Development of an Intelligent Product Design Support System

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Abstract
Design is the process by which the needs of the customers or the marketplace are transformed into a product that satisfies these needs. It is an important phase of the product development process that greatly influences the final cost, quality and time to market. The traditional view of the design to manufacture process is that it is a sequential process; the outcome of one stage is passed on to the next. This tends to lead to iteration in the design and can make products more expensive and extended lead time. A better approach is for the designer to consider the stages following design to try and eliminate any potential problems. The present work aims to develop a product design support system that applies guidelines for ease of manufacture at the design stage. This system extracts geometric features from the product design model being created on a Computer Aided Design (CAD) system, and then this information will be stored at design information subsystem. Knowledge based subsystem computes design variables which reflect the model ease of manufacturability. Finally the guidelines that have been violated by the designer will automatically be introduced into the design model. In order to demonstrate the capabilities of the developed system, injection moulding process has been selected, but this could equally be extended to other manufacturing processes. Also the developed system could be extended to accommodate all design guidelines for manufacture, assembly, disassembly, and etc that collectively referred to DFX.

Introduction
The traditional view of the design to manufacture process is that it is a sequential process; the outcome of one stage is passed on to the next. This tends to lead to iteration in the design which means having to go back to an earlier stage to correct mistakes. This can make product more expensive and delivered to the marketplace late. A better approach is for the designer to consider the stages following design to try and eliminate any potential problems. This means that the designer requires help from other experts, for example the manufacturing engineer to help to ensure that any designs could easily be manufactured. Therefore the use of design support methods and tools aimed at the optimisation of the product development process is required [1]. One of the approved methods is the use of design guidelines referred to as "Design for X".

Design for manufacture (DFM) is a step towards integrating manufacturing and the design processes. DFM is a proven design methodology that works for any company. For DFM to work, designers must know how to design manufacturable products. Since no formal DFM method exists, implementing DFM is not straightforward. Approaches that can be used [2] are: the use empirical guidelines, applied computer supported DFM, implementation of methods such as CE, QFD, group technology, etc.

Systems that automatically provide information for the designers during the initial design process on manufacturing guidelines that lower costs and reduce cycle times have proven highly effective in achieving their goals[3].

This work is limited to manufacturing guidelines for injection molding process. In this work knowledge based system is developed to implement these guidelines. The developed system is deployed in concurrent engineering environment to rationalise decisions on product design and downstream processes within geographical distributed locations.

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The Objectives
The objectives of the present work could be categorised into the following:

- Developing an integrated system to apply design for manufacturing.
- Developing an approach for evaluating the design.
- Developing a method for evaluating manufacturability by assessing design variables.
- Collecting all the design rules for injection moulding parts.

Previous work
This section presents an overview of the types of DFM-related tools that have been developed.

Conceptual Design Tools
Colton and Ouellette [4] described a computer support tool for the conceptual design of an automobile, called VROOM. In this work the parametric design system, ICAD (Intelligent-CAD), is used for a graphical product representation and a generic blackboard system (GBB) for data storage and decision support. When the designer adds functions or forms, the system checks if the modification is valid via specific automobile design rules. It is possible to include DFM knowledge, but it requires much change.

Design and knowledge-based systems
Gopalakarishnan [5] developed an expert system to support DFM rules. During the conceptual design phase, material and process selections are carried out using information on available shape, size, functionality, and production quantity. Venkatachalam [2] described a software tool that generates feedback during the various phases of the design process. Decisions are evaluated with respect to quality, cost and manufacturability. The tool is limited to casting, forging, end milling and drilling. Included design features are blind holes, through holes, pockets and slots.

Gupta et al. [6] propose architecture of a decision support tool in which the product design is checked for non manufacturable design attributes, cost and time, and overall manufacturability rating for the product is derived by the system. Molloy et al. [7] describe the system DEFMAT. The system helps the designer during the concurrent engineering process with the evaluation of the manufacturability of a product design. Object oriented programming model has been combined with expert system techniques to implement an industrial prototype.

CAD system with DFM functionality
Many CAD vendors introduce DFM functionality in their new releases. Using Pro/DEVELOP with Pro/ENGINEER, enables the development of independent tools that can be fully integrated in the Pro/ENGINEER environment. ICAD and Concept Modeler [8] are rule-based shells that can be used to develop a rule-based design support system. In ICAD processing of knowledge and geometry is integrated, but every steps needs to be programmed using Artificial Intelligent language LISP. Geometric modeling therefore, is not straight forward, nor is it user friendly. The same applies for the Design++ system. This system can be used to add intelligence to the AutoCAD system, but the parametric modeling capabilities of the AutoCAD can not be addressed via Direct++, which implies that hard code, is required [9].

