Review of Knowledge Based Engineering and its Applicability to Optimization of Machining Processes

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Abstract **—***The knowledge capturing methods have evolved from computer aided design (CAD) to Knowledge based engineering (KBE). The KBE systems have been successfully implemented in different fields. Most of the KBE systems were geometry focus. One of the features of the KBE approach is to automate repetitive, non-creative tasks. The optimization of machining process is a repetitive, trial and error and experience based process. A KBE system for optimizing machining process will help the designers and manufacturing planners to select an optimal set of cutting tools and cutting conditions for different material properties and to give users alternatives on how to reduce cost and time. The methodology of this research consists of reviewing different KBE methodologies and developing KBE model for machining process. A suitable knowledge based system was proposed to generate optimum solutions for machining processes by integrating CAD, computer aided manufacturing (CAM), material selection, costing and empirical equations.*

Keywords: Knowledge based engineering; Computer aided manufacturing; Optimization.

I. INTRODUCTION

The integration of CAD, CAM and CNC technology have satisfied the competitive market demand of manufacturing industry but still the competition continues and the ways and means of optimizing manufacturing process is under development. Starting from CAD design to finish product, at different stages, decisions and selections of best solution have to be made. The CAD design should comply with manufacturability and concurrent engineering (CE) techniques. The best tool path, feed rates spindle speeds and cutting tools have to be selected based on the tolerance and surface finish requirements, work material and tool material, machine capabilities and part complexity. Most of the time these are routine works.KBE tries to give some tools to automate routine tasks (Nunes, 2002) so that optimum solutions can be generated with shortest time with KBE technology.

According to Prasad (1997), during the period of 30 years (1960s to 1990s), there had been major innovation in languages for capturing knowledge.

- The first generation of C4 (CAD/CAM/CIM/CAE) languages, first introduced during 1960, only dealt with 2-D drafting and 2-D wire-frame design.
- The second generation of C4 languages dealt with surfaces and 3-D solids.
- The third generation of C4 languages was constraint-based but mostly dealt with geometry. Examples include case-based design, parametric scheme, variational scheme and others.
- Finally is the fourth generation of languages. Today is the age of fourth generation C4 languages. They are knowledge-based techniques giving CE design work groups the ability to capture both geometric and non-geometric information.

This paper introduces KBE and demonstrates KBE applicability in the optimisation of machining processes.

II. OPTIMIZATION

In optimizing the machining process parameters, the selection of machining process parameters is a very crucial part in order for the machine operations to be successful (Rao and Pawar, 2009). To choose the process parameters, it is usually based on the human (or manufacturing engineers) judgment and experience. However, the chosen process parameters usually did not give an optimal result. This is due to the fact that in machining processes; a number of factors also could interrupt thus preventing in achieving high process performance and quality (Benardos and Vosnaikos, 2003). In fact, tuning each machining process parameters would give significant effects to other parameters as well (Yusup, Zain and Hashim, 2012).

Optimization of machining operations requires the following features.

- Knowledge of machining (i.e. drilling, turning or milling);
- Empirical equations relating the tool life, forces, power, surface finish, material removal rate, and arbor deflection, etc., to develop realistic constraints;
- Specification of machine tool capabilities (i.e. maximum power or maximum feed available from a machine tool);
- Development of an effective optimization criterion (e.g. maximum production rate, minimum production cost, maximum profit or a combination of these); (Onwubolu, 2005)

III. KNOWLEDGE BASED ENGINEERING (KBE)

According to Stokes (2001), Knowledge Based Engineering can be defined as ‘The use of advanced software techniques to capture and reuse product and process knowledge in an integrated way.

Chapman and Pinfold (1999) explained the above definition as follows. KBE is an engineering method that represents a merging of object-oriented programming (OOP), Artificial Intelligence (AI) techniques and computer-aided design technologies, giving benefit to customised or variant design automation solutions. The KBE systems aim to capture product and process information in such a way as to allow businesses to model engineering design processes, and then use the model to automate all or part of the process. KBE tries to give some tools to automate routine tasks. In fact, for 100 h of work, an engineer works 20 h on creative task, 10 h on administrative task and 70 h on routine task (Nunes, 2002).

