IMPLEMENTATION OF AUTOMATED MANUFACTURING PROCESS PLANNING IN ENGINEERING DESIGN

Timothy J. Jones[*], C. Reidsema[*] and A. Smith**

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

t.jones@student.unsw.edu.au,

ABSTRACT

Transfer of information between CAD models and downstream manufacturing process planning software typically involves non-productive human interaction. Knowledge acquisition and the reapplication of manufacturing knowledge is a key aspect of automating manufacturing process selection. Many tools are process-centric and unsuited for selection of a "best process" in the context of existing concurrent engineering design tools. The aim of this paper is to introduce an implementation of tools in the ICAD computer system, required to support automated manufacturing process planning; including feature recognition and manufacturing knowledge management. Recommendations include suitable feature recognition algorithms and manufacturing process capture specific to metallic components in the aerospace industry. The application will have the ability to offer advice on appropriate manufacturing options utilising functional and economic criteria of the design.

Key Words: DSS & Expert Systems

1. INTRODUCTION

There is extreme commercial pressure within the engineering industry to reduce non-recurring design costs for new products, while maintaining high quality standards. To be successful, an organisation must effectively integrate design and downstream activities like manufacturing process planning, analysis, assembly and inspection (Ozturk et al, 1999). Consequently, there is a need for engineering companies to develop knowledge-based engineering tools that automate these processes. Some tools exist for limited aspects of this goal, Computer Aided Process Planning (CAPP) being the foremost. To maximise to concept of concurrent engineering, one must go further than this highly specific manufacturing aid, and use the output of CAPP type tools on a conceptual design model to give the designer feedback on suitable manufacturing processes early in the design cycle. Feature recognition provides a useful starting point for fulfilling this task.

Feature Recognition (FR) is a technique for identifying and extracting design features from a geometric Computer Aided Design (CAD) model. This feature information is comprised of geometry and design intent, in relation to functional requirements, and the manufacturing and assembly implications of that geometry. By automating the extraction of design features from a CAD model, FR can minimise or reduce the lead-time of downstream engineering processes. Rapid assembly of feature information invites the possibility of comprehensive analysis of many concepts, in the time traditionally allocated for a limited number. The role of FR in relation to downstream processes and the CAD model is depicted in Figure 1~~Figure 1~~.

