AUTOMATED FEATURE RECOGNITION SYSTEM FOR SUPPORTING CONCEPTUAL ENGINEERING DESIGN

T. J. Jones[1], C. Reidsema[1] and A. Smith[2]

[1]School of Mechanical and Manufacturing Engineering, UNSW, Australia
[2]GKN Aerospace Engineering Services, Port Melbourne, Australia

Corresponding Author: reidsema@.unsw.edu.au,

ABSTRACT:

A computer based Feature-Recognition (FR) process is being developed to extract critical manufacturing features from engineering product CAD models. Feature-recognition technology is used for automating the extraction of data from CAD product models to minimise redundant user interaction with a product model. The feature-recognition process was developed using rule-based methods with wire-frame geometry extracted from an IGES neutral file format. Use of wire-frame models simplifies product geometry and has the potential to support rapid manufacturing shape evaluation at the conceptual design stage. The FR process is demonstrated using a range of typical metallic aerospace components.

Keywords: Feature Recognition, Manufacturing Design Advisor, Neutral Format

1. INTRODUCTION

Rationale

Engineering organisations are under increasing commercial pressure to integrate design with downstream activities like manufacturing process planning, analysis, assembly and inspection [1]. Contemporary engineering design software is typically comprised of two complementary, yet independent types; Computer Aided Design (CAD) software for geometry creation and analysis, and Computer Aided Manufacturing (CAM) software for process planning analysis. Although, they can be found operating together as computer integrated manufacturing suites that support a concurrent design philosophy, they do not bring design and manufacture together early in the design cycle. The point in the design of a product at which a change is most economic is at the conceptual stage, where the downstream manufacturing effects of the change are lowest [2]. This conceptual design phase is where product geometry is sufficient to encapsulate design intent, but does not yet contain detailed shape and manufacturing features. CAD and CAM software are commonly created by independent software developers, and their differing formats and standards can limit the seamless interaction of CAD and CAM operations. As such, design type features of CAD software are not necessarily equivalent to manufacturing features of CAM; commonly design is an additive philosophy and manufacturing is subtractive. CAM software is expensive and a company that provides design services to a manufacturer may not be able to economically justify outlay on these tools. Consequently there is a requirement in industry for tools to provide feedback to the designer about the manufacturing considerations of a product as it is being created. The objective of this research is to develop a Feature Recognition (FR) algorithm for manufacturing support of engineering design at the preliminary design phase.

Existing Software

Historically, there has been little in the way of manufacturing aids available to the engineer to support the conceptual phase of product design. Computer Aided Process Planning (CAPP) tools are available to assist in the creation of detailed process plans, however they tend to focus on a manufacturing process that has already been evaluated. Supporting the design engineer at the conceptual phase requires a feature recognition methodology operating in a period of minutes and able to handle the users CAD format. Tools intended to give early manufacturing feedback to the designer do exist in research [3]. Like CAPP tools, they are commonly directed at specific manufacturing domains like electroplating, machining [4] or metal forming [5] or specific materials like plastics [6]. This research presents a simple and robust FR algorithm for supporting conceptual design models spanning multiple manufacturing domains.

Solution Approach

Design and manufacturing of engineering products commonly involves transfer of information between designers and manufacturers who may be located in different companies and, often, different countries. While each company has different requirements of its software, the CAD model of the product is the most important embodiment of the design and manufacturing knowledge of that product and its designers. Further, engineering companies have differing standards of product data management (PDM), which include: software, modelling practises, version control and file naming strategies. Such differing PDM systems have considerable ramifications for customers and suppliers of these companies. For companies who concentrate on providing engineering design services to a client, the constraints of PDM compliance constitute an enormous overhead to the contractor and may affect the service provider's competitive advantage. Non-specific CAD file formats (neutral file formats) can be used to eliminate problems associated with CAD software and modelling practices. When neutral files are generated from a CAD specific file type, the new file is written in terms of final geometry only and the order of construction (the user's modelling technique) is removed. The neutral file format therefore provides a consistent geometry starting point for downstream FR processes that we believe has not been fully exploited. Additionally, this work is proposing that in the field of contemporary surface and solid based feature recognition techniques, revisiting wire-frame models can provide solutions for less complicated feature recognition methods suitable for supporting manufacturing evaluation of conceptual product models. Such a technique is particularly valid in the sheet-metal industry, where CAD models are still generated in wire-frame for simplicity and can in fact unambiguously represent such products [13]. To further support the development of generic FR algorithms we propose that a common starting point in regard to CAD model geometry be used to eliminate problems associated with applying contemporary FR processes to legacy CAD models. Neutral files can remove the effects of modelling practise and specific aspects of CAD software that can change the hierarchical history of the part without altering the geometry. Such behaviour can be beneficial to contemporary approaches to FR.

2. FEATURE RECOGNITION METHODOLOGY

Existing Approaches to Feature Recognition

FR is an automated technique for identifying and extracting design features from a geometric CAD model in order to obtain manufacturing and analysis information about a product. Feature information is comprised of geometry and design intent in relation to functional requirements. The manufacturing and assembly implications of the product geometry may be deduced by leveraging knowledge of manufacturing process capability, product material and the existence of and relationships between design features. Automating extraction of features from a CAD model has a positive effect on reducing the lead-time of activities downstream of engineering design analysis by minimising user interaction with the product model. Combined with a database of manufacturing knowledge, FR could provide rapid manufacturing upstream feedback advice to the product designer.

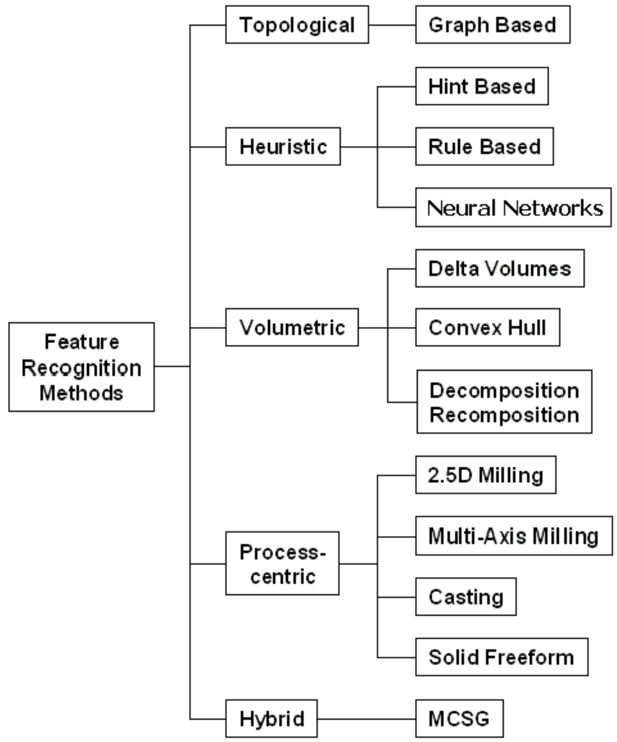

Figure 1: Taxonomy of feature recognition methods [14]

Knowledge-based Engineering (KBE) involves designing a product in which knowledge about the product (design, manufacturing etc) is incorporated into the computer product model . KBE tools for feature recognition are already well established in research [15,16] and may be categorized by the type of algorithm used to identify features. This classification is depicted in Figure 1. Many FR processes in literature have been implemented with a bias toward a specific feature domain like machining [17] or moulding and casting [3, 18]. Unfortunately, process specific FR methods are not generally adaptable to a new domain. For example, feature recognition algorithms designed for 3-axis milling signatures are not generally applicable to the complex shapes associated with cast or forged products. Feature recognition algorithms may be based on:

1. CAD model/system features: design by feature methods, specific to each CAD system;
2. Manufacturing type processes: destruction by machining features, or material removal;
3. Synthesis by design features, more commonly used by contemporary CAD software than type 2 above. Synthesis features encompass addition and removal of material volumes, and so not all design features will equate to manufacturing features. Feature recognition algorithms developed for specific CAD systems may not be sufficiently generic or robust enough for use by a generic manufacturing design advisor tool, therefore a distinction between design and manufacturing features needs to be developed for feature recognition applications.

