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A KNOWLEDGE BASED EXPERT SYSTEM FOR MOULDED PART DESIGN

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ABSTRACT

In today's competitive market many consumer products are designed with complex curved shapes to meet customers' demands for styling and ergonomics. These styled products are commonly manufactured using moulding processes because they can produce a wide range of freeform shapes at relatively low cost. However, although injection moulding and metal casting allow a great deal of design freedom they also make significant demands on the designer to ensure that parts are designed with due regard for manufacturability.

This paper describes a knowledge based moulding advisor that has been developed to provide design for moulding advice to designers during the design process. The main contributions of the research are the development of a hierarchical knowledge representation to allow moulding advice to be generated at different levels of detail and the integration of the expert system with a geometric part description extracted from a Computer Aided Design (CAD) solid model. A demonstrator for the manufacturing advisor has been implemented using the expert system shell CLIPS and integrated with CAD using feature recognition.

The moulding advisor is able to generate tailored design for moulding advice for a range of manufacturing processes and materials and evaluate the manufacturability of a designed part at the feature level. The paper provides a case study for a simple moulded test part.

Keywords: injection moulding, metal casting, expert system, knowledge based system, design for manufacture

1   INTRODUCTION

In today's manufacturing industry there is continuous pressure to drive down costs and increase quality. The high level of competition in global manufacturing means that companies must continuously improve their product development processes. Product designs are analysed and optimised from an early stage to ensure that they meet their functional and aesthetic requirements at minimum cost. Design for manufacture is an important part of the product development process because it ensures that the manufacturing constraints of a product are taken into account from an early stage in the process. Bralla [1] states that "the most significant manufacturing-cost reductions and cost avoidances are those that result from changes in product design rather than from changes in manufacturing methods or systems."

Manufacturing engineers are often not involved in product development until late in the design process when it may be too late for them to influence design decisions that might have a major impact on manufacturing feasibility or cost. Effective design for manufacture requires design engineers to have extensive knowledge of the capabilities of available manufacturing processes and materials and the design requirements for those processes. Design for manufacture is particularly important for moulded parts because the cost and quality of parts that are manufactured using moulding processes is highly geometry dependent due to the behaviour of the molten material as it fills and cools in the mould.

The aim of this research is to develop techniques to help designers of moulded parts to incorporate design for manufacture guidelines in their part designs.

2   LITERATURE REVIEW

There have been a number of research projects that have developed knowledge based systems to aid moulding design in the recent years. Chin and Wong [2] developed a knowledge based system for

conceptual injection mould design. Their prototype system EIMPPLAN-1 is able to select appropriate materials and generate mould design features. Tolga-Bozdana and Eyercioglu [3] developed a frame-based modular expert system called EX-PIMM to determine injection moulding parameters and select an appropriate machine and material for a product. Er and Dias [4] describe a rule based expert system for casting process selection with five interconnected levels that take into account material selection, geometric factors, accuracy factors, production run size and cost. These research projects have all developed knowledge based tools to support for some aspect of design for moulding, but they are mostly focussed on manufacturing parameters and mould design rather than to part design. The tools do not provide advice on how to improve the manufacturability of a moulded part design.

There are also a number of analysis based tools that perform simulations to evaluate mould filling or hot-spot detection [5][6] and can evaluate the manufacturability of a part design. These tools use a CAD model or simplified geometry description as the basis for a numerical simulation, but they do not provide advice on how the design could be improved. Yin, Han Ding, Li and Xiong [7][8] developed a geometric mouldability analysis tool for moulded parts which used feature recognition to extract moulding features from a CAD model, but they did not integrate their tool with an expert system.

Past research in expert systems for moulding processes have concentrated either on mould design and processing parameters or on moulding simulation. The aim of this research has been to develop an expert system that is integrated with CAD and can provide design for manufacture advice for moulded part design.