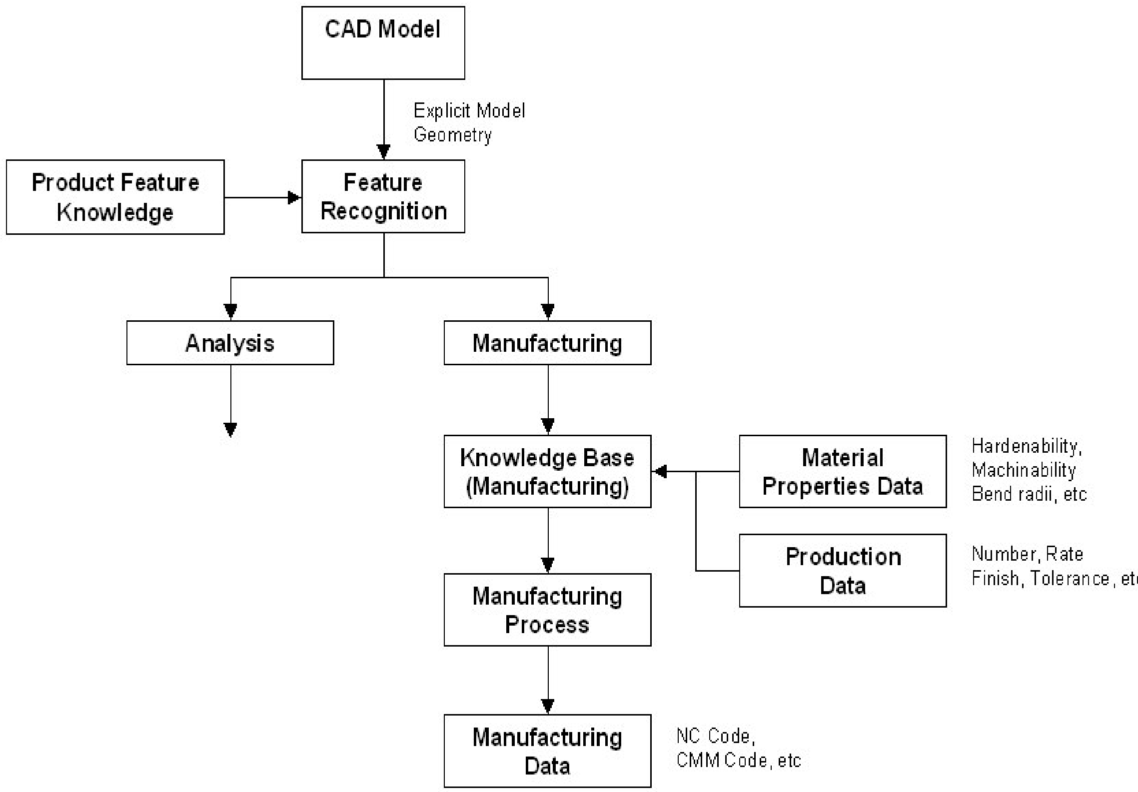

Figure 1: Feature Recognition in relation to CAD model and downstream manufacturing processes

It is suggested that while computer based technologies make the creation of new designs and processes easier (Houtzeel, 2001), they are not necessarily the most appropriate for a particular manufacturing environment. Upwards of 80% of a new design will utilise existing parts or designs. The knowledge captured in past creation of these designs can control the behaviour of this design information when instantiated in a new context. The largest proportion of final product cost is determined during the product design phase. Optimisation for cost in the context of manufacturing process at preliminary design, using concurrent engineering, is most effective in terms of speed and expense. Design is typically the first process in the design cycle and thus easiest to change. The designer requires feedback on manufacturing process options as early as possible in the design cycle. Unfortunately, at the conceptual stage, comparatively little information is available to support manufacturing or costing objectives.

Many CAPP processes are geared towards the creation of manufacturing process plans with respect to a well defined manufacturing domain. CAPP as an in-depth analysis of the detail of a manufacturing process is tailored more towards manufacturing and not design. For example, a component may have a material assigned, or geometric characteristics that control the suitability of available processes, but the software is designed to arrange process specific characteristics of the part and process: its stock, the manufacturing process machinery, machine tools and cutting parameters. No conceptual design information can be extracted from this data. Additionally, much of this work is using a design that is either frozen or finished. CAPP software does not allow the passing of possible manufacturing processes to the designer in the context of concurrent engineering and so we are left with the problem of feeding downstream knowledge to the design engineer at the conceptual or preliminary design phase as illustrated in Figure 2~~Figure 2~~.