In each case, features are domain dependent and *"representing and recognizing interacting features is still a bottleneck"* [19] that hinders feature recognition techniques. Features common to one manufacturing or design field do not necessarily appear in the set of features common to a different field. This is important for the company offering design services to clients of different backgrounds because it reduces the utility of contemporary FR algorithms when applied to broader manufacturing investigations. As an alternative to searching for the distinctive pattern of geometry identifying a feature, some FR methods use rigorous naming conventions to deduce a feature from a hierarchy of parent geometry. Such methods, like that of Wu et al [20] are useful for integration of FR with CAD software and used interactively with the designer. Feature naming methods are not useful for handling non-solid geometry or product models that contain geometry only and no parent history of features. Using a neutral CAD format to support FR processes loses existing features and CAD naming conventions, and FR using such methods are no longer useful. An 'online' FR method is not suitable for a post-processing application used by an engineering services provider or for processing legacy models.

Employing characteristic traits or signatures that identify the existence of a feature is common in published FR methodology. Many contemporary FR techniques use some form of hint-based methodology to identify features as the method is simple, robust and expandable. A hint is a pattern in the relationship between faces of the geometry that indicate the presence of a feature. Examples of these methods include the graph-based approach, where the boundary relationships between faces are described pictorially (a matrix for computer based algorithms) and matching a pattern representative of each feature to the product model identifies a feature. For example, Figure 2 shows a part and its representative Attribute Adjacency Graph (AAG) in pictorial form. The AAG method of feature recognition uses patterns in the relationships between faces of a feature to match a library of existing features, or sub-graphs, to the graph assembled from the product model.

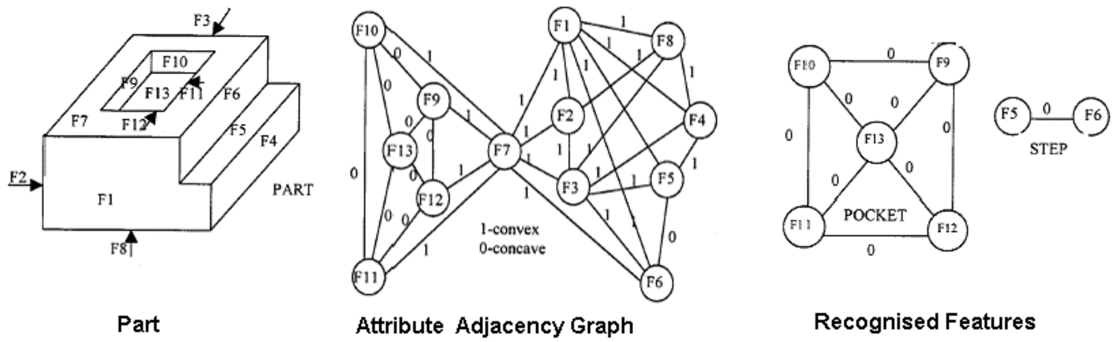

Figure 2: Example of Hint Based Pattern Matching for Feature Recognition [14]

Feature recognition methods like AAG and heuristic methods like hint and rule-based methods offer advantages for development of an Intelligent Design Advisor that include:

1. Low complexity of computer algorithms;
2. Easy user addition of sub-graphs or hints to expand feature libraries; and
3. Robust matrix manipulation routines are commonly available, making processes that utilise them, like AAG and rule-based approaches, desirable from a software development perspective.

While the topological FR methods like AAG suffer from problems associated with the complex algorithms required to define interacting geometry features, many engineering products are composed of simple planar surfaces. Volumetric FR methods like the convex hull and cell-based decomposition methods rely on a process of incremental material removal. The difference between each volume and its convex hull, or the delta volume, can be associated with a particular material removal process. The delta volumes are broken down into volumes for which a known manufacturing process exists. Each difference is subjected to the same process until the difference is null. The group of bottom level shape objects should then, ideally, be representative of manufacturable processes. The volumetric methods avoid complexities of feature interactions by analysing removal volumes that in themselves are reduced to machineable shapes. As a feature recognition tool, it is highly process-centric but capable of handling complex shapes. Similarly, process-centric FR methods are restrictive in relation to their applicative domains and are not suitable for supporting development of a broad range manufacturing design advisor. From the perspective of the engineering services provider, FR methods that are easily expandable and robust with low computational requirements are most desirable. The two part solution of feature gatherer and hint-based combination of multiple FR algorithms, each successful at solving a small aspect of the overall domain has the ability to reduce computational time for FR while maintaining operational flexibility and domain independence. This approach has the potential to create more robust solutions than are currently possible to support a broad ranging manufacturing tool to assist designers at the conceptual product development phase.

CAD Model Types

There are three types of model geometry representations used in Computer Aided Design software [21]. These geometry types are:

1. Wireframe Model, (points and curves of varying complexity);
2. Surface Model; and
3. Solid Model.

Wireframe models are composed of points and curves that represent the edge boundaries of product geometry. Complex part geometry is seldom created in wireframe, however it is easily and automatically generated by neutral file transfer protocols like IGES and STEP. They are computationally easy to handle when compared to equivalently complex solid models, however they can be quite ambiguous in regard to what is 'solid' and what is not, requiring human intervention for interpretation of geometry. This ambiguity has traditionally been too complex to handle with automated feature recognition systems. Feature recognition using wire-frame models has been explored in the past, however contemporary work has shifted to surface and solid models for reasons of model ambiguity [10,14]. We believe that the wire-frame model still has much to offer in the areas of:

1. Feature recognition of legacy product models that are often used in new designs;
2. Lower resource requirements than surface or solid models, necessary for rapid feature recognition;
3. Simplification of complex surfaces and faces to assist rapid feature extraction;
4. Feature interaction, as new geometry is created from solid models at interfaces between features.

Solid models are of two types, the Constructive Solid Geometry (CSG) and Boundary Representation (B-Rep). CSG models are stored in an unevaluated or implicit form, and the final part must be calculated from set theory carried out on solid primitives. B-Rep is an explicit representation of the solid boundary including all vertices, faces and edges. One major advantage of CSG feature trees is that the features may be easily arranged by order of construction or destruction, however CSG is no longer widely used. Geometric solid models in either CSG or B-Rep format evaluate to the same form when translated to a neutral file format, like IGES or STEP. As our proposed feature recognition algorithm does not use specific design features of the CSG modelling format, its application is no more limited than an algorithm using the more popular B-Rep format. In this research, we have elected to revisit wire-frame models for FR to order to exploit their low complexity and reduce time to extract features from a conceptual design model. A side-effect of creating wire-frames from solid models (the generation of new curves at the boundary of intersecting features) can also be utilised to overcome the ambiguous geometry problem for contemporary FR algorithms.

Extracting Data from CAD Software

One common issue associated with feature recognition tools designed to handle generic CAD formats, especially Constructive Solid Geometry techniques is a dependence on known and consistent modelling practices. Neutral files compare well to these FR techniques as a starting point for FR algorithms by providing independence of modelling technique and contributing to algorithm robustness. The International Graphics Exchange System (IGES) and Standard for Exchange of Product Model Data (STEP) are accepted international CAD file standards and commonly referred to as neutral formats [11,12]. One significant problem in developing software applications that utilize a client's CAD product model is that while the client company will have standards for CAD modelling, the construction history and thus the product feature hierarchy of a product can differ between designers for otherwise identical geometry. The use of neutral files provides a number of key advantages to the developer of a FR application:

1. The developer can remain independent of proprietary CAD software formats;
2. Inconsistent modeling techniques used to create a product model can be avoided, as the product feature tree is rewritten using consistent geometry types without parent/child feature relationships.