3 DESIGN FOR MOULDING KNOWLEDGE REPRESENTATION

The design of moulded parts requires many different skills. Designers need to consider the product design from many aspects including styling and ergonomics, part function and strength as well as its manufacturability. Depending on the application the designer may start with creative design aspects or with engineering design evaluation.

Traditionally designers have obtained design for manufacture information from experienced manufacturing engineers, but as companies continue to outsource manufacturing activity it can be difficult for young or inexperienced engineers to obtain the support they require. Design for manufacture information can also be found in design handbooks, but it can be extremely time consuming to find the relevant information and can require some experience to interpret the guidelines. A designer may need to refer to many different information sources to find all the relevant information.

The design for moulding information used in this research has been collated from design handbooks; however it could straightforwardly be expanded to include knowledge from industrial experience. The following sections describe the information sources that have been used, and the knowledge classification scheme.

3.1 Design for Moulding Information Sources

Generic design for manufacture information for a range of manufacturing processes can be found in design handbooks such as Boothroyd, Dewhurst and Knight [9] or Bralla [1]. There are also many web based resources that provide generic design for manufacture guidelines such as Efunda [10] and EngineersEdge [11]. More specific design for manufacture information for particular materials can often be obtained from the material supplier [12][13]. Some examples of design for manufacture guidelines from GE Plastics [13] are presented below:

- "Ideally the nominal wall thickness is kept constant due to shrinkage and cooling related issues"
- "In most applications, a thin, uniform wall with ribs is preferred to a thick wall"
- "Where changes in thickness are involved, care should be taken that the direction of melt flow during the moulding process is always from a thick area into a thinner section"
- "Wall thickness variation influences cooling rates of the moulded component and unequal thickness causes an imbalance of cooling… which can result in warping and appearance defects."
- "In order to reduce sink marks on prime appearance surfaces, the base thickness of the rib should not exceed 50% of the adjoining wall thickness." [13]

It can be seen from these examples that the information is often very general in nature, providing the designer with general guidelines rather than specific rules.

3.2 Knowledge Classification Scheme

The manufacturing knowledge that has been collated from design handbooks has been converted into formal rules for use in the expert system. Design rules have been extracted manually from the guidelines, and the design parameters have been separated from the design rules and stored as facts. Separating the rules from the facts allows rules to be stored in a generic form where possible to increase flexibility and avoid repetition in the knowledge base. When a rule is fired the generated advice is tailored using the relevant facts for the specified manufacturing process and material. Table 1 shows an example of a design for manufacture guideline relating to draft angle design for sand casting [11] and the design rule and associated facts that have been extracted from the guideline.

Table 1. Sample Manufacturing Guideline with extracted rule and facts.

Manufacturing Guideline (source [11])	**Draft Angle** To facilitate removal of the pattern from the weak brittle moulding sand cast draft should be defined and accounted for. Standard draft for sand casting is 2 degrees with a minimum of about 1 degree for external and internal features.		
Extracted Rule	Parts must be designed with appropriate draft angle to facilitate removal from the mould		
Extracted Facts	Sand casting nominal main wall draft angle	=	2°
	Sand casting features minimum draft angle	=	1°

The manufacturing knowledge has been encoded using a classification scheme to allow each piece of knowledge to be associated with its reference source. The classification scheme uses a three letter code to define the relevant manufacturing process, followed by a one letter code to indicate whether the knowledge is a rule or a fact, and a unique identifier for the knowledge item (for example SCF1 refers to sand casting fact number 1).