Product Information tools
Product information is the logical accumulation of all relevant information concerning a given product during the entire life cycle. Several examples of product information system are provided in the following. Lindeman and Wijaya [10] have defined requirements for a concurrent engineering data structure and have implemented it. It enables the monitoring of the progress, quality and maturity of the product design. Wong and Srim [11] describe an object oriented implementation of a product information model (MADED), which represents data using multiple levels of abstractions, constraints and a geometric representation via multiple views. Kals and Lutters [12] add information to the product structure. The product information structure (PRIS) manages all information generated by any decision in the product realization process.

From the above review, it can be seen that most previous work has considered only specified aspects of the total design and some are too theoretical to be applied to practical design. These systems are based on
practical and heuristic knowledge of the designers. The KB systems have demonstrated great potential to assist designers to interact with a CAD system to conceptualize design as well as perform final engineering design of a product by using engineering rules of thumb with extensive analytical procedures. In general, the major advantage of KB systems for product design over conventional computer-aided design systems is the explicit representation and manipulation of a body of knowledge. The knowledge is based on human expertise that is referred to as "Design for X".

**Manufacturability Evaluation**

One of the main functions of DFM is analysing the manufacturability of the product design, i.e. to assess the ability to produce the design within the specified requirements. To analyse manufacturability, the CAD model must be decomposed into elements with a manufacturing meaning such as surfaces, dimensions, tolerances, and their relationship, in order to identify non-manufacturable objects and assess the level of manufacturability [6].

The required data to evaluate manufacturability includes:

1. Aggregate data (overall description of the part, such as volume and center of mass)
2. Feature data (parameter values of geometric features)
3. Relational data (relations between features and geometry).

In this work, all the required data types are automatically extracted from the CAD model.

**Production process**

Injection molding is a manufacturing technique to make parts mainly from thermoplastic materials. Molten plastic is injected at high pressure into a mould which is the inverse of the product shape [13]. The mould is made by a mould maker (or toolmaker) from metal such as steel and then, it is precision-machined to form the features of the desired part. Injection molding is widely used to manufacture a variety of parts from the smallest component to entire body panels of cars. In the present work, this production process was selected for testing and applying the design guidelines in the developed intelligent system.

**Design guidelines**

Helander [14] distinguish 3 types of information in DFM guidelines:

- Descriptive information presenting the user with the possibilities and limitations of the design;
- Normative information, which introduces standardized materials, processes and dimensions;
- Procedural information to coordinate cooperation between the design and production disciplines.

When information is placed in a specific context and then, applied in that context, knowledge is created. In this work some descriptive and normative information are used in injection molding and applied to correct the designed products. Two sample design guidelines in the form of constraint and rule are introduced here.

Constraint:

| Hole Diameter | >= | Wall thickness |

Rule:

If **Tensile Strength** is Low then **Material can be** HD polyethylene and LD polyethylene and Polyvinyl chloride

There are a number of design guidelines associated with injection moulding that are given in Appendix A [15,16].

**Knowledge-Based Approach**

A knowledge-based approach broadly means to build up a system, usually called a knowledge-based system (KBS), to solve complex decision problems in a specific domain. A KBS, normally in the form of an intelligent computer program, uses knowledge and inference procedures to solve problems that are
difficult enough to require significant human expertise for their solution. The knowledge of a knowledge-based system consists of facts and heuristics. The "facts" constitute a body of information that is widely shared, publicly available, and generally agreed upon by experts in a field. The "heuristics" are mostly private information that characterize expert-level decision-making in the field. The typical structure of a knowledge-based system is shown in Fig. 1. It comprises the knowledge base, containing encoded expertise from one or more domain experts. The inference engine provides strategies to process the encoded knowledge in order to reach final solutions. The KB system also provides a user interface for system/user interaction, and, possibly, sensors to collect data from monitoring devices. Finally, links to a traditional database provide the KB system with the opportunity to import and use data in its inferences or reasoning.

Reference Model and System Architecture
In order to obtain the required integration, a reference model must be selected on which design support tools are to be based [18]. Since the designer is no longer involved directly, the computer must carry out its design evaluations on its own. As such, the location of the intelligent system and its relationship with the CAD system is an important factor. This model is schematically illustrated in Fig. 2.
Fig. 3 shows the architecture of the product design support system developed in this work. The system consists of three major components. The first one is a DFM knowledge base containing design guidelines and materials selection information for the injection molding process. The second is a feature extractor and recognition component that extracts features of a designed product and then recognizes them by using developed algorithms. Finally, a product design information component facilitates and manages the extracted data.

