Casting Knowledge Management for Concurrent Casting Product Process Design

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ABSTRACT

The management of knowledge is gaining momentum in the manufacturing industry to enable capturing domain knowledge and building intelligent systems. In this work, we show how casting knowledge can be stored, updated and applied to generate tooling design and process planning solutions at the product design stage itself. This helps in concurrent product-process design, necessary for early identification and prevention of potential manufacturing problems and casting design optimization. The casting knowledge is stored in the form of cases, equations, if-then rules and process planning parameters in XML (eXtensible Markup Language). For adding and updating the knowledge in the form of if-then rules, a Knowledge Editor has been developed. This is integrated with a casting design software AutoCAST and a web based casting project management system WebICE, to demonstrate the application of casting knowledge for automatic methoding (feeding and gating design) and process planning (selection of process steps and parameters), driven by product design parameters. Such an approach will enable casting industry to manage their respective specialized knowledge and utilize the same to support web-based collaborative casting development between product, tooling and foundry engineers.

Keywords: Casting Design, Concurrent Engineering, Knowledge Management, Process Planning, XML

INTRODUCTION

There is continuous pressure on foundries to supply castings at lower prices, shorter lead times with assured quality. Unfortunately, even after spending significant resources (human-hours, materials, machines, overheads and energy) on methoding and sample casting production, a high percentage of defective castings and poor yield are often observed during regular production. To overcome these problems effectively, foundries need to work closely with original equipment manufacturers starting from an early stage in casting life cycle. Designing a process friendly cast component requires the application of in-house knowledge and expertise gained over several years for every class of castings (geometry-metal-process combination). Manufacturability assessment at the product design stage helps in early prediction and prevention of potential problems. However, the casting manufacturing knowledge is not readily available at the design stage, but continuously generated in daily operations. This knowledge because of its magnitude often becomes unmanageable, and is usually inaccessible to design engineers. Also, engineers working in foundries acquire considerable knowledge that mainly resides in their memory, and lost to the organization when they retire or leave (Ravi, 2000). In addition, situations such as, reinvention of solutions, repetition of mistakes, loss of knowledge after project completion and inconsistent decision-making because of change in team members are quite common. All these challenges can be met by knowledge management.

Knowledge exits in different sources and forms. It is defined as information with guidance for action, that is, how to act given the information) (Courteney, 2001). Different sources include persons, projects (successful as well as unsuccessful), paper based media (such as books, magazines and newspapers) and electronic media (Henriksen, 2001). The knowledge may be explicit (documented) or tacit (understood); declarative (know what) or procedural (know how); esoteric (highly specialized) or exoteric (common sense); deep or shallow. Knowledge management deals with managing these knowledge assets and processes that act upon the assets. These processes include developing, preserving, sharing and using the knowledge. Therefore, knowledge management involves identification and analysis of available and required knowledge assets and related processes, and subsequent planning and control of actions to develop both the assets and the processes to fulfill organizational objectives (University of Edinberg, 2002).
The principles of knowledge management are fairly well established, and are being successfully applied in many sectors. Many product manufacturing and design organizations are learning the importance of manufacturing related knowledge, which could be obtained through experience and knowledge sharing among different individuals. Turng developed a web based knowledge management system for injection molding process to create, share and leverage the engineering information and knowledge between the team members involved in design and manufacture of injection molded parts (Turng, 1999). Leake developed a case based decision support system ‘Stamping Advisor’ for sheet metal automotive parts by storing previous sheet metal components and retrieving them at product design stage (Leake, 1999). Mejasson developed a knowledge management system for material selection for submarine cable industry using case based reasoning (Mejasson, 2001). Yoo developed a web based knowledge management system for storage and sharing product data such as product specifications, bill of material (Yoo, 2002). Rozenfeld proposed knowledge management architecture for collaborative product environment to share and acquire new knowledge (Rozenfeld, 2002). In the metal casting domain, Nagasaka developed a casting knowledge management system focused on explicit knowledge in the form of graphs and equations (Nagasaka, 1999).