The manufacturing rules are classified into a hierarchy of generic, process and feature specific rules as shown in Figure 1. The objective of using a hierarchical rules classification is to define the scope of application for each rule, and to allow the moulding advice to be tailored based on the available design information.
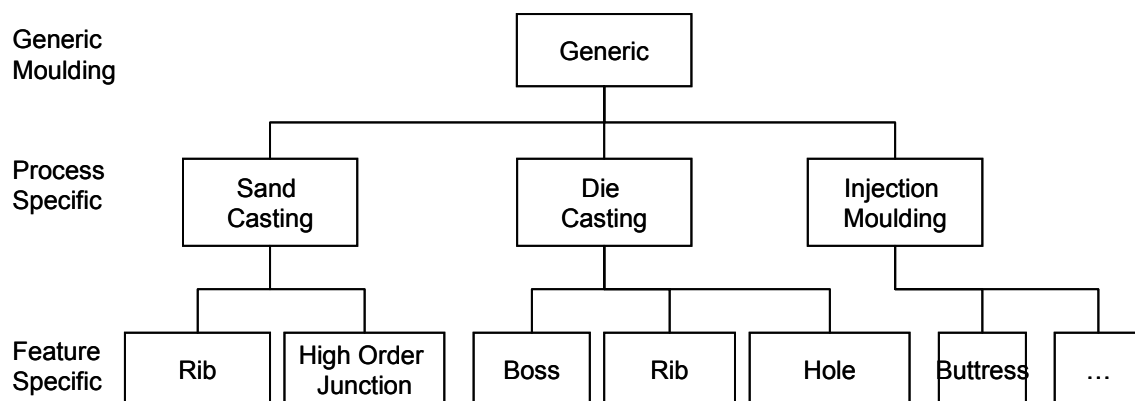

Figure 1. Moulding Rules Hierarchy

The facts are also structured in a hierarchical manner. Figure 2 shows an example of the facts hierarchy for the minimum wall thickness parameter. The facts hierarchy allows the parameter values to be refined based on the available design information. For example in Figure 2 the minimum recommended wall thickness for sand casting is stated as 6.35 mm, but for sand casting using aluminium alloys this value may be decreased to 2.54 mm. In some cases the parameter values may be inconsistent if they have been collated from different information sources.
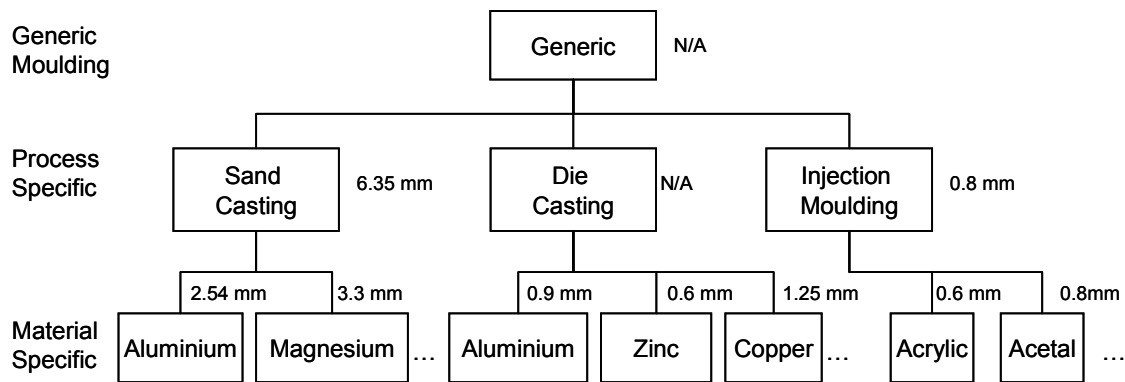
Figure 2. Sample Facts Hierarchy for Minimum Wall Thickness