These components were developed for this work using Microsoft .NET Technologies [19] and MS SQL Server as a Relational Database Management System (RDBMS) with an architecture based on a service-oriented approach. It should also be mentioned that the SolidWorks [20] CAD system is used for user interaction with the system. It is possible to extract all the functionality of Solidworks by adapting existing programming interfaces. Obviously, if another CAD system is chosen, the required programming interfaces will require development.

![Fig. 3. Product Design Support System Architecture.](image)

**System Functionalities**

In order to specify the behavior of a system, its functionalities should be obtained. The functionalities of a system represent how the system performs in a specific environment. These are the developed system's functionalities:

- Design the product using a CAD system;
- Extract geometric features and design properties (such as wall thickness, hole diameter, etc.);
- Convert product information to facts for inferencing purposes;
- Inference and propose the design rate and material for production;
- Automatically correct the design defects and introduce them into the model.

Initially the designer designs the product on the CAD system. After that, in order to obtain the design rate and material selection, some procedures must be carried out by the system. First of all, properties of the product features should be extracted. These are converted to product facts that are the basis for inferencing. Now the inference process can be accomplished and the design variables are output. The computed design variables (in this work: design rate and material for production) are automatically imported into the CAD system and the possible defects of the product design are automatically corrected.

In the developed system, in order to extract geometric features as well as modify the designed model, the Solidwork Programming Interface was used. As well, the knowledge was represented in the following format:
IF $<O-A-V>$ and/or $<O1-A1-V1>$ and/or … and/or $<Om-Am-Vm>$ THEN $<O-A-V>$ and/or $<O1-A1-V1>$ and/or… and/or $<On-An-Vn>$

where $O$ stands for object; $A$ for attribute; and $V$ for value. For inferencing, forward chaining, which is one of the most efficient approaches, was selected.

**System Testing and Verification**

From the above discussions, it is obvious that through the developed system it is possible to access information that is useful to improve the product design. This is very important for rapidly developing new products. The product design support system can be called up to analyse the current state of the design, point out problem areas, and indicate possible improvements. The DFM is particularly best applied at the conceptual product design stage, i.e., before major decisions about product and process characteristics have been finalised [21]. At this early stage of the design, there may not be much information to work with, but the system will make sure that all the existing information is made available to the design team which may be globally distributed in a concurrent engineering environment.

In order to test the system, a sample product (Fig. 4) with 3 holes, 3 ribs and a uniform wall thickness was designed. The given test sample satisfies some rules for injection molding product and denies some others.

In order to calculate the design rate which serves to indicate ease of product manufacturability, and to propose a material suitable for manufacturing, the features of the product should be extracted as shown in Fig. 5.
At this stage, the developed system converts features properties such as hole diameter, rib thickness, etc. into facts as shown in Fig. 6.
Now the design rate can be calculated and the material selected from these facts. The calculated design rate is shown in Fig. 7 and the material for manufacturing is applied to the model. It must be mentioned that features that did not satisfy the rules such as Hole 3 in the test sample, will automatically be recognised and the system will alert the designer for correction.

![Fig. 7. Test sample after calculation of design variables.](image)

**Conclusions and Suggestions for Future Work**

In this paper, a new approach to developing a product-design decision-support system for rapid design of new products is introduced. Design guidelines for injection molding were introduced; the reference model for design support was developed; and the architecture and functionalities of the system were presented.

The developed system allows an engineer to achieve design alternatives, with immediate feedback provided by the system leading them to the most cost effective and rapid design. The system has several important features:

1) It can be used in a concurrent engineering environment;
2) The developed system is based on a comprehensive DFX model;
   a. Various software tools employed at different stages of product development can easily access this model without requiring a data transfer interface;
   b. Management of the DFX data/knowledge base is relatively simple;
   c. DFM guidelines are organised in an appropriate form and can be adapted for other manufacturing process guidelines;
3) The system can easily be integrated with other product development software tools or systems.

Integrating the developed system with other production systems such as Computer Aided Process Planning (CAPP), Computer Aided Manufacturing (CAM) is a subject that should be investigated in the future work.
Appendix A
The knowledge base developed in this work is based on the following sources:
1) Handbooks and technical papers;
2) The authors’ expertise, accumulated over ten years in the plastic manufacturing industry;
3) Knowledge acquired through interviews and discussions with experts of some local companies.

Two types of rules consisting of material selection and manufacturability evaluation are introduced.