The present investigation deals with capturing casting manufacturing knowledge and applying it for concurrent casting product process design, essentially methoding and casting process planning at the product design stage. Methoding involves determining the feeding and gating parameters; and process planning involves determining the manufacturing methods, steps and process parameters (such as metal pouring time, pouring rate, sand composition) (Chougule, 2003). Our research is based on the premise that current product-development methodologies do not adequately address the capture and use of casting manufacturing knowledge. The product development teams are unable to leverage this knowledge because most of the formal and informal knowledge along with the context associated with it is lost after the process is completed.

KNOWLEDGE MANAGEMENT FRAMEWORK

Our work is mainly focused on capturing and sharing casting manufacturing knowledge. This knowledge is captured and stored in the form of process plans (case base and library), equations and ‘if-then’ rules. The knowledge in the form of ‘if-then’ rules is captured through a knowledge management program called Knowledge Editor developed by us. The knowledge in the form of equations is used for methoding (feeding and gating design), and knowledge from case base and library is used for process planning. These tasks, performed at the product design stage, enable early castability evaluation.

The overall methodology is shown in figure 1. The main inputs include the part solid model and attribute values for the retrieval of methoding and process planning knowledge. For methoding the casting, the part solid model is the main input. The methoding (gating and feeding design) involves use of empirical equations that vary for every material, geometry and process combination. These equations are stored in an XML (eXtensible Markup Language) format. They are retrieved using ‘if-then’ rules and used in a 3D casting design software for methoding. The process plan includes the manufacturing methods, steps and process parameters. The knowledge from case base and library is retrieved by case based reasoning (CBR) methodology and ‘if-then’ rules respectively. The CBR involves retrieving similar previous case (along with process plan) based on casting attributes (such as casting material, weight, size) and their weights. In the absence of a suitable case, the process planning knowledge from the library is retrieved using ‘if-then’ rules. If necessary, the retrieved knowledge is interactively modified by the foundry engineer and used for process planning of a new casting. The new process plan is added to the case base and used for further reference.

The most critical elements of the knowledge management system are knowledge capture, knowledge storage and knowledge retrieval. These are explained in detail in the following sections.

KNOWLEDGE CAPTURE AND STORAGE

The knowledge that has been captured and stored should be easily available to design and foundry engineers working from different locations. To accomplish this goal, the knowledge is stored in a server. The users are authorized or restricted to access knowledge in the central server based on preferences that can be set by system administrator or group leader of the project. Each user is given a unique access login and password for accessing the knowledge. The team member can further add new knowledge, update the same and share it with others. The manufacturing knowledge is represented and stored in the form of process plans in a case base (previous projects), process planning libraries, equations and ‘if-then’ rules. The knowledge in the form of ‘if-then’ rules is captured through a knowledge management program called Knowledge Editor. The Knowledge Editor and storage of different forms of knowledge is explained in detail here.
KNOWLEDGE EDITOR
The Knowledge editor allows inputting casting manufacturing knowledge in a user-friendly manner (figure 2). It is a menu based client software, so that any kind of knowledge can be added directly to the server. Its main features include the following:

- Facility for adding new knowledge (‘if-then’ rules, equations, tables, documents, notes, books and web pages)
- Facility for specifying the quality of knowledge or source added, to enable retrieving the most valuable knowledge
- XML file viewing facility to view the ‘knowledge bits’
- Facility to update the knowledge bits
The present focus of Knowledge Editor is on capturing and storing ‘if-then’ rules. Each rule is represented by a ‘knowledge-bit’ or K-bit. These K-bits are stored in a format suitable for both machines and humans. Standard XML (eXtensible Markup Language) has been used owing to its self-describing ability, suitability for web-based exchange and platform independence. All the K-bits stored in the knowledge base may not be equally valuable. In order to differentiate them based on importance, frequency of usage and ‘recentness’, a knowledge quality value is assigned to each knowledge bit. The value may range from 0.1 to 1 where 0.1 implies that the knowledge is of low quality, whereas a widely used rule of thumb may have a value of 1.0. Other relevant information such as the name of author, date and key words can also be entered and stored along with the knowledge bit.

Different forms in which knowledge can be stored, are explained next.