4 EXPERT SYSTEM ARCHITECTURE AND IMPLEMENTATION

The moulding advisor has been implemented as a knowledge-based expert system. Manufacturing knowledge is encoded in the system as production rules, and a forward chaining strategy is used to generate appropriate manufacturing advice. A top level diagram of the manufacturing advisor architecture is shown in Figure 3.
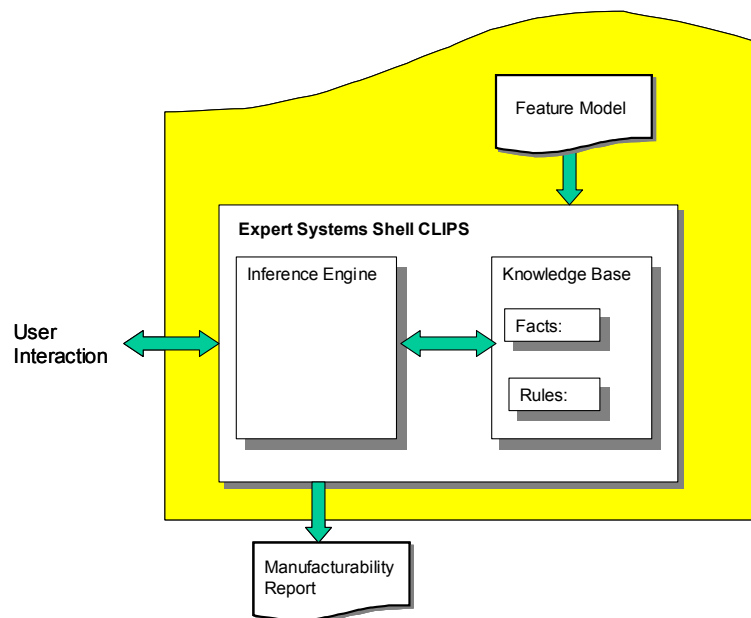

Figure 3. Moulding Advisor Expert System Architecture.

The expert system has been developed using the expert system development environment CLIPS (C Language Integrated Production System) originally developed by NASA in the 1980s [14]. The user interacts with the program through an interactive dialogue session, and the program can also read design information from a CLIPS formatted input file. The input file facilitates integration between the expert system and a CAD model. Design features are identified from a CAD model and written to the CLIPS file using a feature recognition methodology developed by the authors [15]. The design for moulding results are output as a manufacturability report.

Rules are stored in the expert system in premise/ action pairs. Rules are defined as an antecedent (the "if" portion of the rule) and a consequent (the "then" portion of the rule). A pattern-matching operation is performed to match the antecedent conditions and determine whether the rule should be fired, and if the conditions are met then the set of actions in the consequent is executed. The moulding advisor contains two types of rules: firstly rules to elicit design information from the user or feature file, and secondly manufacturing rules to generate tailored manufacturing advice.

The knowledge elicitation rules form a flexible user interface for the system and guide the user to provide all the required information. Flexibility is achieved by controlling the rule firing based on the user's responses to the knowledge elicitation rules. The user can respond "unknown" to any question which will trigger the system to ask further questions that will allow it to assign appropriate answers. The system also allows the user to specify design preferences that will further tailor the moulding advice results. For example in the demonstrator the user can specify the relative importance of appearance and strength for their part, which will further influence the rules that are fired and the advice that is generated.

The manufacturing rules are fired in response to the design information that is input by the user. Table 2 shows an example of a knowledge elicitation and manufacturing rule.

Table 2. Example Knowledge Elicitation and Manufacturing Rules

Knowledge Elicitation Rule	Manufacturing Rule
If *Premises* (Material-Type = Metal) and (Material-Name = unset) are true then Perform *Actions* Print (Is the part to be manufactured from aluminium, copper, zinc or steel?) Read response Assign value to template (Part-Name (material-name material))	If *Premises* (Process-Type = Injection Moulding) and (Strength is unimportant) and (wall-thickness is too-thick) then Perform *Actions* Print Advice (Wall is too thick, and strength is a low consideration. You are recommended to redesign the wall with a smaller wall thickness)

4.1 Feature Representation

The manufacturing advisor has been integrated with Computer Aided Design (CAD) to allow the manufacturability of designed parts to be evaluated. A feature recognition methodology has been developed by the authors to allow moulding features to be identified from CAD solid models. The methodology uses an automatically generated mid-surface representation as the basis for feature recognition which provides more direct access to the features of interest for moulding design. A simple example of the feature recognition process is illustrated in Figure 4. Figure 4 (a) shows the solid model of a simple T-junction part, Figure 4 (b) shows the mid-surface representation of the part and Figure 4 (c) shows a geometry graph of the mid-surface model. In Figure 4(b) it can be seen that three faces are connected at edge E1 indicating the existence of a T-junction. The feature recognition is performed by searching for patterns of face-edge connectivity in the geometry graph, for example in Figure 4 (c) the existence of a T-junction is indicated by the connectivity between edge E1 and the three faces F1, F2 and F3. A more detailed description of the feature recognition methodology can be found in the authors' publication [15].