The marshalling of data provided by neutral files provides a robust and consistent initial CAD model configuration for extracting key elements of the product in order to relate the features of that product to manufacturing process capabilities. Neutral formats allow the designer of a FR application to focus on procedural aspects of feature extraction rather than a tedious analysis of design feature types and their hierarchical history before beginning to extract and order required design and manufacturing features. The IGES format has been selected for its fast and well-documented handling of wire-frame models and no common application protocol is required between file reader and writer as in the STEP format. While the use of neutral formats has advantages, they lose *Design-By-Feature* information, reducing the design intent captured by a product model. Feature-recognition processes may restore this design intent by applying rules of engineering design and manufacture to the product geometry.

The role of feature recognition should be to improve speed and accuracy of iterative computer-aided design operations and to minimise loss of design intent from product models when translating CAD models from one computer system to another, or between computer programs. FR treats the geometry of a product model not as a mathematical form, but as a set of 'features' with inherent attributes related to design intent and function. The first aspect of a computerised tool to match a production process to a product begins with extracting elements of the product geometry to relate to manufacturing process capability. Commercially available CAPP software uses specialised feature recognition processes for this purpose, however their domain specific nature makes them unsuitable for suggesting a process in the first instance. Current literature covering feature recognition highlights the difficulty associated with developing a broad feature recognition method that can be successfully applied to all aspects of the product development process. Loss of design intent in regard to manufacturing has a close relationship with the generic nature of FR processes. Corney et al state that the more process specific one makes a FR algorithm, the more design intent can be extracted from a geometry only product model [23]. The corollary of process specific FR lies in the capability of an algorithm to identify similar geometry but in a different manufacturing context, thereby losing utility as a generic FR tool. The domain of a generic feature recognition tool is potentially vast, even if constrained to certain products and materials, like aerospace metals for example. A number of solutions have been put forward to solve this problem that includes:

1. Development of new Design by Feature CAD systems with more robust feature descriptions [14].
2. Application of rigorous naming conventions to track the interaction of different features [24].

Whilst these methods may go someway towards solving the problems associated with finding features in the first instance, they restrict the software that may be used in terms of the focus of utilisation such as Design for Manufacture (DFM), or model analysis and detail design. Additionally, the design by feature methodology does not address the problem of applying FR techniques to legacy product models, which are a source of valuable Intellectual Property (IP) retained by an organisation. What is required is a combination of various FR algorithms, each successful at solving a small aspect of the overall domain. This approach has the potential to create faster, more efficient, and more importantly, more robust solutions than are currently possible. With prior knowledge of the engineering intent implied by the product model, the user may manually select limited groups of feature recognition algorithms to enhance the execution speed of the combined FR processes. This is important, as time for execution, and computational resources required by some feature recognition algorithms may be excessive for the requirements of a specific application. The designer is interested in feedback on manufacturing alternatives using the outline geometry of the part and complementary information concerning the product material and desired production rate and number. At the conceptual design phase, there is comparatively little information available to support product costing, however with knowledge of relative economics of manufacturing processes, key product features and material combined with production batch sizes, the designer is able to focus detailed features of the design on the suggested manufacturing solution. Such a method is preferable to the traditional 'over the wall' approach to design for manufacture, and further reduces design cycle time in an existing concurrent engineering environment. To facilitate the successful combination of independent FR algorithms, we propose that a common standard for CAD data be used by all FR routines applied to a problem. Such a standard would require:

1. Consistent input data;
2. Dependence on geometry only;
3. An ability to retain and utilise legacy knowledge held by a company; and
4. Alleviate problems associated with transferring product models between independent design and manufacturing organisations.

Feature Interaction

A significant obstacle to robust FR algorithm design is the problem of identifying interacting features. To counter problems associated with feature interaction complexity, the authors are investigating the use of the IGES wire-frame neutral file format as an intermediary between a CAD solid model and a FR algorithm. Neutral files like IGES, while devoid of design-by-feature information used in many contemporary CAD software programs, offer benefits like:

1. Conversion of a CAD model into a standard (neutral) format effectively marshals the data into a consistent and known format that is not subject to variability associated with vendor software or user modelling practices.
2. Model verification: cleanup of CAD files can be problematic for feature recognition processes, as poor modelling practises can lead to split surfaces and curves, overlapping points and so on. Software programming and IGES files can be used to evaluate the suitability of a CAD model for FR evaluation; and
3. Independence of computer aided design software.

Similar methods have been adopted in the past, using STEP neutral files as an integrator of Computer-Aided Design and Computer Integrated Manufacturing software [28], however computational resource problems occur with solid model STEP files and the use of the neutral format to provide consistent data to downstream processes has not been fully explored. Given the pseudo-planar nature of many products in engineering industry (Figure 4 for example), one of the key features of this wire-frame approach is reducing analysis required to extract overlapping features when compared to other surface- and solid-model based algorithms. Simplifying complex surfaces, by assuming that they are planar for purposes of feature evaluation, and searching for key curve-groups that identify features requires less complicated mathematics than for complex surfaces. We do not regard such simplification of the product model as problematic at the conceptual design phase where geometric detail is typically absent and other characteristics of common parts are more likely to sway selection of manufacturing processes. Our proposed FR algorithm attempts to detect features by patterns of geometry that cross some manufacturing domains, but not all; pockets in machining and casting for example. The context of a suitable manufacturing solution can be identified using knowledge of manufacturing process capability and production information, like batch size, surface finish and material, provided by the designer. These techniques are also viable when applied to generic FR benchmark models like those of Han and Rosen [29]. Such an approach, we believe, is more useful for conceptual design manufacturing feedback than highly process specific FR required by CAPP software.

The difficulties associated with handling a wide range of feature types, particularly when a variable number of these features are allowed to interact, is concerning. At the early design stage, manufacturing process capabilities are not yet known and designs contain many features with conflicting manufacturing alternatives, so FR methods must not be process specific. Further, certain FR methods are often more robust when used with surface and solid CAD models (Attributed Face Adjacency Graph and Cell-Based Decomposition for example), however the computer resources required to support such models are much greater than that required for a wire-frame model. The wing-rib model in Figure 4 requires 2.3 times more memory to support as a solid model (3.1 megabytes) than as a wire-frame model (1.3 megabytes). IGES neutral format files typically contain only geometry type data that must be sifted by FR algorithms. Since surface and solid geometry is built on wire-frame data, they require more computer memory than their wire-frame counterparts.

Wire-frame models suffer from problems associated with ambiguous relationships between closed groups of curves. Consequently, the process of determining what is solid, and what is a removal volume, may require human intervention or a complex rule base, but may be overcome using simple mathematical analyses. While from an algorithmic FR perspective the wire frame model solution may be more cumbersome than selecting a surface or solid model, a tool presenting advice to the engineering designer in a small time frame provides more scope for experimentation and conceptual iteration than a complex time-consuming analysis. For this reason the curve based IGES model will be used for development of this generic FR algorithm. Of particular benefit to feature recognition processes, marshalling of product geometry into a structured format through the use of neutral files permits simpler aggregation of multiple smaller feature libraries. This is useful in decomposing the FR problem so that combined algorithms suitable for identifying the most suitable set of features of a geometric shape can be used. Finally, the removal of both design-by feature information and feature creation order reduces the overlap between individual FR algorithms and allows the developer to focus on the manufacturing and analysis aspects of a part without influence from the design processes. This process is effective for aerospace structural components as they are generally defined by planar *machined-type* faces. Consequently all features result in wire-frame outlines contain sufficient information to define the geometry of the feature. Figure 3 illustrates the process graphically for a simple component.

