CIRP Annals - Manufacturing Technology 57 (2008) 153–158

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Computer aided manufacturability analysis: Closing the knowledge gap between the designer and the manufacturer

G. Molcho*, Y. Zipori, R. Schneor, O. Rosen, D. Goldstein, M. Shpitalni (1)

Laboratory for CAD and LCE, Faculty of Mechanical Engineering, Technion-Israel Institute of Technology, 32000 Haifa, Israel

ARTICLE INFO

Keywords:
Knowledge management
CAPP
Manufacturing

ABSTRACT

Manufacturing today is marked by increased competition and dispersed global organization, thus necessitating enhanced collaboration among designers and manufacturers. Nevertheless, while Design for Manufacturability (DFM) has been the subject of in-depth research over the past decades, the supporting software solutions have not as yet matured. In this paper we present a holistic approach and supporting software tool, termed the *Computer Aided Manufacturability Analysis* (*CAMA*) tool, for capitalizing on available manufacturability knowledge. This is achieved by closing the knowledge loop between the design and manufacturing environments. CAMA captures the knowledge in a structured manner and incorporates this knowledge within the product design tools (CAD systems), thus enabling improved product timeliness and profitability. CAMA represents proof of concept and constitutes a demonstrative prototype of an adaptive and open DFX tool. It is based on industrial surveys of the Knowledge, Information and Data (KID) flows in CAD, CAPP and CAM processes within the manufacturing outsourcing environment. CAMA differs from other approaches in that it is an open system that enables continuous and intuitive capture, modification and implementation of updated manufacturability KID.

1. Introduction

In response to technology progress, fierce market competition and changing business environment, modern industry must continually improve product functionality and quality to gain market advantage [1]. To this end, various Design for X (DFX) methodologies have been developed over the years to address the "hottest" design problems or bottlenecks in marketing.

Each Design for X label incorporates a broad collection of specific design guidelines. Each design guideline addresses aspects either caused by or affecting product characteristics. The guidelines themselves usually propose an approach and corresponding methods for generating and applying technical knowledge to control, improve, or even invent specific product characteristics. Such guidelines represent an explicit form of knowledge that contains information about "knowing-how-to."

The current scientific edge, therefore, resides in incorporating this know-how, as well as additional customer needs, manufacturing experience and other product life-cycle aspects into the design of new products. In particular, taking the above factors into consideration in the early design stages is expected to significantly increase product profitability. Despite the expected benefits, only a few mature tools are available to support designers in defining product functionality and structure that incorporate additional DFX considerations [2].

This paper describes a software analysis tool that addresses this critical issue: the *Computer Aided Manufacturing Analysis* system (CAMA). This feature-based analysis system is capable of capturing diverse DFX "know how" in a structured manner. Moreover, it enables the evaluation of a product's CAD model for conformity to a selected DFX, in particular DFM in the early design stages, thus significantly improving product timeliness and profitability.

1.1. *CAMA motivation*

1.1.1. *Closing the knowledge gap between design and manufacturing*

Process planning and product design are concurrent processes requiring collaboration among all parties. To achieve such collaboration, technology and business processes must be improved through a more systematic and structured approach [3].

CAMA stems from the Design for Manufacturing (DFM) methodology. The need for CAMA was indicated by the results of a survey of SME manufacturers, leading PLM solution providers and designers, carried out as part of this research. The results of the survey highlighted the knowledge and cooperation gap between designers and manufacturers, and the lack of appropriate software tools to support this cooperation [4].

Solution providers such as UGS, PTC and Dassault have recognized the need to improve collaboration among the design, process planning and manufacturing environments. To this end, they are currently working in three directions:

(a) Providing well-defined compound features recognized by the CAPP system, to be used as building blocks in product design, along with a recommended process plan [5];
(b) Implementing standards for transferring engineering KID between the different CAD/CAPP/CAM/PLM systems (i.e.,

---

* Corresponding author.

0007-8506/$ – see front matter © 2008 CIRP.
doi:10.1016/j.cirp.2008.03.046

tolerances, thermal treatment, coating), for example by incorporating this additional KID into the STEP standard [6];
(c) Including CAPP capabilities in CAM systems, thus closing the gap between process planning and manufacturing.