**IF-THEN RULES**

The knowledge in the form of ‘if-then’ rules (how to act on a particular situation based on a set of conditions) is often applied in decision-making. As human experts usually tend to think along ‘some condition leads to a some action’ or ‘some situation leads to a some conclusion’, ‘if-then’ are the predominant form of encoding knowledge. These are of the form,

$$\text{IF } a_1, a_2, \ldots \ldots \ldots a_n \text{ THEN } b_1, b_2, \ldots \ldots \ldots b_m.$$

where, each $a_i$ is a condition or situation, and each $b_i$ is an action or a conclusion. A simple example of this form of knowledge bit is:

$$\text{IF (core aspect ratio is more than 4)}$$
$$\text{AND (metal is ferrous)}$$
$$\text{AND (surface finish required is high)}$$
$$\text{THEN (use hot box process for core making)}$$

After inputting knowledge through Knowledge Editor, key-words in the knowledge bit are automatically converted into standard words (to enable integration with other software) and stored in an XML file. Such a K-bit is shown in figure 3.

![Fig 3. A knowledge bit - ‘if-then’ rule in XML format](image)

**EQUATIONS**

Methoding involves use of empirical equations related to the design of parting, pattern, cores (and core box), feeding, gating and venting. They cannot be ‘hard-coded’ into a computer program since they have to be continuously tuned to specific combinations of casting geometry, metal and process based on new experience. For example consider the empirical equations for optimal mold filling time. The empirical equations for this are typically written as functions of up to three parameters:
casting weight, section thickness and fluidity (or pouring temperature), developed for a specific cast metal based on extensive experiments and observation. The coefficients for the parameters may vary depending on the casting weight and section thickness. The number of parameters and the form of equation vary widely for different metals. This makes it difficult to evolve a standard approach for knowledge management related to gating design. To overcome the above problem, we have developed a generalized equation for optimal filling time, applicable to all cast metals, as follows:

\[ t = K_0 [K_F L_F / 1000] [(K_S + (K_T T / 20))] [K_W W]^p \]  

where \( t \) is the filling time in seconds, \( W \) is the weight in kg, \( T \) is the section thickness in mm, \( L_F \) is the fluidity length in mm, \( K_0 \) is an overall coefficient, and \( K_F, K_S, K_T, K_W \) are the coefficients for fluidity, casting size, thickness and weight, respectively. The above equation is stored as a knowledge bit in an XML file on a server. The user can view the equation for a specific metal-process combination, along with all coefficients, by accessing the server through a standard web browser and can select appropriate equation/coefficient for gating design using ‘if-then’ rules. The coefficients can be modified based on new experience. The modified equation can be used to complete the design of the gating system in a 3D casting design system.

CASE BASE
The storing of knowledge in the form of ‘if-then’ rules is the most popularly used method in all knowledge management systems. However, in metal casting domain it is difficult to formalize the rules and the number of rules required may be unmanageably large. Further, knowledge and experience are not well structured and it is difficult to acquire and represent them in the form of rules. Storing knowledge in the form of cases alleviates this problem to the great extent. A casting case comprises complete details about the product, materials and process plan. The systematic collection of previous cases in a foundry enables quick process planning for a new casting by retrieving a similar previous case. The casting cases are stored using the XML-compatible Casting Data Markup Language (CDML) developed for handling casting project information in a previous investigation. The CDML has been extended to handle the detailed information related to a casting process plan. The process planning information is divided into activities viz: pre-casting activities (such as core sand preparation, mold sand preparation, mold making, core making), casting activities (such as melting, holding and pouring) and post-casting activities (such as shakeout, fettling and cleaning). The information regarding steps, process parameters and equipments used for performing each activity is systematically stored in XML format. The information regarding process particular (such as project name, casting material, casting weight, section thickness etc.) is used for retrieving the process planning knowledge, which is explained in detail later.

LIBRARY
The process planning knowledge stored in the form of cases is related to a particular product in which each activity is performed by a specified method. In practice, a number of methods are available for performing each activity. For example, the activity of MOLD MAKING can be achieved by methods of green sand molding, dry sand molding, shell molding, carbon dioxide molding etc. and each method has different steps and process parameters. This information is stored in the process-planning library. Thus library facilitates storing of information in a systematic way and offers alternative options for performing each activity. Similarly, libraries have been developed for foundry equipment. A particular option from the library can be selected based on knowledge stored in the form of ‘if-then’ rules.

