuition of experts that lead to the right choices being made. Capturing the knowledge and experience of these employees is essential to creating more realistic, aggregate plans. This is the aim of new knowledge capture and management tools, which are being developed at the University of Durham. This next generation of aggregate planning will use novel knowledge management methods to analyse the knowledge content of a process plan to identify areas where detailed planning and optimization using tools such as a digital mock-up would be most beneficial.

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