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Integrated manufacturing features and Design-for-manufacture guidelines for reducing product cost under CAD/CAM environment ☆

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ABSTRACT

The main contribution of the work is to develop an intelligent system for manufacturing features in the area of CAD/CAM. It brings the design and manufacturing phase together in design stage and provides an intelligent interface between design and manufacturing data by developing a library of features. The library is called manufacturing feature library which is linked with commercial CAD/CAM software package named Creo Elements/Pro by toolkit. Inside the library, manufacturing features are organised hierarchically. A systematic database system also have been developed and analysed for each feature consists of parameterised geometry, manufacturing information (including machine tool, cutting tools, cutting conditions, cutting fluids and recommended tolerances and surface finishing values, etc.), design limitations, functionality guidelines, and Design-for-manufacture guidelines. The approach has been applied in two case studies in which a rotational part (shaft) and a non-rotational part are designed through manufacturing features. Therefore, from manufacturing feature library a design can compose entirely in a bottom-up manner using manufacturable entities in the same way as they would be produced during the manufacturing phase. Upon insertion of a feature, the system ensures that no functionality or manufacturing guidelines are violated. The designers are warned if they attempt to include features that violate Design-for-manufacture and Design functionality guidelines. If a feature is modified, the system validates the feature by making sure that it remains consistent with its original functionality and Design-for-manufacture guidelines are re-applied. The system will be helped the process planner/manufacturing engineer by automatically creating work-piece data structure.

1. Introduction

Product variation, market competition, globalisation, product customisation, product diversification, etc., are the major challenges facing manufacturing enterprises in the 21st century. They are in a quandary because those issues work at the core of product design along with environmental characteristics. A product after manufacturing in terms of poor performance, emergent behaviour, and high cost tend to company liquidation (Curran et al., 2007). Thus, it is essential for manufacturing enterprises to apply innovative techniques in various phases of product to guarantee a sustainable business development.

In a large manufacturing company, new ideas/systems have been generated by product engineers and designers mutually in product design stage by analysing various aspects of the design, investigating capabilities and limitations of the production system (Groover & Zimmers, 1984). Currently, conventional CAD/CAM systems are commonly used for swift design and revision of products. However, in those systems product design is based on ordinary geometric modelling method (Shah & Mantyla, 1995). Other tasks of the product development cycle for instance: process planning, group technology classification, coordinate measuring machine programming, path planning, and assembly planning are absolutely absent in those systems. On the other hand, Design-for-manufacture (DFM), Design-for-assembly (DFA) and Design Functionality (DF) have been analysed manually, which is tedious, time consuming and also complicated tasks. However, DFM/DFA and DF are used widely for optimum cutting cost, significant improvement in quality, reliability and superior product design.

Recently, great verities of feature based CAD/CAM systems are available in market place. Features are more helpful in many design tasks comprises of part geometry creation, tolerance specification and assembly design, etc. In addition, feature based design system takes less-time aspect of it considering the re-design issue. Therefore, it has become a defacto standard (Sunil & Pande, 2008). Fig. 1 shows that a part has been designed via commercial feature based CAD/CAM software where features violate several DFM

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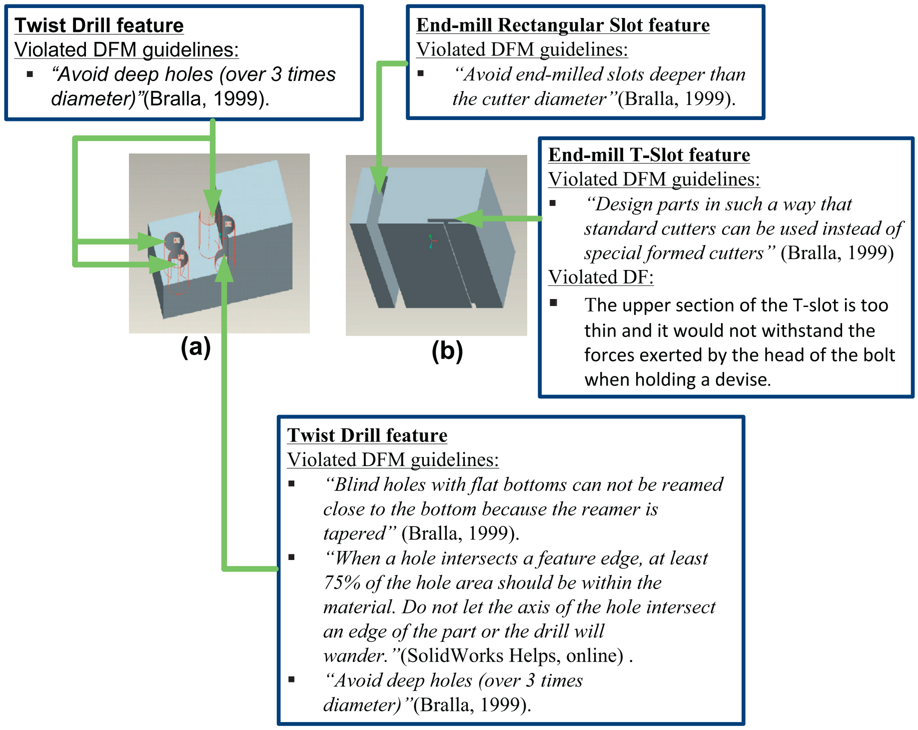