KNOWLEDGE RETRIEVAL
Knowledge retrieval forms an important element of knowledge management system. It involves retrieving the knowledge stored in the case base, equations, library and ‘if-then’ rules. It is the process of searching and using the appropriate knowledge from the knowledge base. The knowledge from the precious cases is retrieved using case based reasoning methodology while knowledge from the library and equations is retrieved by execution (firing) of ‘if-then’ rules.

USING CASE BASED REASONING
Case based reasoning is a problem-solving methodology in the field of artificial intelligence in which previous similar situations are retrieved and used to solve a new problem. It is based on human reasoning model, that is, mentally search for similar situations happened in the past and reusing the experience gained in those situations. In practice, situations recur with regularity and what was done in one situation is likely to be applicable in a similar situation. This provided us the motivation for using CBR as the main tool for storing process planning knowledge in cases and reusing later for decision-making.

For retrieving the process planning knowledge, nearest neighbor algorithm has been developed. In this, the user specifies attribute values and predetermined weights corresponding to the attributes. The attributes that are identified for knowledge retrieval are casting material, geometry related attributes (such as casting length, weight, minimum and maximum section thickness, minimum and maximum core size, and shape complexity), quality related attributes (such as surface finish,
tolerance and maximum void size) and production related attributes (such as order quantity, production rate, sample lead time and production lead time). The weights are specified for all the attributes except casting material.

Based on the attribute values and corresponding weights similarity of a new project to projects in case base is determined by using equation,

\[ \text{Sim}(N,O) = \sum_{i=1}^{n} w_i \times \text{sim}(n_i, o_i) \]  

(2)

where,

\( \text{Sim}(N,O) \) = Similarity of new case to old case in the case base

\( \text{sim}(n_i, o_i) = \) Similarity of individual attribute values of new case to old case

\( n_i = \) Value of attribute \( i \) of old case in case base

\( o_i = \) Value of attribute \( i \) of new case

\( w_i = \) Weight of attribute \( i \)

\( n = \) Number of attributes

In a similar manner, the similarity values are determined for all cases (casting projects) in the case base using the weights and the corresponding attribute values. Based on these similarity values, the nearest three cases (to the new case) are identified. If the nearest cases are found suitable, process-planning knowledge in these cases is retrieved and made available to the design engineer for process planning of new casting. If the knowledge is not suitable, then further knowledge can be extracted from libraries and ‘if-then’ rules, and can be applied to the new situation, which is later added to the case base as new knowledge.

USING IF-THEN RULES

This knowledge retrieval is useful especially in the absence of suitable case in the case base. As mentioned earlier, the process planning library contains alternative options (methods) for the particular activity. The ‘if-then’ rules are used to select a particular method from library along with process parameters, and equipment for performing each activity. The knowledge stored in ‘if-then’ rules is first processed based on product attribute values given by the designer. For this, the conditions in ‘if’ block of the ‘if-then’ rules are evaluated against the attribute values specified by the design engineer to retrieve knowledge in ‘then’ block. Similarly, equipment selection is done for a new product from the equipment library based on ‘if-then’ rules. For example, a simple rule for equipment selection may be of the form,

If (casting size is less than 300 mm) AND (delivery quantity is more than 10000) THEN (use Flaskless molding).

In this way ‘if-then’ rules are executed to select methods, process parameters and equipments for all the activities to generate process plan from scratch. Later this process plan forms a part of case base.

The ‘if-then’ rules are also used for retrieving the appropriate equations involved in methoding. For example in gating calculations (please refer equation 1) the user can select the equation/coefficient for a specific metal-process combination, using ‘if-then’ rules stored in K-bit as shown below.

IF (cast metal is grey iron) AND (process is green sand casting) AND (part weight is in between 1 and 10 kg) AND (average wall thickness is in between 1 and 10 mm) THEN \( (K_{c} = 1, K_{p} =1.1, K_{w} = 1.0, K_{t} =1.4, P=0.5) \)

Other examples of ‘if-then’ rules include selection of type of gating (horizontal/vertical), ingate shapes, ingate location and number of ingates.