Knowledge based systems (KBSs) are software programs designed to capture and apply domain-specific knowledge and expertise in order to facilitate solving problems. Languages can be used as a means to build KBS. KBE deals with processing of knowledge (Prasad, 1997).

Older definitions of KBE are more narrow and technology-oriented; for instance, the notion of KBE as a combination of CAD and AI techniques. More recent definitions of KBE are wider and less restrictive; for instance, they do not contain the geometry focus that often seems to constrain KBE applicability. Instead, newer definitions focus on the automation of repetitive engineering tasks while capturing, retaining and re-using associated knowledge.

KBE has to date not achieved a convincing breakthrough, apart from major aerospace and automotive companies. The reasons for this are varied and complex. Notably, the KBE research field is still in development, with methodological and technological considerations constantly evolving (Verhagen et al, 2011).

KBE is not by definition suitable for all design tasks. The following as identified by Stokes (2001) stand out:

- The design task is relatively straightforward and can be modeled and executed using less resource than a more demanding KBE approach.
- The organisation does not have the will, money or resources to introduce a KBE system. Nowadays, companies tend to move towards Commercial-Of-The-Shelf (COTS) solutions and tend to shy away from in-house software development, which is necessary in the case of KBE development.
- The design process consists of creative processes and products that are highly subject to change.
- The knowledge for the desired application is not available.
- The design process cannot be clearly defined; it is not possible to isolate and define particular stages in the design process.
- The technology in the design process is constantly changing

Successful efforts to implement KBE have been made in various fields. In the automotive field for example, Chapman and Pinfold (2000) described the design analysis response tool (DART) created to aid in the design /analysis of a body-in-white (BIW) structure or structural body of a vehicle consisting of structural beams, joining methods and body panel creation. The Table 1 shows the summary of results of some KBE projects.

Table 1. Successful implementations of KBE systems

Subject	**Effects**	**Reference**
A computer-based intelligent system for automatic tool selection	Determine the optimum cutting conditions that leads to short cutting time, and subsequently, to low cost	Edalew, Abdalla and Nash, 2000
Parametric modeling of movables for structural analysis	Up to 8% time savings in FE model generation(From 8 h to 1 h for specific instances)	Van der Laan et al, 2005 cited in Verhagen et al, 2011
The application of a knowledge based engineering approach to the rapid design and analysis of an automotive structures	BIW mesh generation from 15 man weeks to 'minutes	Chapman and Pinfold, 2000
Composite aerospace structure:cost and weight estimation	Rapid evaluation of cost and weight for composite structures:supports trade-off capability	Choi et al.,2007 cited in Verhagen et al, 2011
Manufacturing process design: hot forging	New designs in hours rather than days or weeks. Supporting accessible knowledge base	Kulon et al, 2006
Automated tool design : age forming tool for aerospace panels, international ICAD users Group Conference Proceeding 1996.	Deployment of tooling design application of Textron Aerostructures delivered a 73 % reduction in design time	Brewer ,1996 cited in Chapman and Pinfold, 2000
777 rule based design: integrated fuselage system, International ICAD Users Group Conference Proceeding 1996	Approximately 20 000 parts for the Boeing 777 aircraft have been designed using KBE	Heinz,1996 cited in Chapman and Pinfold, 2000
Achieving competitive advantage through knowledge-based engineering-A best practice guide	Using KBE and using holistic approach the design and analysis of entire wing of A340 -600 was done in 10 h	Cited in Chapman and Pinfold, 2000
See all, know all, tell all, Professional Eng.	Jaguar cars company's KBE group devised a system that reduced the time taken to design an inner bonnet from 8 weeks to 20 min	MacLeod, 1998 cited in Lovett, Ingram and Bancroft, 2000

A. The Rationale for KBE

A major advantage in adopting KBE is highlighted in Figure 1. As the definition of KBE states, one of the hallmarks of the KBE approach is to automate repetitive, non-creative design tasks. Not only does automation permit significant time and cost savings, it also frees up time for creativity, which allows exploration of a larger part of the design envelope. This is helped by another advantage of KBE: it enables knowledge re-use (Verhagen et al, 2011).