Nevertheless, solution providers have yet to capitalize on the expected benefits of increased collaboration between designers (CAD) and process planners (CAPP) in the early design stages. Bridging this collaboration and knowledge gap is expected to reduce product development lead time and improve product quality and performance, thus providing a more timely and profitable solution for industry.

CAMA closes the knowledge gap between the designer and manufacturer by incorporating manufacturing considerations in the early design phase. CAMA is an adaptive system that enables continual capture of manufacturing knowledge. The system also facilitates structured incorporation of this KID within the designer's environment.

1.1.2. Addressing multiple design methodologies

Past initiatives aimed solely at improving product cost, quality, or time-to-market are no longer sufficient for gaining market advantage [7]. The focus today is on innovation: products differentiated from those of competitors that are also affordable, reliable, and early to market.

Though CAMA originated to support the DFM design methodology, the tool has since evolved to incorporate additional DFX methods, including Design for Assembly (DFA) and Design for Disassembly (DFD). Multiple analyses are possible, either in parallel or consecutively. Designers seeking to develop, manufacture, market and sell innovative, economical and environmentally conscious products must consider all these aspects. Most designers, however, do not have the cognitive capacity to incorporate considerations and guidelines from all these paradigms. The aim of CAMA is, therefore, to enable designers to focus on product functionality and innovativeness, while the software analyzes the CAD model and points out where the model does not conform to the requirements of the selected design method.

1.2. The CAMA environment

As today's organizations become increasingly distributed, the gap between knowledge-based industry and resource-based industry is growing. Hence, care must be taken to capture and store core competencies and to close the growing KID gap between functionalities. This need is even more urgent when manufacturing and assembly are outsourced, often generating a conflict of economic interests.

The interface between design and process planning functionalities can usually be summarized by three KID flows (Fig. 1).

The first flow is a formal flow of engineering data from the designer to the process planner. This flow is usually supported by a configuration control mechanism.

The second flow involves interactions about changes or corrections required based on manufacturability issues, which are then either accepted or rejected by the designer. This flow varies as the product matures. In the early phases of product design, prototyping and release (the focus of our research), communication is usually limited, informal and not well documented due to differences in status between process planners and designers, as well as time constraints or conflicts of interest. These interfaces often become evident in an organization only when a new set of design and engineering data is formally released. Thus, no organizational learning occurs at this stage. Indeed, one of the main Achilles' heels of small and medium enterprises (SMEs) manufacturers and process planners is that errors tend to recur [4]. As a product matures, this communication becomes more formal and takes the form of Engineering Change Orders (ECOs).

The third KID flow is a post-analysis report from the manufacturer to the design department (usually Quality Assurance). This report, usually available only to market-dominant companies, incorporates all the difficulties encountered in process planning and manufacturing. These analysis reports are used mainly to ensure that the correct procedures for completing missing data or formally releasing a new product version have been carried out.

These feedback forms do not usually include the informal interactions that took place between the parties. In particular, substantial changes required in the product due to such interactions are not recorded and remain "off the record". Furthermore, there is no structured mechanism to capture and analyze this feedback or to provide it to designers; therefore, the learning effect is not achieved.

1.3. CAMA aims

CAMA aims at decreasing the number of iterations/multiple KID flows between designers and process planners, thus reducing efforts on the part of these two expensive and core resources. In particular, the aim is to decrease the number of KID flows in the informal interface (Flows 1 and 2) *until a final product is manufactured* (Fig. 2).

An additional aim of CAMA is to capture, store and reuse the knowledge created at this stage of the product life cycle. These aims will be achieved by:

- Creating a structured mechanism for capturing interactions between the designer and the process planner or manufacturer.
- Creating a structured mechanism for capturing the post-analysis.
- Creating a capability for analyzing these structured databases.
- Incorporating an intelligent component into the designer's environment. On demand, this component can evaluate product

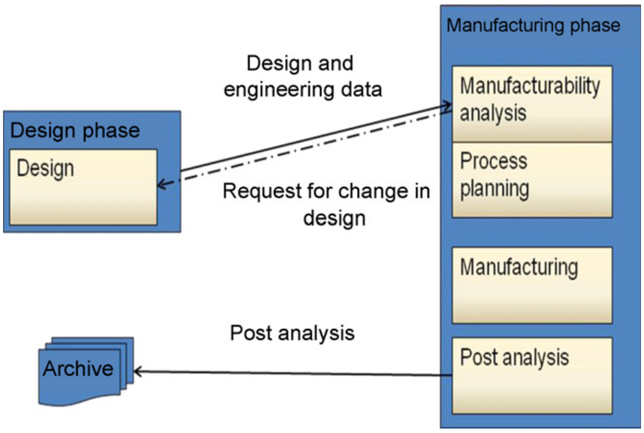


Fig. 1. KID flow between design and manufacturing phases.