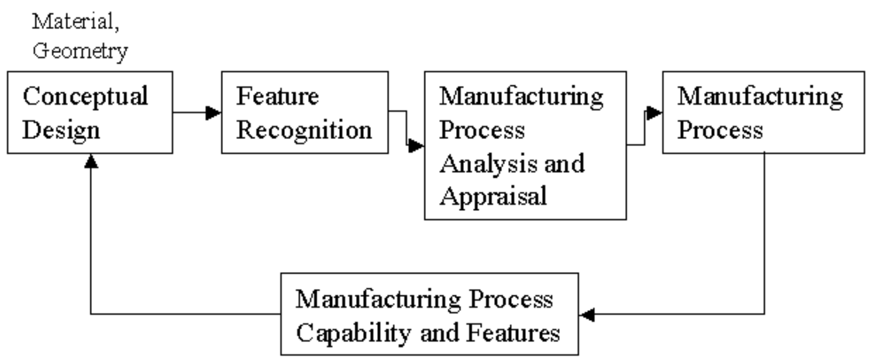

Figure 2~~2~~: Manufacturing Feedback to Engineering Design

Feature Recognition (FR) has existed for decades yet remains a complex challenge (Holland et al 2002, Huang et al 2002, Fu et al, 2002). Contemporary FR processes tend to use domain specific algorithms unsuited to a general manufacturing design assistance tool such as the one proposed. as that should be usable in the concurrent engineering philosophy. FR is a process for extracting information from a computer design model by finding and extracting the features used to create it. This technology is already used by CAPP applications, however the design industry requires a broader scope from FR tools; to handle partial designs and designs lacking fine design detail, and return non-process specific features to assist an intelligent agent to select an appropriate manufacturing process. The intelligence to match a product to a process by means of automated feature recognition goes beyond decision tables of goal, rule and action, by encompassing economic and functional criteria to suggest a manufacturing solution most appropriate to company circumstance – for example, minimum cost may not be as important as manufacturing time for example. Additional drivers are preferred processes of a company, or available plant (scheduling).

MANUFACTURING

At the preliminary stages of design, material, product shape and manufacturing process are relatively independent or soft. (Lovatt et al 1998, Cooper 1998) As the design evolves, the decisions regarding each of these criteria become interactive and thus the interdependencies become harder and more complex. Also present is a difference between design features, typically additive features and manufacturing features (typically destructive features, although with composites this tends more towards additive). The choice of manufacturing processes from design features given this dichotomy of strategies to develop a product can require translation between feature types. There is an additional challenge brought by the current generation of CAD software using feature based design principles. Feature based design makes some recognition processes easier by extraction referencing the CAD design feature set, however this process is not generic. An engineering design company may use a number of CAD tools, and extraction of features may be required from a range of sources, including CAD models, finite element and stress models.

A software tool for engineering design assistance may be based on constraint-based problem solving systems for manufacturing process selection. In such systems, all alternatives remain valid until excluded for reasons of technical, functional or economic unsuitability. The engineering design advisory concept for manufacturing would produce a number of characteristics including:

- Manufacturing process input to design earlier than traditional linear approach aims to reduce feedback time of concurrent design by making available process information and analysis of conceptual product models for manufacturing feature matches;
- Processes are selected based on merit; economic and functional criteria;
- A database of process alternatives and process capabilities may be maintained by manufacturers, suppliers and so on, providing online data sources for designers that are both current and timely.
- Computerised feature recognition and decision-making tools reduce design time and effort by automating iterative parts of the design process.

It should be noted that the requirements for the design process differ between an existing product or redesign of one, as opposed to those for a new product. The design advisor proposed here is focused towards new product design, however the principles should be applicable to the redesign of existing components. To operate within the computerised framework of existing design tools, an IDA requires information about a product. Most product information lies within a CAD product model and this information should be directly accessible by a software tool to reduce double handling of data by the human designer and maximise software performance. To reduce the scope of such a research task, the domain has been limited to the metallic materials and associated processes of the aerospace industry.

SOFTWARE

The computer software selected for a knowledge based engineering tool to support design and manufacturing integration at the conceptual design stage has significant impact on the success of that tool. Existing FR processes are either unpublished or exist as non-commercial implementations. Software encompassing feature recognition processes exist in the engineering domain, like Solidworks. These tend to be limited to design areas only and do not provide sufficient means of linking to manufacturing knowledge (SolidWorks Corporation, 2004). For example, MSC.PATRAN claims to automatically simplify a finite element model by removing fillets, chamfers and geometry not considered important from a stress analysis perspective. A number of factors about software language selection should be considered before choosing a language for implementation; however consideration should be given to:

- Suitability of language for the task;

- Support and maintenance of legacy applications;
- Testing and validation; and
- Licensing and deployment: cost and availability.

A number of knowledge enabled engineering CAD software packages exist in the aerospace design field, including:

- ICAD (Knowledge Technologies International);
- Genworks, Intent, Rule-Stream;
- Knowledge Fusion (Unigraphics); and
- CATIA V5 Knowledgeware.