(a)   *(b)*   *(c)*
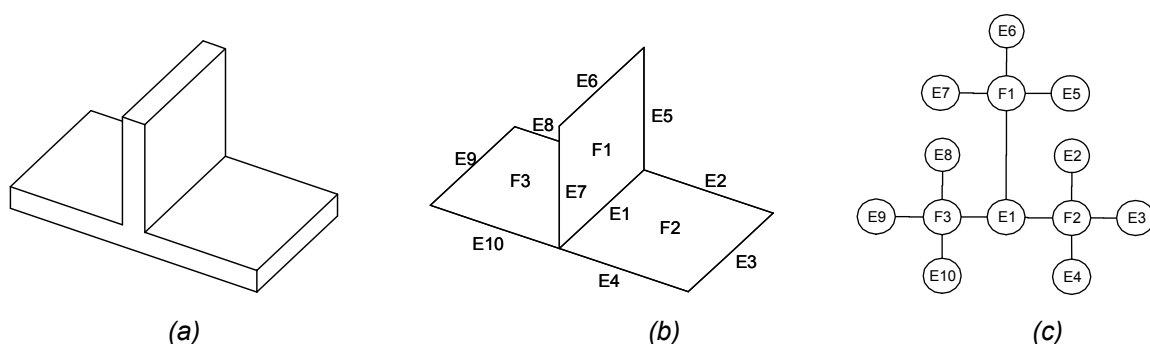
Figure 4. Example of Feature Recognition for a T-junction (a) Solid Model (b) Mid-surface Representation (c) Geometry Graph of Mid-surface Representation

The feature recognition software outputs a description of the part as a collection of connected wall entities which are categorised as "main wall" and "attached" features. The "attached" features are further classified as ribs, buttresses, bosses and holes. The results can be written to a CLIPS formatted feature file which describes each feature and its attributes; at present the feature file contains the type and the wall thickness for each feature. A sample feature file is shown in Figure 5.

```
(feature (feat-number 1) (feat-type main-wall) (face-id F1) (thickness 2.5))
(feature (feat-number 2) (feat-type main-wall) (face-id F2) (thickness 2.5))
(feature (feat-number 3) (feat-type rib) (face-id F11) (thickness 2.0))
(feature (feat-number 4) (feat-type rib) (face-id F12) (thickness 2.0))
(feature (feat-number 5) (feat-type buttress) (face-id F13) (thickness 3.0))
(feature (feat-number 6) (feat-type boss) (face-id F14) (thickness 4.0))
(feature (feat-number 7) (feat-type rib) (face-id F15) (thickness 1.0))
```