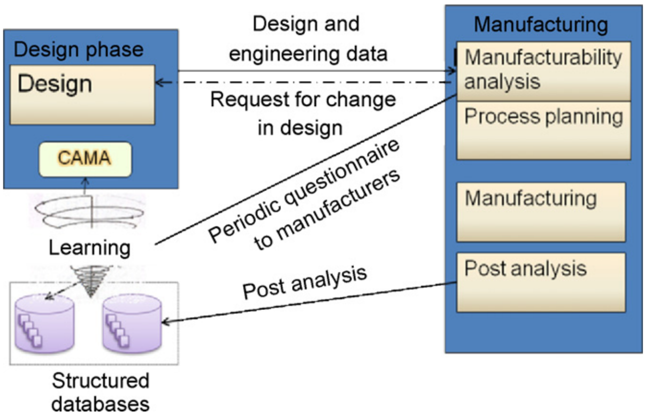


Fig. 2. Closing the KID loop.

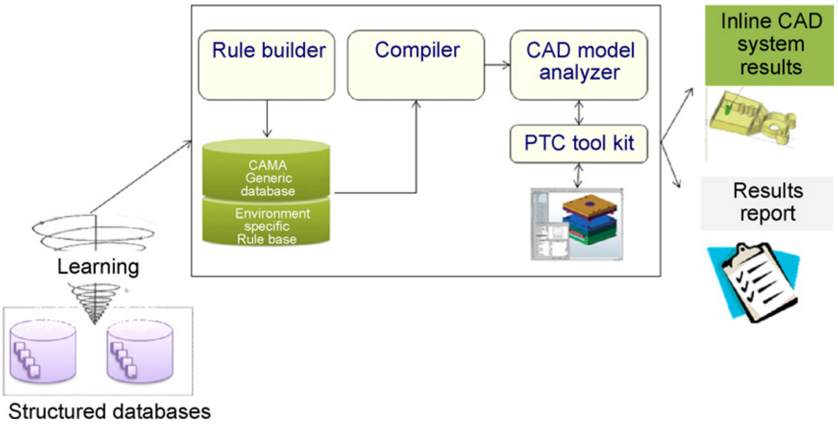


Fig. 3. CAMA components.

model conformity to a selected design methodology, in particular DFM, based on the knowledge captured in the system.
- Incorporating the capability of continually modifying the knowledge captured in the system.

Implementing these capabilities ensures not only knowledge capture but also knowledge capitalization. Furthermore, the knowledge captured is always updated and does not become stagnant as industry evolves. Moreover, each specific industry can prioritize the different DFXs and can, with minimal effort, analyze conformity to any additional DFX at any given moment.

2. CAMA overview

CAMA provides designers with the ability to analyze whether a product model conforms to the "know how" of various design methodologies. Special emphasis is placed on DFM, which is the core of the system. The analysis of CAMA V 1.0 remains at the level of model features and feature attributes and does not incorporate additional geometry analysis. CAMA comprises three main components (Fig. 3):

i. A rule-base building and modifying capability for continual updating of the rule base according to industry requirements.
ii. A capability for analyzing CAD models based on the rule base, developed currently on the PTC Pro-Engineer environment.
iii. An interfacing capability that converts the captured rule-base into program code recognized by the Pro-Engineer tool kit, enabling model analysis.

2.1. CAMA input

New knowledge is incorporated in CAMA by technologists, designers, process planners or knowledge engineers. The new knowledge may become available after analysis of the structured KID bases, or as new knowledge is adopted from external sources (i.e., introduction of new technologies or materials) or created in the company (i.e., new manpower).

2.2. CAMA output

The output of the CAMA system is in the form of a digital report summarizing nonconformity elements as well as inline coloring to indicate problematic features requiring change.