ICAD is a software programming Computer Aided Design package, with the capacity for:

- CAD output to many file types, including UniGraphics and CATIA, giving tight integration with company existing software;
- CAD input in a number of neutral formats, including IGES and STEP;
- Object oriented programming, allowing the creation of specific software modules that are reusable in many different contexts with little effort;
- Rapid application development;
- Input and output to databases and catalogues; and
- Stability – software first released in 1984 and has since been well tested for stability and usability of tools.

Essentially, software for an intelligent decision support tool should be selected to:

1. Reduce time and cost impact of highly iterative design processes;
2. Capture knowledge of design intent in a product model that is reused upon implementation of the same model in a different context; and
3. Link a design to a decision making process, to select a most appropriate manufacturing process for the product (Jones et al, 2003).

The ICAD system has been selected over others for deficiencies of programmable CAD software in ability to fulfil these requirements, most notably, the stability of the CATIA V5 platform, otherwise seen as an excellent design and analysis tool for the aerospace industry. Implementation of KBE software is common among the larger aerospace and automotive design companies. (Knowledge Technologies Int'l, 2004). The ICAD system has been selected for its capability as a programmable CAD package, using a language with long history of testing and evaluation in the field of expert systems, comparatively low number of code lines for a given task, yielding a low test and debugging overhead. It is important to gain industry acceptance of software selected for a new tool, as it is expected that an intelligent design advisor will work closely with existing 3D CAD systems and manufacturing process costing databases. Increased return on investment resulting from existing knowledge of the ICAD system brings enhanced likelihood of industry acceptance

FEATURE RECOGNITION

In the context of concurrent engineering, the role of feature recognition should be to improve speed and accuracy of iterative design operations and to minimise loss of design intent from product models when translating CAD models from one computer system to another, or from one computer program to another. 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. There is little evidence to suggest that feature information in one domain is of any use in another (Shah et al, 2001). Therefore geometry remains the most important aspect in feature recognition processes. Feature recognition algorithms may be selected without regard for utilization of existing features present in a model, suggesting that use of a neutral file for FR is no worse than a CAD specific file (Shah et al, 2001). Feature recognition processes may be broadly classified by the method used to identify features:

1. Topological;
2. Heuristic;
3. Volumetric;
4. Process-centric; and
5. Hybrid.

Some of these methods are more adept at representing simple and complex features, including interacting features, than others, at the expense of computational resource requirement or risk of combinatorial explosion (Shah et al, 2001). Unfortunately, many processes are, or have been, developed for a specific domain manufacturing or analysis process, and are not suitable for building generic tools for economic implementation by a general engineering company.

Whilst the methods of finding geometry features are numerous, many feature recognition processes use a variety of 'hints' for analysing the existence of product features. This library of feature hints is useful for capturing company knowledge and process, and may be expanded or modified without recourse to altering the underlying algorithm. This combination of feature gatherer and hint based feature recogniser is a hybrid approach to FR and felt to most closely suit the engineering problem posed by matching a product to a manufacturing process.

To counter the problem of part 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 are devoid of design-by-feature information used in many contemporary CAD software programs, and offer benefits such as:

1. Model verification;
2. Independence of user modelling technique; and
3. Independence of CAD software.

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. This limitation partly justifies the need for an analysis and development of robust, multi-domain feature recognition processes for commercial application for engineering design assistance. Most useful to the problem of finding features suitable for general manufacturing process selection and design assistance is that IGES allows us to marshal data into a consistent format (NIST, 2004), making the development of FR tools and associated KBE applications more consistent and robust. An approach is being developed to extract design features from wire-frame models generated by an IGES conversion of a CAD application product similar to that shown in Figure 3~~Figure 4~~. Under co-development with the feature recognition routines is a knowledge base of rules and relations governing the interaction of design and manufacturing features with their associated materials and manufacturing process.