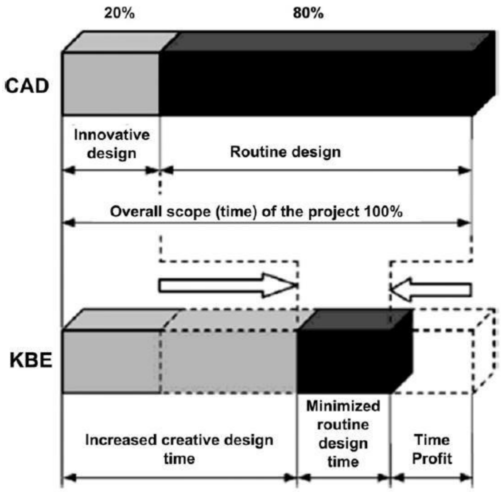


Figure 2. Achievable design time allocation by KBE (Skarka, 2007)

B. Existing Methodologies for KBE

A number of KBE methodologies are available to support the development of KBE applications and systems. By far the most well-known of these is the Methodology and software tools Oriented to Knowledge-Based Engineering Applications, or MOKA methodology.

This methodology, consisting of six KBE Life-cycle steps and accompanying informal and formal models, is designed to take a project from inception towards industrialization and actual use (Oldham, et al, 1999; Stokes, 2001). The informal model consists of so-called ICARE forms: Illustrations, Constraints, Activities, Rules and Entities. The formal model uses MML (MOKA Modelling Language, an adaptation of UML) to classify and structure the ICARE informal model elements, which are translated into formal Product and Process models (Curran, et al 2010).

Another available KBE methodology is KOMPRESSA: Knowledge-Oriented Methodology for the Planning and Rapid Engineering of Small-Scale Applications (Lovett, Ingram and Bancroft, 2000). This methodology aims to support KBE implementation at Small to Medium Enterprises (SMEs) and shares many principles with MOKA, with which it was developed in parallel (Verhagen et al, 2011).

To better address the integration of multidisciplinary engineering knowledge within a knowledge based engineering (KBE) framework, the KNOMAD methodology has been devised. KNOMAD stands for Knowledge Nurture for Optimal Multidisciplinary Analysis and Design and is a methodology for the analytical utilization, development and evolution of multi-disciplinary engineering knowledge within the design and production realms. The KNOMAD acronym can also be used to highlight KNOMAD's formalized process of: (K)nowledge capture; (N)ormalisation; (O)rganisation; (M)odeling; (A)nalysis; and (D)elivery (Verhagen et al, 2011).

C. Challenges of KBE Technology

The first commercial KBE system arrived on the market in the 1980s; however, KBE technology has only started to be used seriously during the last 10–15 years. Notwithstanding its huge potential, KBE was not able to score the same market success of CAD systems in their first 15 years. The reason for this limited KBE technology success can be attributed to a combination of the following causes:

- High costs of software licenses and needed hardware
- General lack of literature, study cases and metric
- Lack of KBE development methodology
- Low accessibility level: Due to the inherent complexity of the technology (at least when compared to that of contemporary CAD systems), a different category of users and dedicated training programs were required. Indeed, the use of the programming approach demands higher abstraction ability and stronger analytical background, more typical of software developers and engineers than typical CAD operators.
- Arguable marketing approach by KBE vendors (Rocca, 2012)

D. KBE for optimisation of machining processes

Edalew, Abdalla and Nash (2000) developed an intelligent prototype system for automatic cutting tool selection, for different work material properties. The developed system enabled users and manufacturing planners to select suitable cutting tools, that could machine the work piece material and generate the desired feature, determine the optimum cutting conditions that leads to short cutting time, and subsequently, to low cost. The developed system was an effective tool for automatic cutting tool selection. It provided users with rapid results via a user-friendly interface.

The system comprised of several modules; the knowledge acquisition module, the knowledge base module, the inference engine, the user interface, and the database (Figure 2). The system is capable of selecting cutting tools. It calculates cutting conditions and estimates component cost, based on the properties of the workpiece material and features attributes, which include surface finish and tolerances, as well as using a number of production criteria such as material removal rate, tool life, machining time, and cost.

Machinery handbooks, production handbooks, cutting tool and machine manufactures, and discussions with experts from industry and academic research groups are main sources of knowledge capturing. Further sources of expertise come from consultations.