CONCURRENT CASTING PRODUCT PROCESS DESIGN

The knowledge management system has been used for concurrent casting product process design. This essentially involves methoding and process planning at the product design stage. The methoding determines feeding and gating parameters while process planning determines the manufacturing methods, manufacturing steps and process parameters (such as metal pouring time, pouring rate, sand composition) for casting manufacturing. For this purpose, the knowledge management system has been integrated with a casting design software AutoCAST and a web based casting project management system WebICE. These two applications are explained here.
INTEGRATION WITH 3D METHODING SOFTWARE
The real benefits of a knowledge management system can be exploited by integrating it with a 3D casting design software. The CAD software selected for this purpose is casting design and analysis software called AutoCAST. The software enables parting line generation, core design, gating system design, feeder design, solidification analysis and mold cavity filling analysis. All the equations and knowledge involved in casting design and analysis are coded in the software program. It is difficult for end user (foundry) to change the equations and knowledge base in software without sharing them with software vendor or other firms. The integration of Knowledge Editor with AutoCAST allows foundry to capture and use its valuable in-house knowledge for design and analysis purpose without any access to the source code of the CAD software. For example, the pouring time equation can be modified using the knowledge management system (as explained earlier) and then imported into the casting design software for completing the gating design (figure 4). Thus the end-user in a foundry does not have to share his proprietary or in-house knowledge with the casting software vendor or other firms, while being able to capture and use such knowledge to optimize the castings.

INTEGRATION WITH PROCESS PLANNING SYSTEM
The casting process planning involves determining the manufacturing methods, manufacturing steps and process parameters (such as metal pouring time, pouring rate, sand composition) for casting manufacturing. The process planning has been demonstrated in a web based framework WebICE (Web-based Integrated Casting Engineering) developed for collaborative engineering of cast components in our laboratory (Akarte, 2002). The input parameters for process planning are product attributes (casting material, weight, size, section thickness, etc.) that are finalized at the design stage. Based on these input parameters process plans of similar previous castings has been retrieved using case based reasoning methodology as mentioned earlier and used for process planning of new casting.

In the absence of similar previous case knowledge from the library is retrieved using the ‘if-then’ rules. As mentioned earlier, the libraries have been developed for storing information related to manufacturing steps, process parameters for each activity using different methods. The ‘if’ block of the ‘if-then’ rules are evaluated against the product attribute values specified by design engineer to select a particular method or equipment in ‘then’ block. In this way, manufacturing methods including steps, process parameters and equipment can be selected at the design stage, even by engineers with limited knowledge of the casting processes involved. Such a process planning knowledge retrieved from library is shown in figure 5. The web based implementations enables modification in retrieved knowledge (process plan) by the foundry engineer working from different location. This knowledge is again added to the case base as a new case that can be used for the future reference.

CONCLUSION
Collaboration and sharing of knowledge between team members within an organization and beyond (suppliers and customers) has become necessary for cost-effective product design and manufacturing. The importance of design for manufacture for predicting and solving manufacturing related problems at early stages is increasingly gaining momentum.
The casting knowledge management system developed in our work enables managing the casting knowledge and making it available at the product design stage. By providing a web-based environment this knowledge management system can be accessed whenever and wherever required, thus shortening time to solutions.

The web-based implementation also provides a collaborative environment in which information and knowledge can be accessed and shared between design engineer (buyer) and foundry engineer (supplier) located anywhere in the world. This enhances communication and team synergy that leads to better product quality, shorter time to market and lower product development and manufacturing cost. By making the knowledge available at the design stage, it is possible to test various alternatives at the early stages of design and to design cost effective castings. Similarly a systematic collection of design guidelines for castability assessment and improvement in the form of ‘if-then’ rules helps in predicting the defects. Thus these kinds of problems can be highlighted and taken care at the early design stage.

To the best of our knowledge, it is perhaps for the first time that a web based knowledge management system for casting has been developed. The initial response from industry is encouraging.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. Milind Akarte (framework for web-based integrated casting engineering) and PNV Ajay Kumar (knowledge management for gating design) for their contributions in developing the earlier systems which provided the foundation for the present work.

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