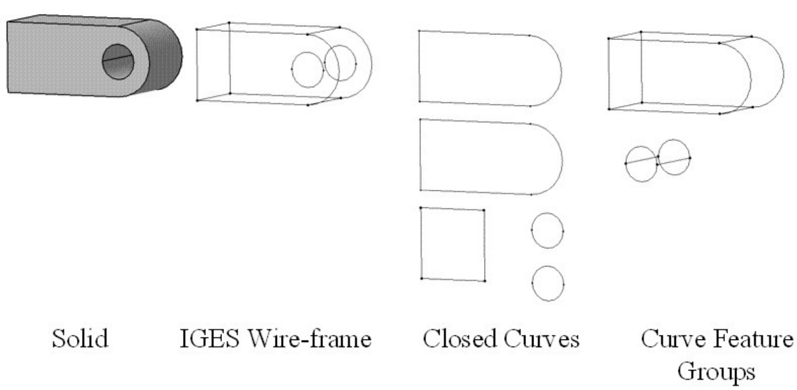

Figure 3: Feature Recognition using Curve Based Models

A solid model of the customers CAD format is first converted to an IGES wire-frame model. The FR algorithm then decomposes the curve geometry into groups of closed planar curve groups and rules are used to relate certain curve groups to others in the collection. Rules establishing common curve and angular relationships between curve groups are used to determine the existence of different feature types that include:

1. Machining features: boss, hole, pockets and slots;
2. Casting/Moulding features: drafts and parting planes;
3. Sheet-metal features: bends and folds; and
4. Special features: Wing rib feet

Selecting a Feature Recognition Method

Current literature covering feature recognition highlights the difficulty associated with developing a generic feature recognition method that can be successfully applied to design, manufacture, analysis or other aspects of the product development process. The domain of a generic feature recognition tool is potentially vast, even if restricted to certain products and materials; aerospace metals for example. A number of solutions have been put forward to solve this problem that include:

1. Development of new Design by Feature (DBF) CAD systems with more robust feature descriptions [14].
2. Application of rigorous naming conventions to track the interaction of different features. [24]

Whilst these methods make progress towards solving the problems associated with finding features in the first instance, they do restrict the software that may be used in terms of the focus of utilisation such as Design for Manufacture (DFM) or analytical or detail design. Additionally these methods do not handle the problem of applying FR techniques to legacy product models, which are a source of valuable Intellectual Property (IP) retained by an organisation. What is required is a combination of various FR algorithms, each successful at solving a small aspect of the overall domain. This approach has the potential to create faster, more efficient, and more importantly, more robust solutions than are currently possible. With prior knowledge of the engineering intent implied by the product model, the user may manually select limited groups of feature recognition algorithms to enhance the execution speed of the combined FR processes. This is important, as low speed of operation inherent in some feature recognition algorithms may be excessive for the requirements of a specific application.

In order to facilitate the successful combination of independent FR algorithms, we propose that a common standard be used for examination by all FR routines applied to a problem. Such a standard would require:

1. Consistent input data;
2. Dependency on geometry only; and
3. An ability to retain and utilise legacy knowledge held by a company.

Such a standard would also alleviate problems associated with transferring product models between organisations. This research uses neutral files for consistent input data, as the effects of DBF and modelling practices are removed from the CAD model in addition providing advantages for the engineering services provider by:

1. Maintaining a competitive resource profile by minimising manpower numbers and skills training in CAD software;
2. Minimising Information Technology (IT) overheads associated with maintaining multiple CAD software licenses; and
3. Ensuring a wide software capability base by remaining independent of proprietary CAD software formats.

Much contemporary FR research uses Hint-based algorithms with solid models for identifying design features in a CAD model. The hint-based approach is regarded as robust, easily modified or extended and a balanced approach to speed and accuracy of feature identification. When one feature penetrates another in a wire-frame model, new wire-frame geometry curves are created at the boundary that can hint to the presence of a feature or, more usefully, the presence of interacting features. This research tests the feasibility of using hint-based methods with wire-frame models to reduce computational time for FR while maintaining operational flexibility and domain independence required of a generic FR tool.

3. FEATURE RECOGNITION DEVELOPMENT

Development Platform

The algorithms in for this research have been developed using Knowledge Technologies International's ICAD™ software. ICAD is a programmable computer-aided design package that allows the programmer to capture knowledge specific to a computer model. Sizing of a shaft diameter based on a stressing code and loads is one example of this application. Both the shaft loads and stressing code are built into the model, meaning that the design should not require the same level of input and analysis when reused in a different context. Using ICAD as a FR development platform provides advantages that include:

1. CAD platform independence; CAD output to many file types, including UniGraphics and CATIA, giving tight integration with company existing software;
2. Deployment on Unix and Windows – operating system and hardware independence;
3. CAD input in a number of neutral formats, including IGES and STEP;
4. Object oriented programming, allowing the creation of specific software modules that are reusable in many different contexts with little effort;
5. Stability – software first released in 1984 and has since been well tested for stability and usability of tools; and
6. LISP Based – one of the foremost Artificial Intelligence languages. Good for representation of logic and decision-making processes when compared to procedural languages like 'C' or Fortran.

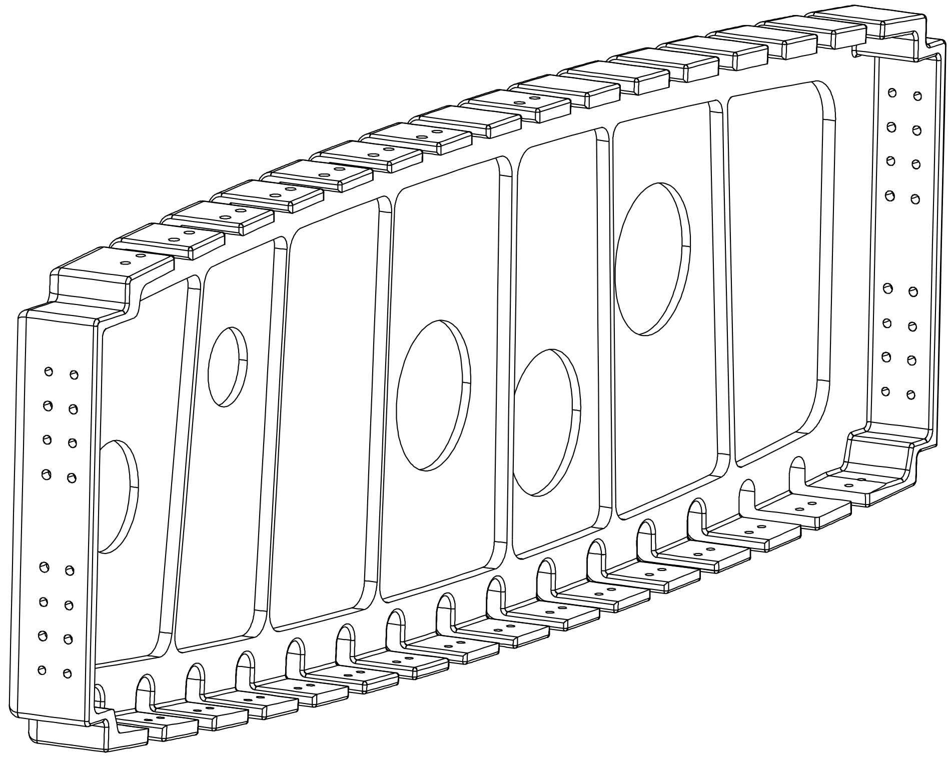

Figure 4: Wire-frame Model of Aircraft Component

Sample products for testing feasibility of a wire-frame FR methodology have been sourced from the aerospace industry. Aircraft commonly contain many similar parts with small variances in shape that have significant influence on selection of manufacturing processes. Parts including a wingrib, Figure 4, and brackets are used to develop our FR algorithm. The small geometry variation in these parts makes the use of FR processes ideal for ensuring design standardisation or testing conformance of shape and expected manufacturing process early in the design cycle.