The following tasks were identified for knowledge base processing.

- Component specification and material selection
- Tool material selection;
- machining process; and
- Cutting tool selection and cutting conditions optimization

Figure 3: KBE system components

A. Inference engine

The inference engine is an essential element of an expert system, which works based on the rules. The inference engine can scan the facts and rules and provide answers to the queries given to it by the user. It has the ability to look through the knowledge base and apply the rules to the solution of a particular problem. The rules are scanned until one is found whose antecedents match the assertions in the database. The scanning resumes and results are deduced, and are finally reported to the user. The process continues until the goal is reached (Edalew, Abdalla and Nash 2000).

B. Database system

According to Edalew, Abdalla and Nash (2000), the system's database consists of six separate groups of data concerning work materials, tool materials, cutting tools, cutting parameters, machining techniques and machining cost respectively.

But these six groups can be categorized in to three main groups by using available software and databases as shown in Table 2. According to Figure 6, the CES Edupack can provide the material properties and cost suitable for optimum design. The DFM concurrent costing software is capable of calculating the total cost (Table 3) of manufacturing based on the selected machine type, machining technique, cutting parameters, tool data, material and process (Figure 7). The CAM software generates the tool path for CNC machining based on the machine type, cutting parameters and tools specified (Figure 8).

Another database can be created by using the data acquired from scientific and research literature to predict the quality of final product. The proposed database communication is shown in Figure 3.

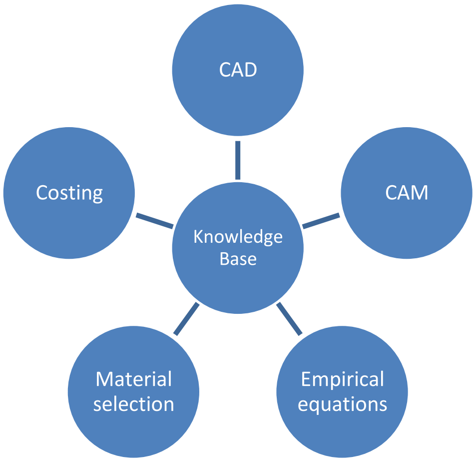


Figure 4. Knowledge base communication

Table 2. Capabilities of databases

CES Edupack(Material selection	**DFM concurrent costing**	**Delcam(CAM)**
Work materials	Work materials	Cutting parameters
Tool materials	Tool materials	Tool path
Material cost	Tool type	Simulations
	Machining Techniques	NC code
	Machine data	Machining time
	Cutting parameters	
	Total cost	