<table>
<thead>
<tr>
<th>IF PART</th>
<th>THEN PART</th>
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<tbody>
<tr>
<td>Tensile Strength is Low</td>
<td>Material can be &quot;HD polyethylene&quot; and &quot;LD polyethylene&quot; and &quot;Polyvinyl chloride&quot;</td>
</tr>
<tr>
<td>Tensile Strength is Medium</td>
<td>Material can be &quot;Polystyrene&quot; and &quot;Polypropylene&quot; and &quot;ABS&quot; and &quot;Cellulosics&quot;</td>
</tr>
<tr>
<td>Tensile Strength is High</td>
<td>Material can be &quot;Styrene acrylonitrile&quot; and &quot;Polyacetal&quot; and &quot;Polycarbonate&quot; and &quot;Acrylic&quot;</td>
</tr>
<tr>
<td>Tensile Strength is Very High</td>
<td>Material can be &quot;Nylon&quot;</td>
</tr>
<tr>
<td>Specific gravity is Low</td>
<td>Material can be &quot;Polypropylene&quot; and &quot;HD polyethylene&quot; and &quot;LD polyethylene&quot;</td>
</tr>
<tr>
<td>Specific gravity is Medium</td>
<td>Material can be &quot;Polystyrene&quot; and &quot;ABS&quot; and &quot;Nylon&quot; and &quot;Styrene acrylonitrile&quot; and &quot;Acrylic&quot;</td>
</tr>
<tr>
<td>Specific gravity is High</td>
<td>Material can be &quot;Cellulosics&quot; and &quot;Polycarbonate&quot;</td>
</tr>
<tr>
<td>Specific gravity is Very High</td>
<td>Material can be &quot;Polyacetal&quot; and &quot;Polyvinyl chloride, flexible&quot;</td>
</tr>
<tr>
<td>Cost is Low</td>
<td>Material can be &quot;Polystyrene&quot; and &quot;Polypropylene&quot; and &quot;HD polyethylene&quot; and &quot;LD polyethylene&quot; and &quot;Polyvinyl chloride, flexible&quot;</td>
</tr>
<tr>
<td>Cost is Medium</td>
<td>Material can be &quot;ABS&quot; and &quot;Styrene acrylonitrile&quot; and &quot;Acrylic&quot;</td>
</tr>
<tr>
<td>Cost is High</td>
<td>Material can be &quot;Polyacetal&quot;</td>
</tr>
<tr>
<td>Cost is Very High</td>
<td>Material can be &quot;Nylon&quot; and &quot;Cellulosics&quot; and &quot;Polycarbonate&quot;</td>
</tr>
<tr>
<td>Shrinkage Rate is Low</td>
<td>Material can be &quot;Acrylic&quot; and &quot;Polycarbonate&quot; and &quot;Polystyrene&quot;</td>
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<tr>
<td>Shrinkage Rate is Medium</td>
<td>Material can be &quot;Nylon&quot;</td>
</tr>
<tr>
<td>Shrinkage Rate is High</td>
<td>Material can be &quot;Polypropylene&quot;</td>
</tr>
<tr>
<td>Shrinkage Rate is Very High</td>
<td>Material can be &quot;HD polyethylene&quot; and &quot;LD polyethylene&quot; and &quot;Polyvinyl chloride, flexible&quot;</td>
</tr>
<tr>
<td>Application is Toy</td>
<td>Material can be &quot;Polystyrene&quot; and &quot;LD polyethylene&quot;</td>
</tr>
<tr>
<td>Application is House Ware</td>
<td>Material can be &quot;Polypropylene&quot; and &quot;HD polyethylene&quot; and &quot;ABS&quot; and &quot;Styrene acrylonitrile&quot; and &quot;Polycarbonate&quot;</td>
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<td>Application is Electrical</td>
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<td>Application is Automotive</td>
<td>Material can be &quot;Polyacetal&quot; and &quot;Polycarbonate&quot; and &quot;Acrylic&quot;</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Row</th>
<th>Feature</th>
<th>Rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hole</td>
<td>1. The minimum spacing between two holes or between a hole and a sidewall and diameter of that hole should be equal or greater than the wall thickness.</td>
</tr>
<tr>
<td>2</td>
<td>Rib</td>
<td>1. Rib thickness should be between 40% and 60% of the wall thickness 2. Ribs should not be higher than 3 times the wall thickness. 3. space between two ribs should not greater than 2 times of wall thickness 4. Draft angle should be between .5 and 1.5</td>
</tr>
<tr>
<td>3</td>
<td>Boss</td>
<td>Like Rib</td>
</tr>
<tr>
<td>4</td>
<td>Corner</td>
<td>1. Sharp corner should be avoided and use fillet and radii with radius of .5mm to 1mm.</td>
</tr>
<tr>
<td>5</td>
<td>Draft Angle</td>
<td>1. should be between .125 and .5</td>
</tr>
<tr>
<td>6</td>
<td>Wall</td>
<td>1. wall thickness should be uniform</td>
</tr>
</tbody>
</table>
References

[21] www.solidworks.com