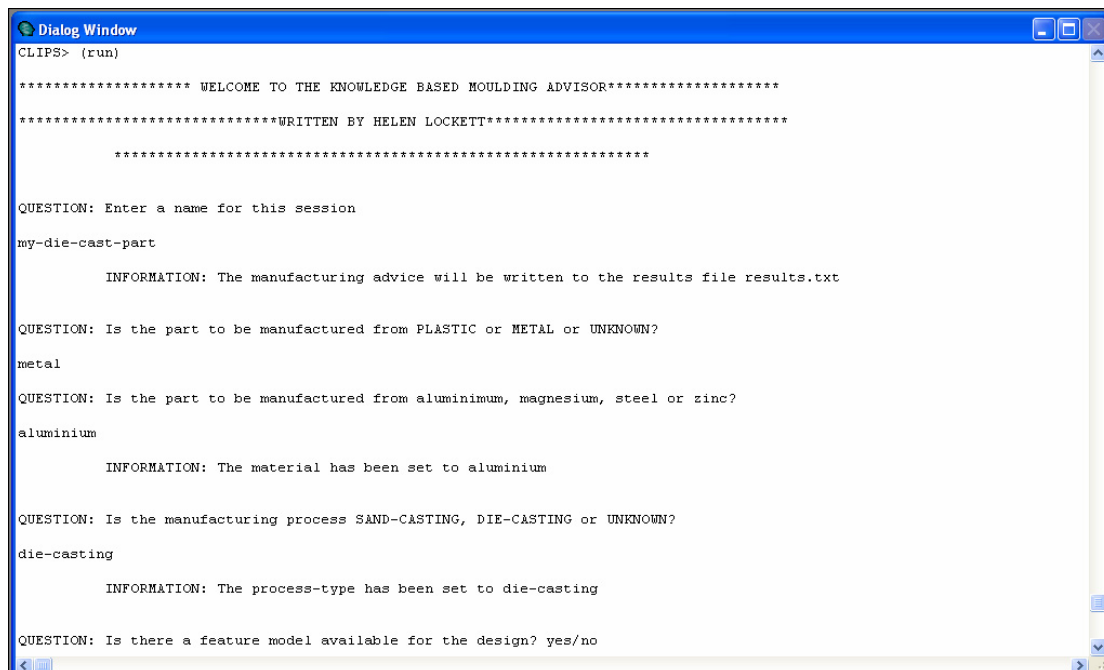*Figure 5. Example Feature File*

The feature file is read by the expert system and allows the moulding advisor to evaluate the manufacturability of the designed part. Each feature is evaluated individually and manufacturability advice is generated at the feature level. The feature information can also be used to provide manufacturing advice for the entire part by combining the attributes of individual features. For example the maximum and minimum main wall thickness of the part can be computed using the thickness values of all the features.

4.2 Problem Solving Strategy

The manufacturing advisor uses the CLIPS inference engine to determine the sequence of rule firing during an advice session. The CLIPS inference engine uses a forward chaining strategy in which the system first identifies all the candidate rules for which the antecedents are true, then uses a conflict resolution strategy to select the rule to execute, and finally executes the rule. The manufacturing advisor uses the "depth strategy" for conflict resolution, which executes newly activated rules in preference to older rules. The depth strategy is the default conflict resolution strategy in CLIPS, but other strategies are also available [14].

4.3 Program Interaction

A knowledge advisor session begins by asking the user to specify the material class for their design (plastic or metallic). If the user selects a material class the system offers the user possible manufacturing processes that are appropriate to the chosen material, and then asks them to select a specific material appropriate to the selected process. If the user states that the material class is unknown the system asks them to select from a list of all available manufacturing processes and offers a list of materials appropriate to the selected moulding process. The user is then asked to input additional design information either by typing responses of by defining a feature file. Figure 6 shows an example of the beginning of a knowledge advisor session.

```
Dialog Window
CLIPS> (run)

******************** WELCOME TO THE KNOWLEDGE BASED MOULDING ADVISOR********************

*******************************WRITTEN BY HELEN LOCKETT********************************

          ****************************************************************

QUESTION: Enter a name for this session

my-die-cast-part

          INFORMATION: The manufacturing advice will be written to the results file results.txt

QUESTION: Is the part to be manufactured from PLASTIC or METAL or UNKNOWN?

metal

QUESTION: Is the part to be manufactured from aluminimum, magnesium, steel or zinc?

aluminium

          INFORMATION: The material has been set to aluminium

QUESTION: Is the manufacturing process SAND-CASTING, DIE-CASTING or UNKNOWN?

die-casting

          INFORMATION: The process-type has been set to die-casting

QUESTION: Is there a feature model available for the design? yes/no
```