In contrast to existing CAD, CAM and CAPP software solutions, CAMA addresses the following two factors:

- The CAMA rule base is comprehensible, enabling rule review and modification, thus facilitating knowledge capitalization.
- Defining new rules in CAMA is intuitive and does not require significant programming skills.

3. The CAMA rule builder

The CAMA rules cannot be written in natural language, as the system must be able to interpret these rules and react accordingly. Moreover, natural language can lead to writing equivalent rules in different ways, which should be prevented to avoid multiplicity and ambiguity. Therefore, in order to ensure intuitive updating of the CAMA rule base and rule-base comprehensibility, three components were required (Fig. 4): (a) ontology, (b) syntax and (c) rule base. The ontology is the dictionary of the words comprising the rule language. The syntax is the rule sentence structure. The rule base is a digital KID-base that stores all CAMA rules in a structured manner.

3.1. Ontology

In artificial intelligence (AI), ontology is defined as "the specification of conceptualizations used to help programs and humans share knowledge. It is a description (like a formal specification of a program) of the concepts and relationships that can exist for an agent or a community of agents" [8].

This research developed a dedicated ontology for CAMA based on two major sources: (a) a process planning environment ontology developed as part of this research [4], and (b) a set of basic rules collected in the system, based on literature and industry surveys. This ontology constitutes the syntactical units for developing the rule base. For example, the DFM rule "Hole depth must not be greater than three times the hole diameter" [9] incorporates a number of different syntactical unit types or ontological elements, demonstrated in Table 1.

The syntactical unit types identified in the system include *features, feature characteristics, actions, conditions, logical operations, severity, manufacturing process, DFX* and *values*. Each syntactical unit type is associated with a fixed set of values. For example, the "feature" syntactical unit type includes the following values: *model, hole, round, surface, axis, extrude, sweep*, and *blend*.

Each feature has a set of related feature characteristic values. For example, the "feature.characteristics" for the "hole" feature

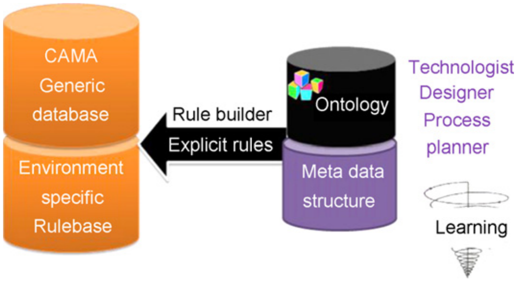


Fig. 4. CAMA rule builder.

Table 1
Syntax unit table

Syntax unit types	Specific value
Feature	Hole
Feature.characteristic	Hole.Depth
Severity	Must
Condition	Not be longer than
Value	Three
Action	Times
Feature	Hole
Feature.characteristic	Hole.Diameter

include: *axis, diameter, start plane, hole type, hole bottom type, hole depth, actual drill depth* and *envelope*.

Feature characteristics are further divided into two types: property and method. For example, hole depth is distinguished from actual drill depth, which may be shorter than the hole depth. The first is a property of the feature, while the second requires geometric calculation (method).

To enable automatic registration of the database in the CAMA model analysis tool, the ontology is hard coded and stored in the database, and any new addition requires further software development. Hence, a broad ontology is required to enable construction of all feature-based rule possibilities.

3.2. Syntax

Syntax refers to the set of abstract grammar rules in a language, governing the order of words in a correct sentence. Syntax is directly related to semantics, since the meaning of a sentence depends upon its syntactical structure. The CAMA syntax governs the structure of the CAMA rules and therefore determines how to combine syntactical units to define new rules.

The rules are built by selecting the syntactical units from the ontology and then appending them into a sentence according to the formal rules. The interface of the rule builder is intuitive and makes available only relevant syntactical unit values for selection. For example, once a feature has been selected, only the relevant feature characteristics will be displayed for selection.

The CAMA syntax specifications dictate the rule structure. For example, a rule must begin with a feature, followed by a corresponding feature characteristic.

Table 2 demonstrates the syntax of a rule dictating the minimal external round radius required for efficient and economic manufacturing. This rule was identified during the construction and investigation of a large post-manufacturing feedback database (see Section 6). This rule defines that the external round radii should be greater than 1.5 mm.

'Round.Radius' is a characteristic of a Round feature that represents the round radius value. 'Round.isConvex' is a characteristic of a Round feature that represents a Boolean value (TRUE if convex Round and FALSE otherwise).