A New Approach to Feature Recognition

In the context of Concurrent Engineering (CE), there exists in industry a number of computer based tools for reducing the 'over the wall' approach to Design for Manufacture (DFM). They do not, however, fully bridge the gap between downstream processes like manufacturing analysis and the upstream processes of conceptual and detailed design where the most economic impact can be realised. There is a need for engineering companies to develop Knowledge-Based Engineering (KBE) tools to automate the process of integrating early design phases and manufacturing analysis. Computer Aided Process Planning (CAPP) software automates the procedure of matching a product to a manufacturing process; a task traditionally undertaken by a human expert. CAPP software tools are useful for reducing demand on skilled human experts and ensuring the production of consistent process plans by eliminating redundancies and conflicts that arise in complex designs. CAPP tools are not, unfortunately, as adept at dealing with variations in product topography as human experts and do not provide feedback information on cost or the basic manufacturability of a product [22]. Additionally, manual feature recognition is a time consuming task. For the human expert, when experience and creativity are not capable of producing a viable manufacturing process plan, the original design must be modified. Contemporary CAPP software does not yet have the ability to interact with the engineering designer sufficiently early to reduce the chance of creating an uneconomic design or one that cannot be manufactured. Additionally, CAPP software tends to be limited to narrow manufacturing domains in terms of process planning and ability to recognise types of design features contained within the product CAD model. A new methodology is required to overcome both the limitations of recognising features in complex problems and the limitations on manufacturing domain knowledge prevalent in current implementations of CAPP software FR techniques.

We propose that by adopting the hint-based approach of other successful FR methods in current literature, the relationships between groups of closed curves can be analysed and if a set of rules defining a feature is satisfied, information about that feature is returned. This process is very similar to the recognised AAG approach to feature recognition, but without the need for surfaces or solid faces in the CAD model. The collection of rules is a hint of the features existence, and an example of the rules required to find the extrusion feature of Figure 3 is outlined in Table 1. To keep analysis time low, rules are evaluated in order, and if one rule is not satisfied, the remainder are not evaluated. The application of FR processes to wire-frame models also means that in most cases, the boundaries of feature geometry remains consistent, so as not to destroy too many of the distinguishing features of the parent feature. Where the interacting feature penetrates the parent, a new set of curves is created, providing geometry data that completely defines the sub-feature. This work, like many contemporary feature recognition algorithms, is still in development.

Table 1: Rules for Finding an Extrusion Feature

Rule ID	Geometry Relationships
1	Minimum 2 curve groups with highest equal number of curves
2	Both groups from rule 1 must be parallel
3	Both groups must be same size - sum of lengths of all curves in each group. ie extrusion is constant cross section
4	Minimum of (maximum curve numbers from rule1) curve groups must be identified having common curves between both curve groups from Rule1. ie are the two groups of curves connected?
5	Each curve in a group must have a vector matching an equivalent vector within the second group of curves
6	To ensure extrusion is the major part, bounding box of extrusion feature must be close to the bounding box of whole product

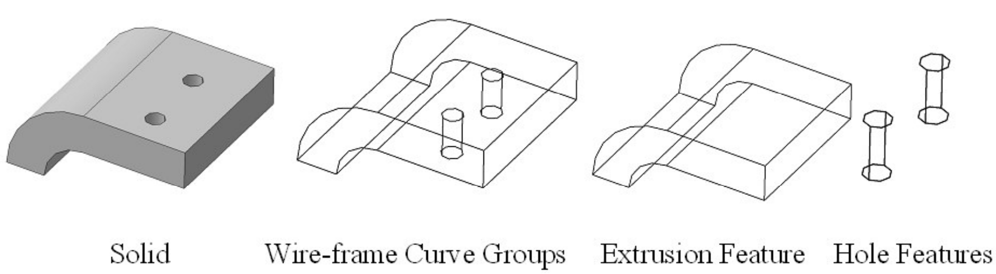

Figure 5: How Wire-frame FR works to identify Wing Rib Foot

The component shown in Figure 5 is one of many identifiable features using geometric manipulation of rule collections. As in Table 2, suitable sets of rules allow identification of features including but not limited to holes, pockets, slots, stiffeners, drafts, sheet-metal features and extrusions.

Table 2: Rules for Identifying a Wing Rib Foot

Rule ID	Geometry Relationships
1	Minimum of 2 groups of closed curves, each with minimum of 6 curves
2	Only two arcs per group of closed curves in Rule1
3	Groups of curves from Rule1 must be parallel
4	Both arcs in Rule2 must not be connected (adjacent)
5	Ray from one point in one curve group must intersect the other curve group from Rule1
6	Minimum of 6 curve groups must be identified having common curves between both curve groups from Rule1. ie are the two groups connected like an extrusion?
7	Both arcs from Rule4 must have parallel vector equivalents in the matching group from Rule1
8	Minimum of one through hole feature must penetrate the two largest area curve groups connecting

Many features in this list require an additional step to test for their status as a 'removal volume'. We propose that the persistent problem of wire-frame model ambiguity can be overcome by testing for the number of curve groups a ray intersects, where the ray begins at the centre of gravity of the geometric points defining the curves of a feature. In order to exit the part, the ray must pass through an arbitrary number of curve groups making up the product, however the last curve group through which the ray passes is always part of a solid volume and not a removal volume. Thus, if the number of intersections is odd, the starting point lies within a solid; if it is zero or even, the point lies within a negative space, or a removal volume. A simple example of this process is shown in Figure 6, a small portion of the rib in Figure 4 testing for whether or not the rib foot like feature at the top is solid or not. The ray, of arbitrary direction, intersects the wire-frame part at the three locations identified by the raised circles on the ray. From the odd number of intersections one can infer that the starting point of the ray lies inside a solid feature.

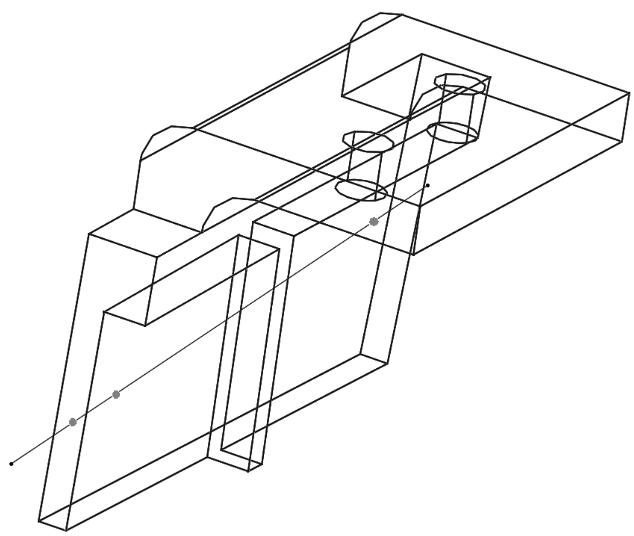

Figure 6: Testing to solve wire-frame model ambiguity

Wire-frame Feature Recognition Example

Described here in pseudo-code is a simplified example of the extraction of a cylindrical hole or boss feature from a wire-frame CAD model, to demonstrate the FR process that has been used in this research. As in the graph-based feature recognition methodology, much iterative computational work in comparing combinations can be removed by capturing the common edge and included angle relationships between curve groups in matrix form.

STEP 1: Collect approximately parallel curve groups, with two arcs only, containing intersecting normals, as in Figure 7:

```
Y = Set of closed planar curve groups, each containing a pair of arcs
only.
For all pair combinations of Y, collect each combination where:
  1. Planar curve group planes are approximately parallel;
     This process groups together the curve sets that define the end
     boundaries of a cylindrical feature. A tolerance is used to
     account for CAD software mathematical precision and holes that
     exit surfaces at small angles.
  2. Curve group normals, beginning at circle group centres,
     intersect; and
  3. Curve radii are equal between groups.
```

If any test fails, test next combination.