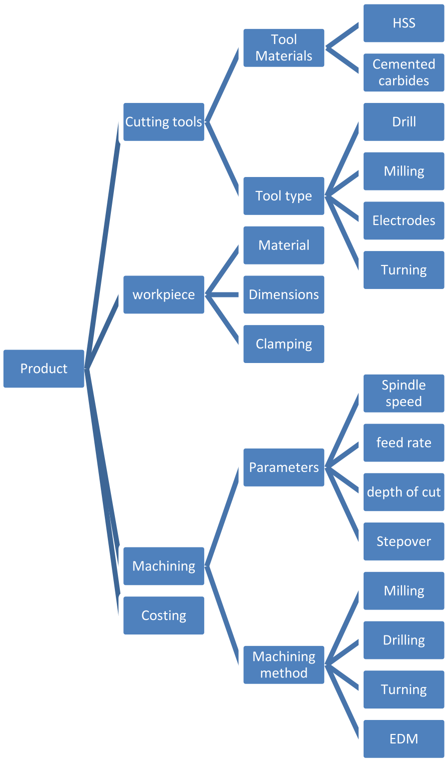


Figure 5. The machining process hierarchy tree

C. The system interface

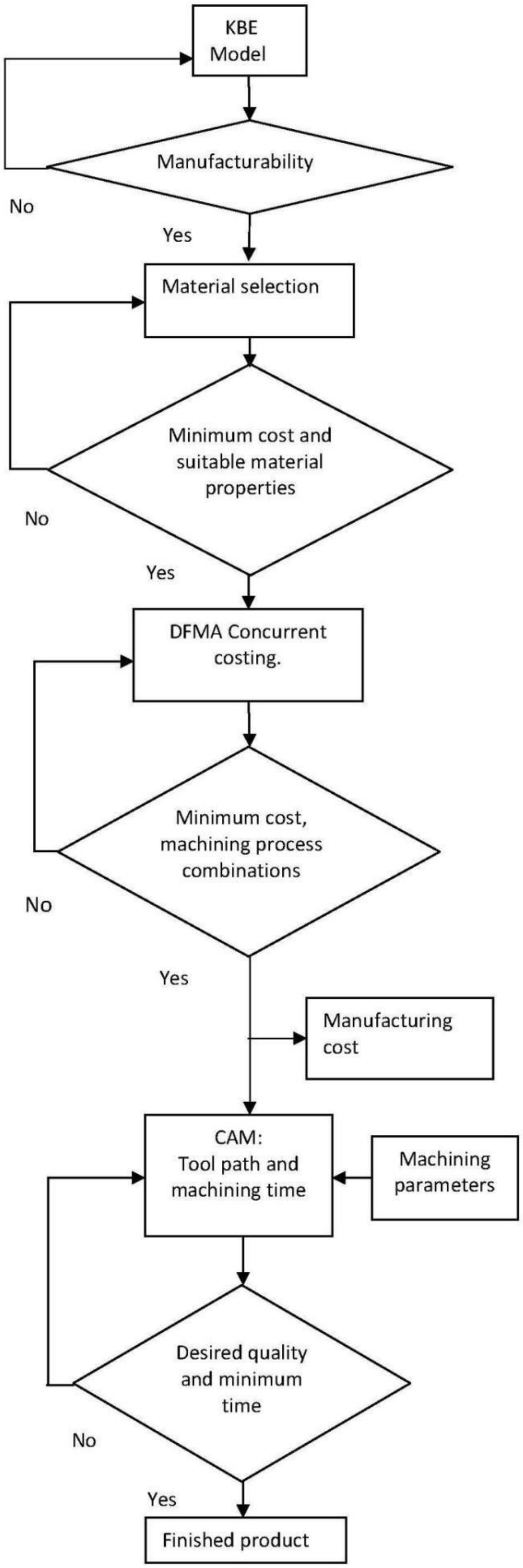
The best material for the component or the work can be selected from the CES Edupack database based on the cost and mechanical and physical properties. Based on selected material hardness and cutting parameters, the system would decide the suitable cutting tool material and the DFM concurrent software can be used to select the suitable manufacturing processes for selected materials. Under each manufacturing option, total manufacturing cost is calculated based on machine type, machining methods, batch size, and material. Several lowest cost solutions can be generated for different production volumes, manufacturing methods and materials. The suitable cutting parameters are predicted by the system for expected surface roughness and tolerance values. CNC machining tool path and NC codes are generated by the CAM software for different cutting parameters. Machining time, cost and final product quality can be evaluated and optimum solution is selected. The machining process hierarchy tree shown in Figure 4 describes the hierarchical relationship between the various components (parts and processes) of the process and the Figure 5 shows the manufacturing process flow chart.