Figure 6. Example of the Start of a Knowledge Advisor Session

5 TEST CASES AND RESULTS

The moulding advisor has been tested on a range of moulded part designs. This section describes the results for a simple moulded test part evaluated for two different moulding processes. The CAD geometry and recognised features for the part are shown in Figure 7. It can be seen in the figure that the model is first simplified to a mid-surface abstraction of the original solid model, and then moulding features are identified on the mid-surface model. A summary of the recognised features for the part is shown in Table 3.
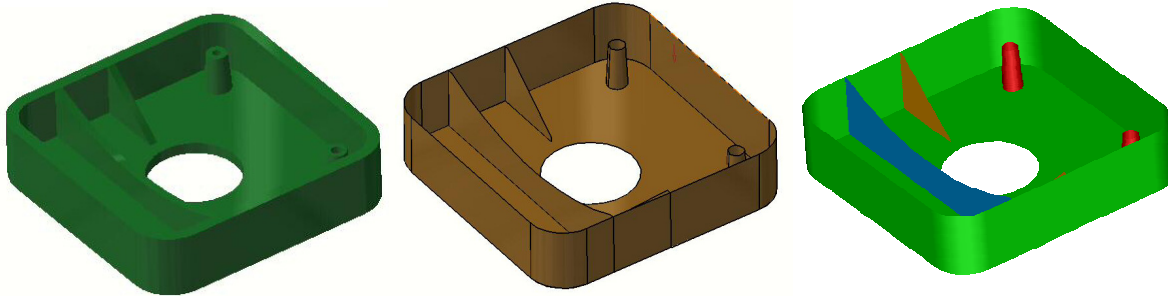
Figure 7. Simple Moulded Part, Mid-Surface Abstraction for Part and Recognised Moulding Features

Table 3. Summary of Features in Simple Moulded Part

Feature Type	Number of Features	Feature Attributes
Main-wall	14	Thickness = 2.5mm
Hole	1	N/A
Boss	2	Thickness = 2.0 mm
Buttress	2	Thickness = 1.4 mm
Rib	1	Thickness = 2.0 mm

The manufacturability of the part has been evaluated for two different manufacturing processes and materials. Firstly for injection moulding in acrylic and secondly for die-casting in zinc. A sample of the manufacturability report is shown as Figure 8 and a summary of all the generated advice for both manufacturing processes in Table 4.

```
***************** OUTPUT FROM KNOWLEDGE BASED MOULDING ADVISOR*****************
****************************WRITTEN BY HELEN LOCKETT************************
****************MANUFACUTRING ADVICE FOR PART plastic1-ij-acrylic*****************
INFORMATION: The material has been set to acrylic
INFORMATION: The process-type has been set to Injection Moulding
INFORMATION: A feature model has been read from the file plastic1-feature-file-tk-
new.txt
INFORMATION: The nominal wall thickness has been set to 2.5 (based on value from feature
file)
INFORMATION: Feature 20 is of type main wall and has thickness 2.5  mm...
INFORMATION: The importance of STRENGTH has been set to 0.3 on a scale of 0.0 to 1.0
INFORMATION: The importance of APPREARANCE has been set to 0.9 on a scale of 0.0 to 1.0
ADVICE: The specified maximum wall thickness 2.5 is acceptable for selected material
acrylic and process injection-moulding (maximum thickness for process is 3.0 ) (GENR2)
ADVICE: The specified minimum wall thickness 1.4 is acceptable for selected material
acrylic and process injection-moulding (minimum thickness for material is 0.6)
```

Figure 8. Sample from Manufacturability Report for Simple Moulded Part

Table 4. Manufacturing Advice for Simple Moulded Part.