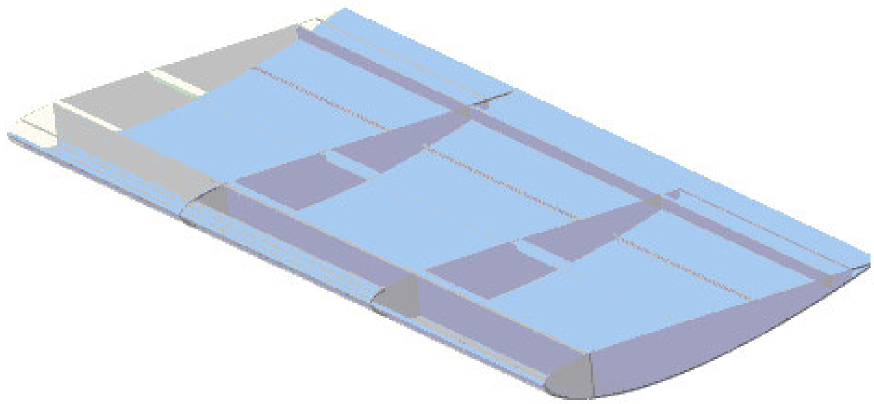

Figure 3~~4~~: Typical aerospace structure used for feature recognition development

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 that contain sufficient information to define the geometry of the feature component.

The effect of interacting features is possibly the biggest hurdle for successful generic FR algorithm development (Gao et al, 1998) The wire-frame model approach is successful at emphasizing through features by the creation of new curves at surface breaches, however blind features remain problematic. Future work may involve the concurrent use of a wire-frame and a solid model for FR algorithms, with features found in one model being isolated from the second by simple use a point cloud match analysis.

An example of operation of this FR process is shown in Figure 4~~Figure 6~~. This part requires the design intent of the product as a whole to determine the likelihood of, say, casting over machining processes, based on a change in section if the same material is specified for both processes. In both manufacturing cases, nominal geometry is identical, however sharp changes in cross section are more suited to a machining from stock process than a casting operation. Design intent in regard to manufacturing process selection for feature recognition algorithms is contained in the product tolerance and surface finish requirements. The existence of parting planes, or overhangs and internal bodies inaccessible by machining tools for instance, also suggest product characteristics that are more suited to one manufacturing process than another. The process specific features of the part in Figure 4~~Figure 6~~ might include:

1. Large depth for a small machining cutter – chatter, low control of tolerance and low production rate;
2. Internal geometry is not suitable for a machine boring operation; and
3. High proportion of material removal suggests that a material removal operation is not the best process to adopt for this part. (Near nett shape processes are desirable for shapes with large internal cavities.)

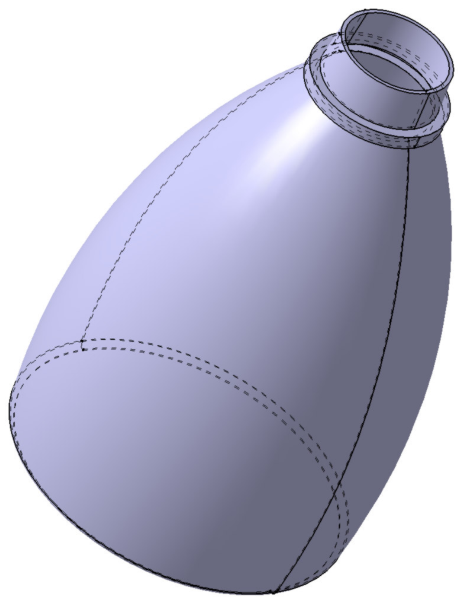

Figure 4~~6~~: Example of part for Feature Recognition through manufacturing

The distinction between manufacturing and design features should be made in the context of FR tools providing design assistance to the engineer. Many existing domain specific FR processes utilise manufacturing type features as a basis for finding those features that constitute the difference between a product and its stock (or convex hull). Further rules or hints can be required to provide a link between the manufacturing (subtractive) features of a finished part, and the additive features used to design that part. The use of a comprehensive library of design and manufacturing features hints will close the design loop to allow automated feedback of possible manufacturing alternatives through an intelligent agent, or Design Advisor, to a designer with ranking using functional and economic design criteria.