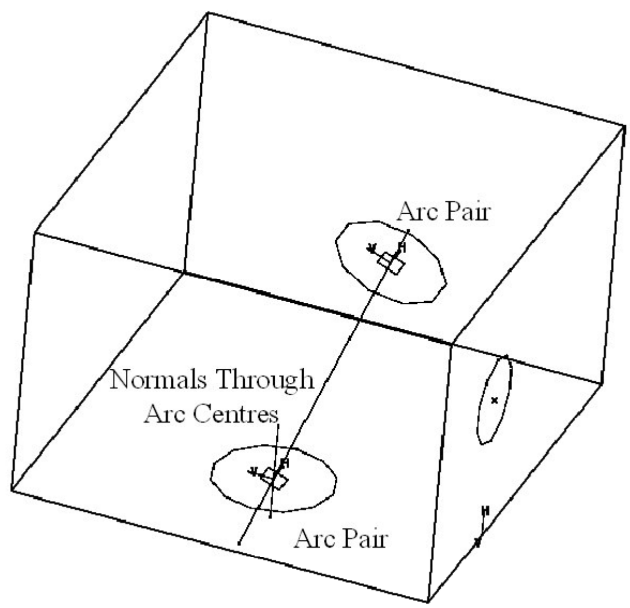

Figure 7: Approximately Parallel Curve Groups with Intersecting Normals

STEP 2: Identify curve groups from step 1 that lie on non-adjacent surfaces. This step removes non-manufacturable curves from the set of possible cylindrical feature curves. The dark shaded shape in Figure 8b shows the non-cylindrical shape that can be inferred from the wire-frame Figure 8a, but is excluded from the set of curves representing cylindrical features.

```
X = Set of closed curve group pairs from step 1
Z = Y \ X (Set of Y minus X.)
If X not empty then
For each member of X:
    Let surf(0) = member of Z that first element of X lies on and within boundary of
    Let surf(1) = member of Z that second element of X lies on and within boundary of
    Let C = members of Z sharing common curve with surf(0)
    Let D = members of Z sharing common curve with surf(1)
    If C ∩ D is nil then
      Store in A, the X cylindrical feature curves.
    End If
  Next X
Else
  "No cylindrical features"
End If
```

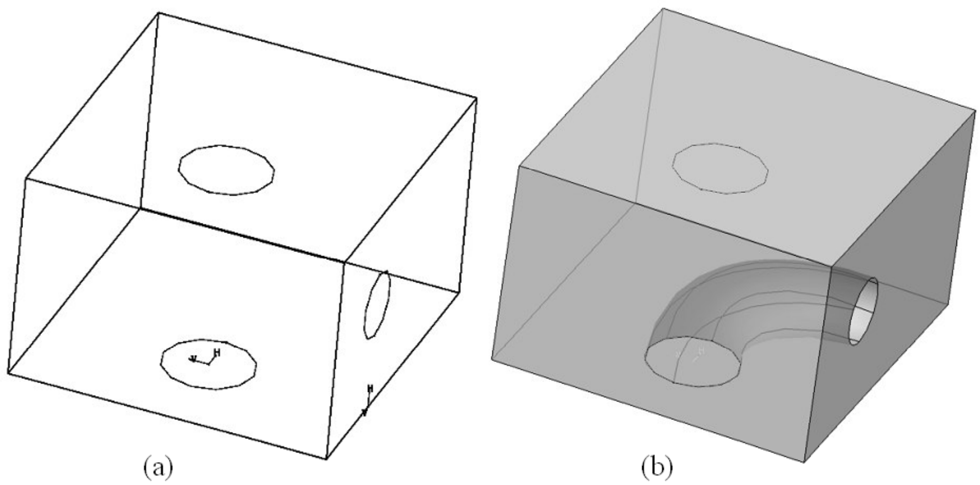

Figure 8: Curve Groups on Adjacent Curve Groups

STEP 3: Test for feature curve groups as 'solid' or 'removal volume', as in Figure 6. This technique uses a 3D variant on the common crossing number (CN) method for testing whether a point lies inside or outside a curve boundary.

```
A = collection of closed curve group pairs from step 2
B = Set of Y minus A.
intersectCounter = 0
If A not empty then
   For each member of A
         Create a ray 'R', beginning at centroid of A, normal to the
           first curve group in A
         For each member of B
              Let P = simplified plane generated from B
              Let Q = R ∩ P.
                   (ie, Q is a point corresponding to the intersection
                     of a line and a plane)
              If CN(B,Q) is odd, increment intersectCounter
       End If
          Next B
              Case: intersectCounter is odd, return A curve groups as
                     hole feature [see Figure 9 for example]
              Case: intersectCounter is even or zero, return A curve
                     groups as solid boss feature
              CaseElse "No cylindrical features"
   Next A
Else
  "No cylindrical features"
End If
```

Figure 9: Result of Cylindrical Feature Algorithm: Removal Volume

The wire-frame method being proposed is aimed at improving the speed of feature recognition processes by reducing the volume of data sifting in the product model and thus the time required to analyse features. IGES neutral files, like finite element analysis files, are text files comprised of points and curves, surfaces and solid entities. The process of hint based feature recognition, like AAG, is essentially a database search of relevant data. Database searches tend to have search times based on an exponent of the number of entities involved. The time required to process a CAD file is important when related to feature recognition algorithm complexity. While the query time for the CAD file itself may scale linearly with the number of data points under investigation [30], the FR algorithm using this data may not scale so readily. This behaviour is particularly evident when calculating minimum distances between points and curves or surfaces [31] or searching for interactions between a two sets of planar curve groups (pseudo-surfaces). Whilst the wire-frame CAD model does have inherent weakness in the ambiguous determination of what is 'solid' and what is not, this problem can be overcome using crossing number theory. A key benefit of the proposed wire-frame approach is the reduction in source data leads to lower computational time for broad domain feature recognition processes.

Additionally, a feature recognition method composed of domain independent hint-based algorithms is expandable by a user, through addition of feature hints or collections of rules. This process is simplified when used to support manufacturing evaluation, as only fundamental features are important. A comprehensive analysis of all features slows down manufacturing appraisal; the presence of a single manufacturing process specific feature is sufficient to demand that process or call for product redesign. The decision making process to determine manufacture requires only those features having an impact on selection of a process capable of satisfying functional criteria of the product at lowest relative cost. The designer should make decisions regarding addition of detailed features to the model by applying design for manufacture techniques from literature or company best practise.

4. FEATURE RECOGNITION TO SUPPORT ENGINEERING DESIGN

Providing the engineering designer with manufacturing process feedback requires integrating knowledge of features extracted from a conceptual product model and a rule base of economic and functional relations to match suitable manufacturing processes to the design characteristics of that model. Contemporary CAPP software creates detailed process plans, using feature recognition with a limited range of application. It is possible that the requirements of domain limited software like CAPP has in the past limited development of FR algorithms capable of recognising features from a diverse range of manufacturing domains. Our proposal for FR supporting manufacturing feedback goes beyond the capabilities of a traditional CAPP system by dealing with a conceptual product model that may have only diminutive feature detail, and covers a broad spectrum of manufacturing alternatives. Utilising computer based techniques for identifying product features and matching them to suitable manufacturing processes gives the designer the opportunity to comprehensively test a large range of conceptual designs in the time traditionally allocated for a limited number.