After a rule is built, rule options must be defined to determine the additional information needed for classifying the rules. These options are:

Table 2
The syntax and corresponding values of the example rule

Structure	Specific value
Feature	Round
Feature.characteristic	Round.Radius
Action	>
Value	1.5 mm
Logical	And
Feature	Round
Feature.characteristic	Round.isConvex
Action	=
Value	TRUE

- *Severity*: represents the severity of the rule (Error, Warning, Recommendation).
- *DFX*: the relevant design methodology (manufacturing, assembly, disassembly, environment, etc.).
- *Manufacturing process*: specifies the expected manufacturing process limitations, when relevant.
- *Subcontractor*: whether the rule is generic or environmental—specific to a certain subcontractor.
- *Rule details*:
  - ○ *Approval details*: composed by, approved by, modification date, etc.
  - ○ *Rule name*.
  - ○ *Description*: the explicitly stated definition of the rule.

3.3. Rule base

Based upon "know-how" from DFM and DFA, over fifty rules have been incorporated in the general CAMA rule base. These rules were collected from available literature [8,10], industrial surveys of SME manufacturers, and post-analysis feedback from manufacturers to designers (see Section 6). All the rules are based on feature characteristics and therefore do not incorporate rules requiring geometrical analysis. The rules are captured in a database to enable easy look-up during the design phase and easy modification when required.

The CAMA rule builder enables an organization to update or expand the rule base as new knowledge becomes available. Each rule is classified as described in Section 3.2, in particular subcontractor-specific and generic rules, DFX methodology and manufacturing process.

4. The CAMA compiler

In general, compilers enable translating from one language to another. The CAMA rule compiler is the link between the rule base and the CAMA design analysis tool. After a rule is defined using the rule builder, the CAMA compiler is activated. The compiler converts each rule in the rule base into a function consisting of a set of C/C++ and Pro/Toolkit commands.

The Pro/Toolkit is a large library of C functions that enable external applications to access the Pro/ENGINEER database and user interface. The Pro/Toolkit library functions are used to retrieve information and data from the design model [11].

The CAMA compiler therefore converts the rule base into (a) a set of toolkit commands for retrieving geometry information and (b) logical and arithmetic commands for additional operations on the retrieved data.

Similar to computer programs, which are not text but rather hierarchical compositions of computational structures [12], the CAMA rules are not sentences written in natural language and therefore can be easily converted into a hierarchical composition of CAMA rule syntactical units.

The compilation procedure:

i. Hierarchically divide the rule according to operation priorities (logical operations, conditions, actions) and build a binary tree that represents the order of operations.
ii. Parse the tree from left to right in post-order and construct a list of sequential operations (Table 3).
iii. Translate each operation to a set of C/C++ and Pro/Toolkit commands.

For example, the implicit rule 'ratio between hole diameter and hole depth should be greater than 0.3 for hole diameters greater than 5 mm' is represented by the following CAMA rule:

feature.characteristic1 <action> feature.characteristic2 <condition> <value> <logical> feature.characteristic1 <condition> <value>

For this rule, the compiler procedures will be:

Table 3
The resulting list of operations based on the tree parsing

ID	Operation	Result
1	feature.characteristic1 (FC1)	Value
2	feature.characteristic2 (FC2)	Value
3	Result1 <action> Result2	Value
4	<value>	Value
5	Result3 <condition> Result4	Boolean value
6	FC1	Value
7	<value>	Value
8	Result 6 <condition> Result 7	Boolean value
9	Result 5 <logical> Result 8	Boolean value

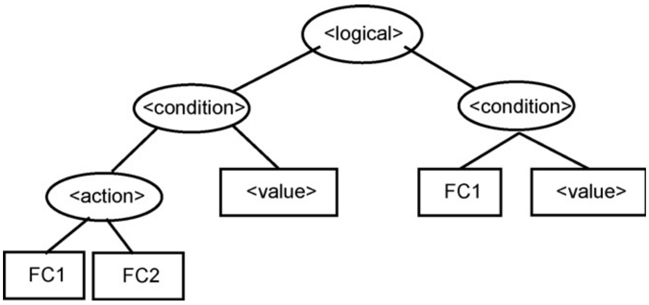


Fig. 5. Hierarchical binary tree.