DESIGN ADVISOR

To provide the engineering designer with manufacturing process feedback requires an intelligent agent, integrating knowledge of features extracted from a conceptual product model and interaction with a rule base of economic and functional relations to match suitable manufacturing processes to the design characteristics of that model. This intelligent agent goes beyond the capabilities of a typical CAPP system by dealing with a conceptual model that may have only diminutive feature detail, and covers a broad spectrum of manufacturing alternatives. Once a process is selected, a product will need to be fine tuned, using CAPP like CAD/CAM assistance and detail design of the part will need to be developed in a comprehensive concurrent design environment to extract maximum effectiveness from the chosen manufacturing system.

An IDA for manufacturing combines product the inputs:

1. Geometry;
2. Material;
3. Specification or functional data;
4. Manufacturing information, like production number, tolerance etc

These product inputs are combined with manufacturing inputs, including:

1. Knowledge base of manufacturing process capability;
2. Knowledge base of materials and interaction with manufacturing processes;
3. Feature recognition algorithms;
4. Decision making processes;
5. Cost based analysis.

to suggest a suitable manufacturing process from economic and functional criteria presented to the system. This framework is described in Figure 5~~Figure 7~~.

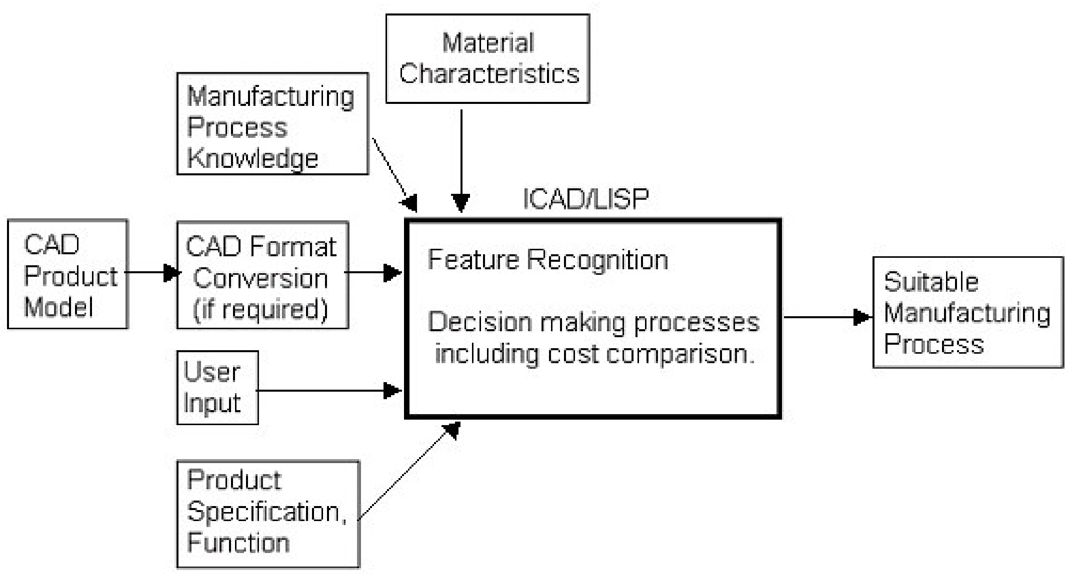

Figure 5~~7~~: Intelligent Design Advisor

The IDA will have the ability to reduce the time involved in selecting an appropriate manufacturing process by:

1. Automating the extraction of features from the product model in order to match them to the process capability of a database of manufacturing processes;
2. Using extracted features and a knowledge base of direct manufacturing costs to analyse the economic trade-off between manufacturing processes once functional criteria are satisfied;
3. Utilising an expandable database of manufacturing processes, larger than the experience of individual designers. Weighting of processes resulting from engineering experience is possible, however a process outside the knowledge of a designer should not be excluded if it can be objectively analysed, at speed, by a computer.