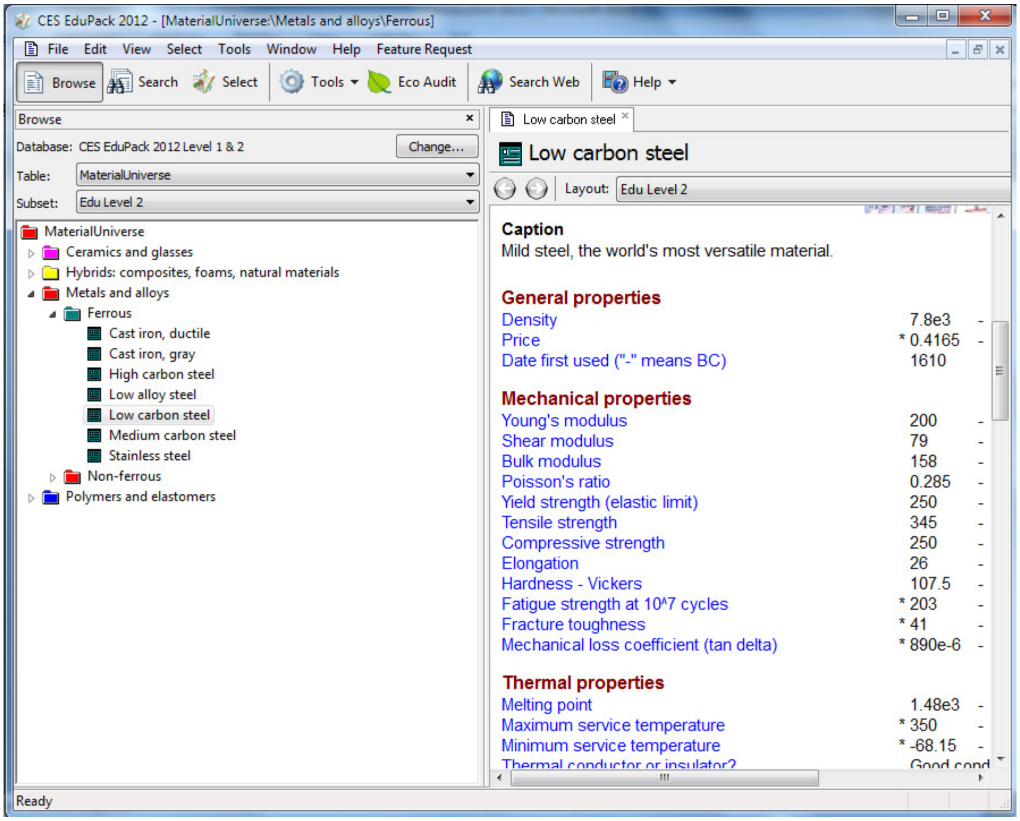
D. Rules

The following example explains the rule for selecting suitable tool based on material properties. If workpiece hardness is less than 250 BHN and Young's modulus is less than 220 GPa, tensile strength is less than 500 MPa, thermal conductivity greater than 10 W/m.K, and less than 60 W/m.K, and cutting temperature is less than 200°C, then a suitable cutting tool material for machining this material is coated, cemented tungsten carbide.

IF
(workpiece:hard>0 BHN) And
(workpiece:hard<250 BHN).
(workpiece:youngs modulus>0 GPa) and
(workpiece:youngs modulus<220 GPa)
(workpiece:tensile strength>0 MPa) And
(workpiece:tensile strength<500 MPa)
(workpiece:thermal conductivity>10 W/ m.K. And
(workpiece:thermal conductivity<60 W/m.K.
(workpiecs:cutting temperature>0°C. And
(workpiece:cutting temperature<200°C.
THEN
(SetValue(toolmaterial:T,coatedcementedtungsten carbide);)；
Tool material is Coated Cemented tungsten carbide.
(Edalew, AbdallaandNash 2000)

Figure 6. Manufacturing process flow chart





Database: CES EduPack 2012 Level 1 & 2

Table: MaterialUniverse

Subset: Edu Level 2

Low carbon steel

Layout: Edu Level 2

Caption

Mild steel, the world's most versatile material.