i. Hierarchically divide and build the binary tree (Fig. 5).
ii. Parse the tree and construct the list of operations (Table 3).
iii. Translate the operations.

```
Function RuleName1( FEATURE feature1) as Boolean
{
 If ProFeatureTypeGet(feature1)== PRO_FEAT_HOLE
then
        Result1 =  ProERetrieveHoleDiameter ( feature1)
        Result2=  ProERetrieveHoleDepth ( feature1)
Result3= Result1 / Result2
Result4=0.3
If Result3 > Result4== TRUE Then
        Result5=TRUE
Else
        Result5=FALSE
Result6 =  ProERetrieveHoleDiameter ( feature1)
Result7 = 5
If Result6 > Result7== TRUE Then
        Result8=TRUE
Else
        Result8=FALSE
RuleName1=Result5 & Result8

Return (RuleName1)
}
```

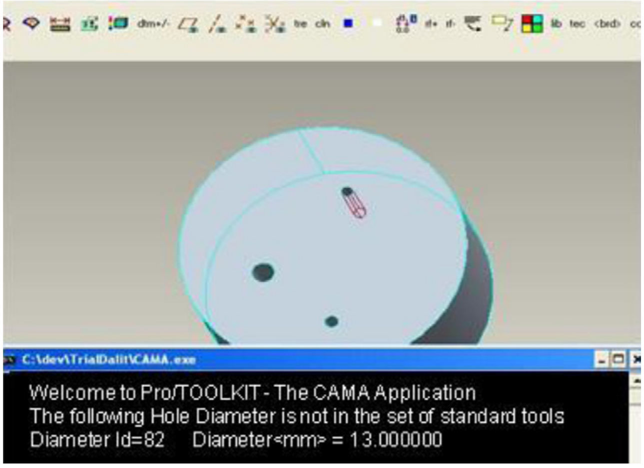
5. The CAMA analyzer

The design analysis process is embedded in the Pro/Engineer CAD system standard menu, so that the designer can activate the CAMA design analysis application in line.

The first step in activating the analysis is to filter the rules by defining relevant DFX, rule severity or other classification fields in the filter dialog. The CAMA analyzer then checks the CAD model for any inconsistencies with the selected rules by executing the appropriate rule functions.

The CAMA design analysis results can be presented graphically in Pro/E. As demonstrated in Fig. 6, features that fail to comply with a particular rule are highlighted in different colors according to rule severity. In addition, failure details are displayed in a separate window.

Finally, the analysis results are also saved in a CSV file for further use or analysis.



```
Welcome to Pro/TOOLKIT - The CAMA Application
The following Hole Diameter is not in the set of standard tools
Diameter Id=82     Diameter<mm> = 13.000000
```

Fig. 6. CAMA analyzer.

6. Closing the knowledge loop

An integral and important part of CAMA is the structured feedback from the manufacturer that is systematically captured and made available to the organization for further analysis. The structuring of this feedback mechanism was based on a review of over 1200 post-analysis feedback forms from more than 50 manufacturing subcontractors.

By creating a digital database of these forms and collecting them in a database structure, we have laid the foundations for knowledge analysis and organizational learning. Work has begun to identify new manufacturing constraints and recommendations based on these input forms. Each new recommendation identified is verified with experts to determine (a) if it is a local/subcontractor specific requirement or a generic limitation and (b) the correct severity of these recommendations. These rules are then ready for incorporation within the CAMA rule base to be implemented in the CAMA analyzer, resulting in instant capitalization on the organizational learning process.

Contrary to the post-analysis stage, where structured feedback can be enforced, collecting such structured feedback in the preliminary manufacturability analysis stage appears to be less feasible because, as noted above (Section 1.2), communication in this stage is more problematic and informal. We propose, therefore, to introduce periodic structured interviews and questionnaires of process planners in order not to lose this knowledge and to be able to capitalize upon it.

7. Conclusions

Process planning and product design are concurrent processes requiring collaboration among all parties to optimize product time-to-market, cost and quality.

In this paper we have presented CAMA, an adaptive and open system that facilitates *capture*, *modification* and *implementation* of manufacturability knowledge. CAMA enables not only the updating of the explicit CAMA rule base, but also provides automatic rule compilation and propagation of the rules in the CAD design environment. CAMA thus, makes the “know-how” available to designers in the context of their specific design activity and can thus influence decisions before the product design is released to manufacturing. CAMA originally focused on supporting DFM, but has evolved to include additional DFX methodologies.