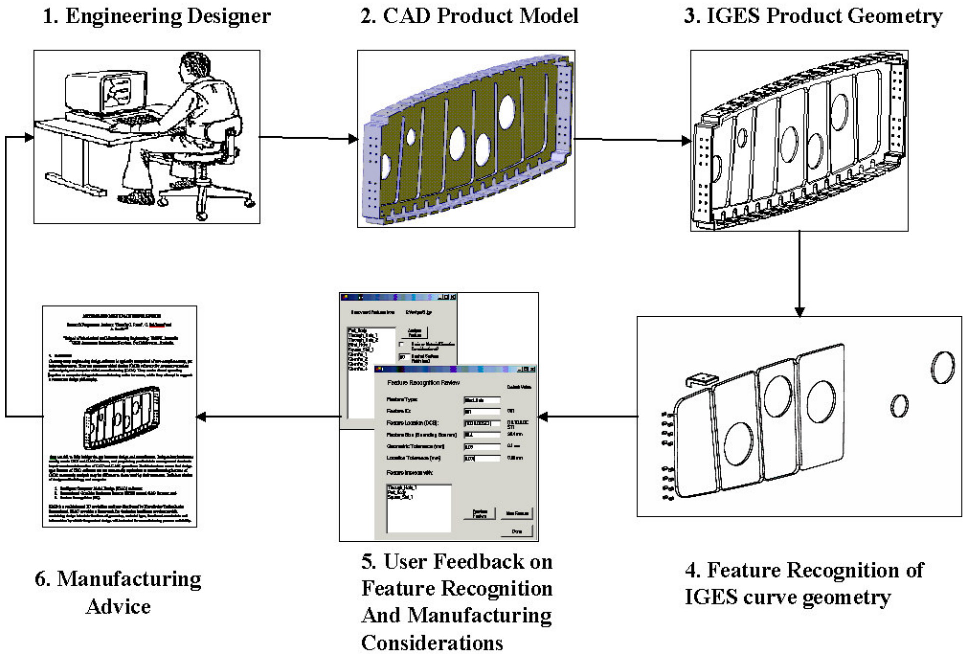

Figure 10: Position of FR and Manufacturing Support in the Design Cycle

The process of using FR for manufacturing feedback to the engineer, outlined in Figure 10, begins with a CAD product model from a designer or client company. The original CAD product model is converted to an IGES wire-frame model and curve group manipulation is carried out using the ICAD system. Rule-based algorithms are applied to groups of closed curves in order to identify fundamental manufacturing features of the product.

The engineering designer is presented with a simple user interface, Figure 11, prompting the user for a neutral file to use for feature recognition and displaying the part for verification. Model verification is undertaken in an automated fashion using Euler-Poincare [10] methods, treating closed groups of curves as a pseudo-surface when solving the boundary model equation. Once the user selects the option to run the Feature Recognition routine, the program generates an XML text file of features and associated characteristics with no further user input. XML is an open source protocol used for transferring data and structure between software programmes that is independent of operating system and computer platform.

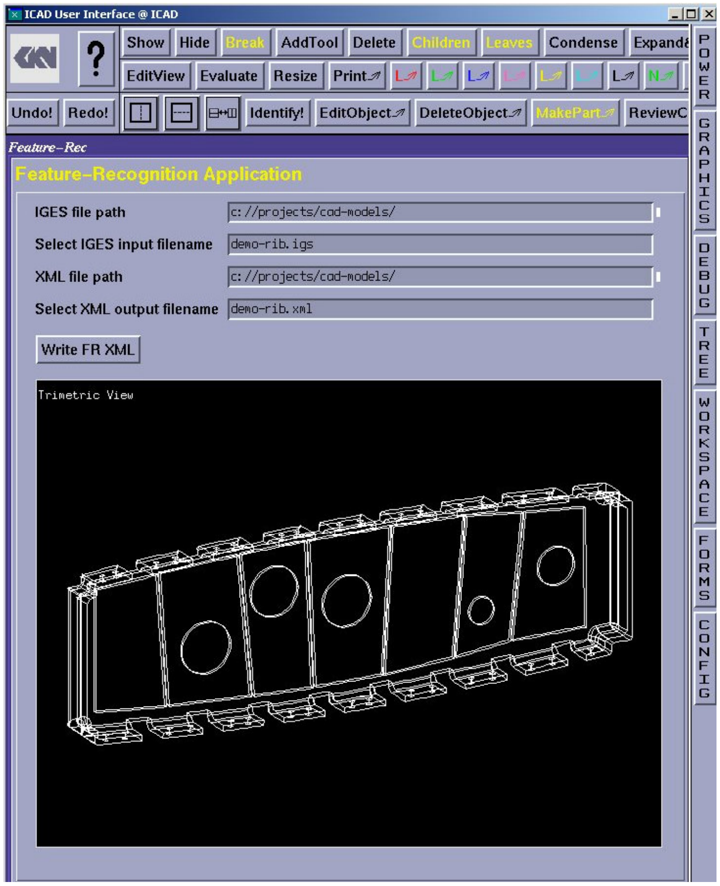

Figure 11: Feature Recognition User Interface

5. FURTHER WORK

The feature recognition work using neutral files and wire-frame product models is complicated by the overlap of feature types and the difference between design features and manufacturing features. Using the web of the wing-rib in Figure 4 as an example, further work is required to distinguish the difference between a series of pockets in a thick web or a series of stiffeners across a thin web. Inference of stiffeners by analysis of any material walls between adjacent pockets in lieu of finding features directly is also to be investigated. At present, however, the approach to supporting manufacturing for conceptual design is achieved not by looking for all types of features that exist in many manufacturing domains, but searches for those features that favour specific processes over others.

To complete development of an integrated FR and manufacturing decision support tool, additional work needs to be undertaken in the areas of:

1. Decision making process, using rules and previous product cases, for evaluating manufacturing process options and matching them to the product model;
2. Complete development of combined feature gatherer and hint-based feature recognition algorithms; and
3. Testing of the decision making process using example parts from industry, like the wing rib of Figure 4.

The decision making process will require development of several supporting knowledge sources:

1. Functional process capability of manufacturing processes. Relationships between manufacturing and design feature types;
2. Economic functions relating relative cost of operations between manufacturing processes and relative cost between different tolerances using the same machine;
3. Relationships of product material to process capability.

It is likely that there will be significant overlap between manufacturing process capabilities and it is unlikely that there is one best manufacturing solution. The objective of this FR algorithm for supporting manufacture is to present the designer with usable recommendations for a process or processes most suited to a product using sound economic and functional rationale. From this recommendation, the detailed design of the product can be addressed by DFM methods very early in the design process. The type of algorithm used to match product geometry to manufacturing alternatives is yet to be confirmed, however manufacturing and design priorities must be set which may be neither explicit, nor exact, and a decision making process should be capable of unique response to these input priorities. This decision-making will be based on what is loosely defined by the industry as 'best practice'. Rule-based reasoning will be selected until the problem becomes sufficiently complex to warrant the use of more sophisticated problem solving techniques like Blackboard Databases or Ripple Down Rules [34,35]. Simple logical rules are simple to generate and test, are undemanding to update and maintain and do not require expensive additional software like expert systems.

6. CONCLUSIONS

With pressure to realize higher quality products for less time and cost, the key to success for an organisation lies in the effective integration of design and downstream applications like manufacturing process planning, analysis and assembly planning. The use of an automated design support tool, integrating cross discipline engineering processes and tools from concept through detail design, manufacturing and support is highly desirable. In this paper we have presented development of a broad approach to FR for manufacturing feedback support to the designer at the conceptual phase of product design. This feedback is provided from feature recognition of a conceptual product model, commonly devoid of all detail but basic shape, and attempts to reduce design cycle time when compared to existing concurrent engineering practice.

Existing hint-based feature recognition techniques have been extended to encompass a broad range of manufacturing domains by utilizing a combination of algorithms, each successful at a small range of features. When combined, these algorithms provide a robust trade-off between computational resources requirements and an FR approach sufficiently generic for manufacturing analysis tools like the proposed Intelligent Design Advisor. Further, the hint-based approach to feature recognition is relatively simple for engineers to update and maintain without the aid of knowledge experts. The feature recognition methods are supported by using neutral CAD files as a standard for data marshalling into consistent formats and an ability to handle legacy product models. The neutral CAD format approach provides a consistent starting point for FR methods and eliminates influences of user modeling practices. Use of the wire-frame form of the neutral format has also the potential to realize a reduction in computational resources, and thus time, required for feature recognition processes utilizing geometry relationships when compared to surface and solid models. Existing approaches to FR are complicated by complex and freeform surfaces and, whilst it sacrifices true design intent, the wire-frame FR methods can assist creation of a rapid, robust tool for a broad range of mechanical products by reducing topological complexity. The ambiguity associated with ascertaining what part of a model is solid and what is not can be overcome through the use of geometry manipulation and crossing number methods. This FR approach does not look for all types of features in a product model that exist in many manufacturing domains, but searches for those features that favour specific processes over others. While not suitable for extraction of detailed feature properties, this simplified method of feature recognition can supply manufacturing feedback to conceptual designers, requiring high speed of analysis and robustness but not necessarily identifying all manufacturing features present in a product model. Mating feature recognition with manufacturing relational data should achieve the aim of providing manufacturing process feedback to the engineering designer at the conceptual stage, reducing design lead-time and cost whilst maintaining high quality standards for which the industry is renown.

7. ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge the contribution from GKN Aerospace Engineering Services Australia in the areas of feature recognition and engineering design support, together with grant support from the Australian Research Council.

8. REFERENCES

1. Ozturk, F., and Ozturk, N., (1999). *Feature Based Environmental Issues: Neural Network-Based Feature Recognition*. Int'l Journal of Vehicle Design, Vol. 21, pp. 190-204.
2. Corbett J., Crookall J. R., (1986). Design for Economic Manufacture. *Annals of CIRP*, 1986, Vol. 35, No. 1 pp. 93-97.

3. Lockett, H. L. and Guenov, M. D. (2005). *Graph-based Feature Recognition for Injection Moulding Based on a Mid-Surface Approach*. Journal of Computer Aided Design, Vol. 37, pp. 251-262.
4. Alberti, M., Ciurana, J. and Casadesus, M. (2005). *A system for optimising cutting parameters when planning milling operations in high-speed machining.* Journal of Materials Processing Technology, Volume 168, Issue 1, pp 25-35.
5. Holland, P., P.M. Standring, H. Long y D.J. Mynors, (2002). *Feature Extraction From STEP (ISO 10303) CAD Drawing Files For Metalforming Process Selection In An Integrated Design System*, Journal of Materials Processing Technology: 125-126, 446-455.
6. Chong, C., Merhar, C., and Ishii, K. (1993), *Simultaneous Design for Manufacturing Process Selection of Engineering Plastics*. Int. Journal. of Materials and Products Technology. Vol. 9, No. 1. pp. 61-78.
7. Shercliff, H. R. and Lovatt, A. M. (2001). *Selection Of Manufacturing Processes In Design And The Role Of Process Modelling*. Progress in Materials Science Vol. 46 pp.429-459.
8. Kheawhom, S. and Hirao, M. (2002) *Decision Support Tools for Process Design and Selection*. Computers and Chemical Engineering, Vol. 26, pp. 747-755.
9. Reidsema. C. and Szczerbicki, E. (1997). *Towards a System for Design Planning in a Concurrent Engineering Environment*. International Journal of Systems Analysis, Modelling and Simulation. Vol. 29, pp. 301-320.
10. Shah, J and Mantyla, M. (1995). *Parametric and Feature Based CAD/CAM*. Wiley and Sons, USA.
11. National Institute of Standards and Technology (USA). [online] http://www.nist.gov/iges/ at 01APR2004
12. International Standards Organisation, number 10303.
13. Jagirdar, R., Jain, V. K. and Batra, J. L. (2001). *Characterisation and Identification of Forming Features for 3D Sheet Metal Components*. Journal of Machine Tools and Manufacture. Vol. 41, pp 1295-1322.
14. Shah, J., Anderson, D., Kim, Y., Joshi, S., (2001). *A Discourse on Geometric Feature Recognition from CAD Models*. Journal of Computing and Information Science in Engineering, Vol. 1, pp. 41-51.
15. Z. Huang and D. Yip-Hoi, 2002. *High-Level Feature Recognition Using Feature Relationship Graphs*. Journal of Computer Aided Design. Vol. 34, pp. 561-582.
16. Holland, P., et al. 2002. *Feature Extraction from STEP (ISO 10303) CAD Drawing Files for Metalforming Process Selection in an Integrated Design System*. Journal of Materials Processing Technology, 2002, Vol. 125, No. 126, pp. 446-455.
17. Kim, Y.S. and Wang, E.,(2002). *Recognition of Machining Features for Cast then Machined Parts*. Journal of Computer Aided Design, Vol. 34, pp. 71-87.
18. Chen, Yuh-Min; Wen, C.; Ho, C.T. (2003) *Extraction of Geometric Characteristics for Manufacturability Assessment*. Robotics and Computer Integrated Manufacturing.
19. Li, W.D., Ong, S.K., Nee, A.Y.C. (2002). *Recognizing Manufacturing Features From a Design-by-Feature Model*. Computer Aided Design Vol. 34, pp. 849-868.
20. Junjun Wu, Tianbing Zhang, Xinfang Zhang, Ji Zhou, (2001). *Face Based mechanism for Retrieving Topology*. Journal of Computer Aided Design Vol. 33, pp. 687-698.
21. Subrahmanyam, S. and Wozny, M. 1995. *An Overview of Automatic Feature Recognition Techniques for Computer-Aided Process Planning*. Computers in Industry, Vol. 26, pp. 1-21.
22. Salomons, O. W. (1994). *Computer Support in the Design of Mechanical Product : Constraint Specification and Satisfaction in Feature Based Design for Manufacturing.* PhD Thesis, University of Twente, Netherlands.
23. Corney, J., Hayes, C., Sundarajan, V. and Wright,P. (2005) *The CAD/CAM Interface: A 25 Year Retrospective*, ASME - Journal of Computing and Information Science in Engineering. Vol. 5, Issue 3, pp 188-197.
24. Yan, X., Yamazaki, K., Liu, J., (2000). *Recognition of Machining Features and Feature Topologies from NC Programs*. Journal of Computer Aided Design, Vol. 32, pp. 605-616.
25. Corbett J., Crookall J. R., (1986). *Design for Economic Manufacture*. Annals of CIRP, 1986, Vol. 35, No. 1 pp. 93-97.
26. Wierda L.S., 1990. Cost Information Tools for Designers: A Survey of Problems and Possibilities with an Emphasis on Mass Produced Sheet Metal Parts, Delft University Press, Delft.
27. M. Ficko, I. Drstvenšek, M. Brezočnik, J. Balič and B. Vaupotic. 2005. *Prediction of total manufacturing costs for stamping tool on the basis of CAD-model of finished product*. Journal of Materials Processing Technology, Volumes 164-165, 15May2005, Pages 1327-1335.
28. Ming, X.G., Mak, K.L., Yan, J.Q., (1998). *A PDES/STEP-based Information Model for Computer Aided Process Planning*. Journal of Robotics and Computer-Integrated Manufacturing. Vol. 14, pp.347-361.
29. Han, J, and Rosen, D. (1998) *Special panel session for feature recognition at the 1997 ASME Computers in Engineering Conference*, Journal of Computer-Aided Design, Vol. 30, Issue 13, November 1998, pp. 979-982.

30. Elmasri, R. and Navathe, S. B. (2000). *Fundamentals of Database Systems, 3rd Ed.* Addison Wesley Publishing, USA.
31. Manocha, D. (1993). *Solving Polynomial Systems For Curve, Surface And Solid Modelling.* Proceedings on the Second ACM Symposium on Solid Modeling and Applications, Montreal Canada.
32. Lovatt, A. M. and Shercliff, H. R., (1998). *Manufacturing Process Selection in Engineering Design. Part 1: The Role of Process Selection*. Journal of Materials and Design 1998. Vol. 19, pp. 205-215.
33. Boothroyd, G. and Dewhurst, P., (1983). *Design for Assembly Handbook*, *University of Massachusetts*, Amherst.
34. Richards, D., (2003). *Knowledge-Based System Explanation: The Ripple-Down Rules Alternative*. Journal of Knowledge and Information Systems, Vol. 5, No. 1, pp. 2-25. Springer-Verlag London Ltd
35. Iain Craig, (1995). *Blackboard Systems*. Ablex Publishing, USA