General properties

Density	7.8e3	-
Price	* 0.4165	-
Date first used ("-" means BC)	1610	

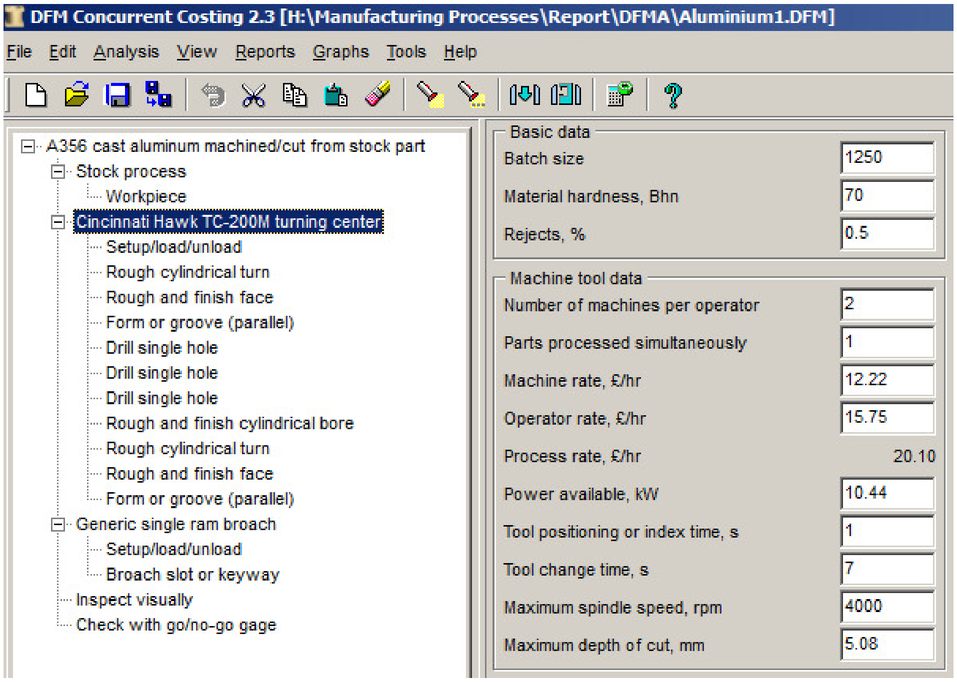
Mechanical properties

Young's modulus	200	-
Shear modulus	79	-
Bulk modulus	158	-
Poisson's ratio	0.285	-
Yield strength (elastic limit)	250	-
Tensile strength	345	-
Compressive strength	250	-
Elongation	26	-
Hardness - Vickers	107.5	-
Fatigue strength at 10^7 cycles	* 203	-
Fracture toughness	* 41	-
Mechanical loss coefficient (tan delta)	* 890e-6	-

Thermal properties

Melting point	1.48e3	-
Maximum service temperature	* 350	-
Minimum service temperature	* -68.15	-
Thermal conductor or insulator?	Good cond	

Figure 7. CES Edupack 2012 material properties interface



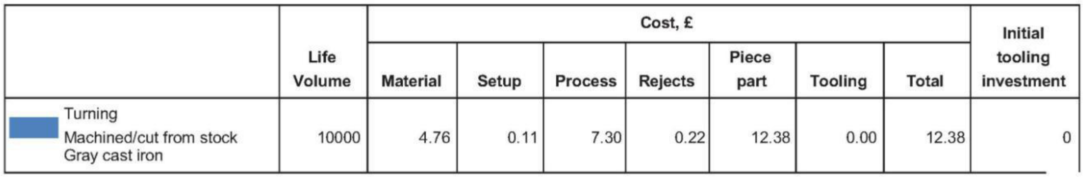
Basic data

Batch size	1250
Material hardness, Bhn	70
Rejects, %	0.5

Machine tool data

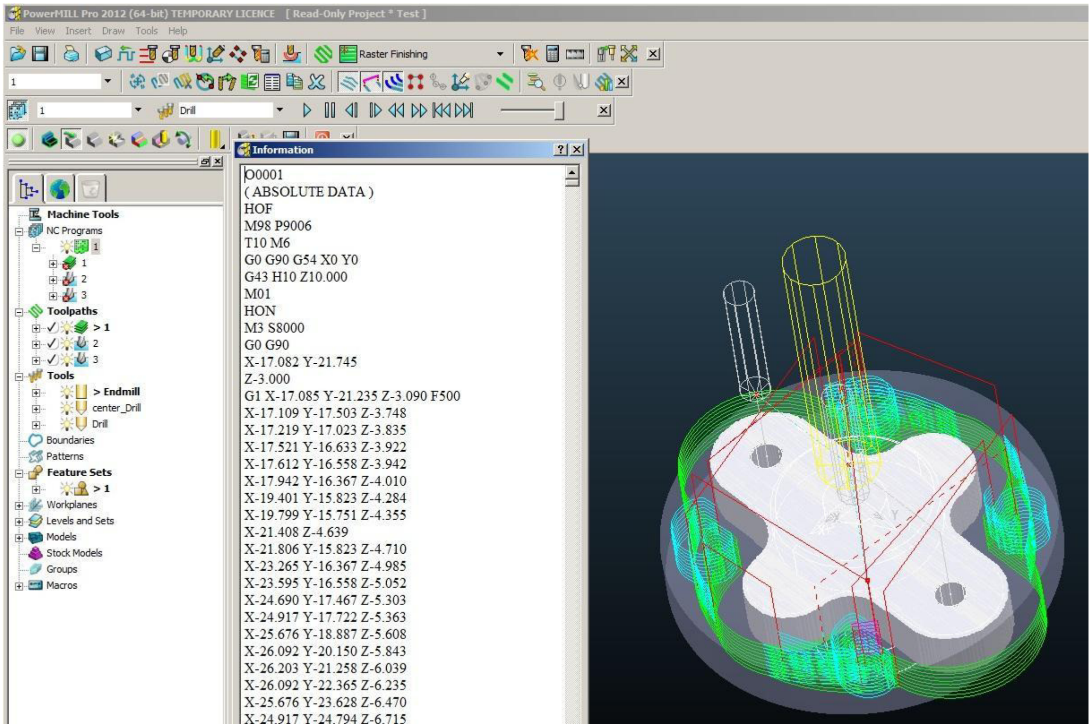
Number of machines per operator	2
Parts processed simultaneously	1
Machine rate, £/hr	12.22
Operator rate, £/hr	15.75
Process rate, £/hr	20.10
Power available, kW	10.44
Tool positioning or index time, s	1
Tool change time, s	7
Maximum spindle speed, rpm	4000
Maximum depth of cut, mm	5.08