CAMA demonstrates the strength of developing semantic ontologies. This strength includes: (a) the common benefit of creating an ontology—creation of a common terminology to be shared among workers or collaborators from different disciplines and (b) the breakthrough of machine (computer tractable) understanding of the terminology. This breakthrough was achieved by developing a complementary syntax and compiler on the ontology platform.

The development and implementation of the semantic ontology, syntax and compiler within the product and process design procedure enable not only knowledge updating but also incorporation of the new knowledge within the CAD environment. This ensures that the knowledge-based tool does not become rapidly stagnant and irrelevant. It furthermore, enables not only efficient working processes but also ongoing organizational learning and knowledge capitalization, thus demonstrating proof of concept for this dynamic knowledge-based tool.

Furthermore, whereas traditionally each DFX methodology is researched separately and requires re-education of designers, CAMA enables gradual incorporation of new design recommendations into the design environment. Thus, not only does it analyze a product design according to a new set of guidelines, but also simultaneously educates the designer regarding new guidelines or simply refreshes designer awareness so the guidelines are not overlooked. CAMA also enables rapid analysis of a design in accordance to several DFX "know how", thus providing insight regarding the tradeoff of adopting one set of guidelines rather than another.

Finally, a systematic and structured complementary feedback process has been implemented to close the knowledge gap between manufacturing and design. This structured organizational learning, in the form of structured digital forms and interviews, enables maximum knowledge capture and capitalization and is required to close the knowledge loop.

In conclusion, to improve product manufacturability and profitability in today's business environment, appropriate tools, procedures and business culture must be developed to provide product designers with systematic feedback from manufacturers regarding manufacturability guidelines. This knowledge must be incorporated in a structured organizational learning process and imbedded in the design environment to ensure increased product quality and profitability.

Acknowledgements

This research has been funded by the Niedersachsen Foundation, Grant 2005847, and supported in part by the Schlesinger Minerva Laboratory for Life Cycle Engineering and by the VRL-KCiP Network of Excellence.

References

[1] Kimura F, Matoba Y, Mitsui K (2007) Designing Product Reliability Based on Total Product Lifecycle Modelling. *Annals of the CIRP* 56(1):163–166.

[2] Zwolinski P, Tichkiewitch S, Sghaier A (2007) The Use of Virtual Reality Techniques During the Design Process: From the Functional Definition of the Product to the Design of its Structure. *Annals of the CIRP* 56(1):135–138.

[3] Susman GI (1992) *Integrating Design and Manufacturing for Competitive Advantage*. Oxford University Press, USA.

[4] Denkena B, Shpitalni M, Kowalski P, Molcho G, Zipori Y (2007) Knowledge Management in Process Planning. *Annals of the CIRP* 56(1):175–180.

[5] Li WD, Ong SK, Nee AYC (2002) Recognizing Manufacturing Features from a Design-by-feature Model. *Computer Aided Design* 34(11):849–868.

[6] Newman ST, Allen RD, Rosso Jr RSU. (2003) CAD/CAM Solutions for STEP-compliant CNC Manufacture. *International Journal of Computer Integrated Manufacturing* 16(7/8):590–597.

[7] Rostad CC, Myklebust O, Moseng B (2005) Closing the Product Lifecycle Information Loops. *Proceedings of the 18th International Conference on Production Research*, Italy, .

[8] Gruber TR (1993) A Translation Approach to Portable Ontologies. *Knowledge Acquisition* 5(2):199–220.

[9] Bralia JG (1986) *Handbook of Product Design for Manufacturing: A Practical Guide to Low-cost Production*. McGraw-Hill Book Company.

[10] Gupta N (1995) A Systematic Approach for Analyzing the Manufacturability of Designed Parts. *Computer Aided Design* 27(5):323–342.

[11] Srikumaran S, Sivaloganathan S (2005) Proving Manufacturability at the Design Stage Using Commercial Modeling Software: Through Feature Mapping and Feature Accessibility. *Computer-Aided Design and Applications* 2(1–4):507–516.

[12] Teitelbaum T, Reps T (1981) The Cornell Program Synthesizer: A Syntax-directed Programming Environment. *Communications of the ACM* 24(9): 563–573.