Design for Moulding Advice Injection Moulding/ Acrylic	Design for Moulding Advice Die-casting/Zinc
The specified maximum wall thickness 2.5 mm is acceptable for selected material acrylic and process injection-moulding (maximum thickness for material is 3.0) (GENR2)	The specified maximum wall thickness 2.5 mm is acceptable for selected material zinc and process die-casting (maximum thickness for material is 9.65) (GENR2)
The specified minimum wall thickness 1.4 mm is acceptable for selected material acrylic and process injection-moulding (minimum thickness for material is 0.6).	The specified minimum wall thickness 1.4 mm is acceptable for selected material zinc and process die-casting (minimum thickness for material is 0.6).
The specified draft angle 0.0 degrees is less than the minimum draft angle for a part manufactured using injection-moulding you are recommended to increase the draft angle to at least 0.5 degrees (GENR5)	The specified draft angle 0.0 degrees is less than the minimum draft angle for a part manufactured using die-casting you are recommended to increase the draft angle to at least 0.25 degrees (GENR5)
Moulded parts should be designed with uniform wall thickness (GENR1)	Moulded parts should be designed with uniform wall thickness (GENR1)
Variations in wall thickness should be minimised for parts in which appearance is important. The variation in main wall thickness is 0.0 percent. Which is acceptable for a part with high importance for appearance (more than 0.5) (IMR3)	Variations in wall thickness should be minimised for parts in which appearance is important. The variation in main wall thickness is 0.0 percent. Which is acceptable for a part with high importance for appearance (more than 0.5) (IMR3)
The design should not have abrupt section changes. Where a section change is required a gradual taper of 3.0 must be applied (GENR6)	The design should not have abrupt section changes. Where a section change is required a gradual taper of 4.0 must be applied (GENR6)
All Corners should be generously radiussed (GENR7)	All Corners should be generously radiussed (GENR7)
Rib 18 has thickness 2.0 mm which is 80.0 percent of the main wall thickness (2.5 mm). For process injection-moulding the recommended rib thickness is 60.0 percent of main wall thickness. Rib 18 is too thick and thickness should be reduced to 1.5 mm	(Feature 3) Projections and bosses can be difficult to fill: buttresses assist flow of such features and strengthen the component (DCR1). (Feature 3) boss is of acceptable thickness
	(Feature 2) Projections and bosses can be difficult to fill: buttresses assist flow of such features and strengthen the component (DCR1) (Feature 2) boss is of acceptable thickness
	(Feature 18) rib. Ribs should not be square in section. Blended sections and curves buttresses aid die filling (DCR2). (Feature 18) rib has thickness 2.0 mm which is 80.0 percent of the main wall thickness (2.5 mm). For process die-casting the recommended rib thickness is 100.0 percent of main wall thickness. Rib is too thin and should be increased to 2.5 mm (DCR3)
	(Feature 1) Blind holes are preferable to through holes. Through holes can cause problems with flash. (DCR4) (Feature 1) Holes should be tapered. Tapered holes assist with removal of the casting from the die. (DCR5)

6   SUMMARY AND CONCLUSIONS

This paper has presented a knowledge based manufacturing advisor for moulded parts. The advisor can generate manufacturing advice for designed parts for a range of different moulding processes and materials at different levels of detail.

The main research contribution has been the development of a hierarchical knowledge structure to classify the design for manufacture knowledge, flexible user interaction and integration with the CAD using feature recognition. The manufacturing advisor has been designed to allow the user to input design information at a variety of different levels of detail, and the manufacturing advice that is generated is tailored to the inputs that are provided.

The integration of the expert system with Computer Aided Design through feature recognition has brought significant benefits over a standalone expert system. The feature representation allows the expert system to evaluate the manufacturability of each feature in detail as well as providing part level design advice. The advisor also provides a common repository for design for manufacture guidelines from a range of information sources.

One limitation of the current system is the need to manually encode manufacturing guidelines in the CLIPS language. Ideally it would be desirable to store design rules and facts in a separate database that could be updated independently from the expert system. It would also be useful to develop tighter integration with CAD to allow a wider range of design parameters to be accessible to the expert system and to make the manufacturability advice available to the user directly within their CAD system.   The current demonstrator also contains only a limited subset of design for manufacture knowledge and would need to be substantially expanded for implementation as a practical system, incorporating guidelines from industrial practice as well as design handbooks.

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