Any manufacturing design advisory system should compare the implications of a manufacturing process on part life, manufacturing cost, operational and maintenance costs, types of processes available to a company and, ultimately, end of life disposal costs. Other implicit goals need also be considered, including minimizing weight, material use, number of assembly operations and so on.

Expert systems and decision-making algorithms are required to return useful output from a knowledge base of design engineering and manufacturing information, by means of functional and/or economic constraint. At the preliminary design stage, products may be modelled with open-ended process capability, for simple or 'common' components, or a specific process capability, typical of larger and unique products. It is with the former that the capability of an intelligent manufacturing advisor becomes most useful.

Additional avenues for innovation include the development and modelling of decision-making procedures using multiple 'soft' design objectives that may define 'best practice'. These typically include minimum cost, weight, material volume, number of operations or time to market, and may be neither exact, nor explicit (Boothroyd et al, 1983). Output of any expert system is subject to interpretation, and is not always possible if too many contra-indications are present in the data and decision process. The aim of an intelligent system should be to give useful or neutral advice to the engineering designer. Through application of functional and economic constraints, the IDA should be a systematic and unbiased method of selecting the best manufacturing process for the product, showing sound judgment and rationality.

CONCLUSION

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 intelligent design support system, integrating cross discipline engineering processes and tools from concept through detail design, manufacturing and support is a method of meeting such a challenge. Combining product feature information with interpretive algorithms will yield a design advisory tool capable of recommending manufacturing processes based on functional and economic criteria.

Feature recognition algorithm types have been selected for adaptability and expandability to the aerospace engineering domain, together with the support of generic geometry only marshalling abilities of the IGES neutral CAD format. Rule bases for economic and functional decision tree are in development. 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.

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.

REFERENCES

Boothroyd, G. and Dewhurst, P., (1983*), Design for Assembly Handbook*, *University of Massachusetts*, Amherst.

Corbett J., Crookall J. R., (1986). Design for Economic Manufacture. *Annals of CIRP*, 1986, Vol. 35, No. 1 pp. 93-97.

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.

Cooper, David J., (1998). Understanding Multi-state Generative Process Planning. [Online] *http://www.genworks.com/papers/sppa.pdf* (12MAY2004)

Fu , M.W., Ong, S.K., Lu, W.F., Lee, I.B.H., Nee, A.Y.C., (2002). An approach to identify design and manufacturing features from a data exchanged part model. *Journal of Computer Aided Design*, Vol. 35 (2003) pp. 979-993.

Gao, S. and Shah, J. J., (1998). Automatic Recognition of Interacting Machining Features Based on Minimal Condition Subgraph. *Journal of Computer Aided Design*, Vol. 30, No. 9, pp. 727-739. Elsevier Science Ltd.

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

Houtzeel, A., (2001). A CAPP Perspective. [Online] *http://www.mmsonline.com/articles/119504.html* (12MAY2004)

Huang, Z. and Yip-Hoi, D., (2002). High-Level Feature Recognition Using Feature Relationship Graphs. *Journal of Computer Aided Design*. Vol. 34, pp. 561-582. Elsevier Science Ltd.

Jones, T., Reidsema, C., Smith, A., Kelly, D. 2003. *CATIA V5 Intelligent Aerospace Design Advisor for Manufacturing Costing*. Proceedings of International Conference on Manufacturing Excellence, Oct. 2003.

Knowledge Technologies International. (2001). [Online]

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.

http://www.ktiworld.com/our_customers/index.shtml (12MAY2004)

National Institute of Standards and Technology (USA). [online] http://www.nist.gov/iges/ at 01APR2004

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.

SolidWorks Corporation, 2004. FeatureWorks. [Online] http://www.solidworks.com/pages/products/solutions/featureworks.html. (16JUL2004)