Figure 8. Defining machine operations (DFM concurrent costing 2.3)



	Life Volume	Cost, £							Initial tooling investment
		Material	Setup	Process	Rejects	Piece part	Tooling	Total	
🟦 Turning Machined/cut from stock Gray cast iron	10000	4.76	0.11	7.30	0.22	12.38	0.00	12.38	0

Table 3. Calculated cost for turning operation by DFM concurrent costing 2.3



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O0001
( ABSOLUTE DATA )
HOF
M98 P9006
T10 M6
G0 G90 G54 X0 Y0
G43 H10 Z10.000
M01
HON
M3 S8000
G0 G90
X-17.082 Y-21.745
Z-3.000
G1 X-17.085 Y-21.235 Z-3.090 F500
X-17.109 Y-17.503 Z-3.748
X-17.219 Y-17.023 Z-3.835
X-17.521 Y-16.633 Z-3.922
X-17.612 Y-16.558 Z-3.942
X-17.942 Y-16.367 Z-4.010
X-19.401 Y-15.823 Z-4.284
X-19.799 Y-15.751 Z-4.355
X-21.408 Z-4.639
X-21.806 Y-15.823 Z-4.710
X-23.265 Y-16.367 Z-4.985
X-23.595 Y-16.558 Z-5.052
X-24.690 Y-17.467 Z-5.303
X-24.917 Y-17.722 Z-5.363
X-25.676 Y-18.887 Z-5.608
X-26.092 Y-20.150 Z-5.843
X-26.203 Y-21.258 Z-6.039
X-26.092 Y-22.365 Z-6.235
X-25.676 Y-23.628 Z-6.470
X-24.917 Y-24.794 Z-6.715
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Figure 9. Tool path and NC code generated by Delcam Powermill 2012

III. CONCLUSIONS

The main areas of KBE were reviewed. The successful implementations of KBE systems were summarized to realize main benefits. Different KBE methodologies were discussed. KNOMAD methodology has distinct advantages over established KBE methodologies such as MOKA by meeting the identified requirements for an improved KBE methodology. KNOMAD includes an approach for multidisciplinary design (optimization) and for knowledge capture, formalization, delivery and life cycle nurture.

The importance of optimizing machining process was discussed. The proposed system enable users to select suitable cutting tools, machining processes, cutting parameters for desired quality, optimum tool path and type of machining processes based on batch size that leads to short cutting time, and subsequently, to low cost. The proposed methodology for applying KBE for optimisation depend on the organization's will, money or resources to introduce a KBE system and the quantitative assessment of KBE costs and benefits. However during the years, a number of technical developments and strategy changes have created the situation for a sustainable growth of KBE within the world of industry and research; for example, the decreasing cost of hardware and availability of dedicated methodologies to support a structured development of KBE applications.

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