Fig. 1. Violation of DFM & DF guidelines. (See above-mentioned references for further information.)

guidelines and contain insufficiency of the DF requirements. As a result, it brings imprecision in the design. Issues related to re-design may further incur additional cost burden.

Thus, the lack of proper and actual manufacturing information in product design, process planning and machining phases within the environment of available feature based CAD/CAM software invoke the design and development of hierarchically structured Manufacturing Feature Library (MFL) with the following characteristics:

- The system should extend the capabilities of an existing, commercially available CAD/CAM system.
- It should be expandable to include features of different manufacturing processes without difficulty.
- It should permit quick and straightforward composition of parts from manufacturable entities in a bottom-up manner, similarly to how real production would be executed.
- It should facilitate feature functionality consistency to verify in real time and analysis of manufacturing problems at the design phase.
- It has to contain a graphical user interface for intuitive operation by the designer and seamless incorporation with the base CAD/CAM system.

2. Review of previous work

Design-for-manufacture and Design-for-assembly are very ancient concept (at least 200 years old), have been applied in design stage for reducing product manufacturing cost at the same time improves its quality (O'Driscoll, 2002). DFM methodology has been 1st organised by Bolz (1958) in his popular book *"Metals Engineering Processes"*. He provided a series of guidelines to assist the designer in enhancing the manufacturability of metal parts prepared through a number of manufacturing processes. Later on, General Electric Co. (1960) published a Handbook "*Manufacturing Productivity Handbook*" for individual part design considering producibility only for their internal use. At that time, significant benefit were not realised due to lack of systematic DFA. Therefore, in the late 1980s Boothroyd and Dewhurst (1983) conducted an extensive study on DFA for reduction of the assembly cost. Soon after, Waterbury (1985) and Stoll (1988a, 1988b)developed a concept of DFA and DFM to concurrently consider all of the design goals and constraints for manufacturing the product. Numerous researches had been conducted at that time (Andreason, Kahler, & Lund, 1983; Kobe, 1990; Scarr, 1986). Since the late 1980s Hitachi Assembly evaluation method was introduced successfully (Miyakawa, Ohashi, & Iwata, 1990; Shimada, Miyakawa, & Ohashi, 1992). Afterwards, researchers started to bring their attention on specific areas like design for environment, design for recyclability, design for life-cycle, etc. Since the late 1990s, a lot of papers had been presented regarding DFM, focused on different disciplines. Those were: Huang and Mak (1996) developed a questionnaire survey with the aim to find out exploit of DFM in UK furniture manufacturing industry; Fox, Marsh, and Cockerham (2001) described a review of DFM literature and a field survey of construction manufacturers, assemblers and consultants; Mansour and Hague (2003) examined the impact of rapid manufacturing on DFM for injection moulding; Whiteside, Shehab, Beadle, and Percival (2009) worked on DFM in the Aerospace industry; Laskowski and Derby (2011) developed fully functional fuel cell automatic stack assembly robotic station with considering DFM and DFA; Annamalai, Naiju, Karthik, and Prashanth (2013) introduced early cost estimation of washing machine, etc. Following 2000s various approaches and algorithms had been proposed by many researchers for general purpose manufacturing. Those were: Keo, Huang, and Zhang (2001) presented the concepts, applications and perspectives of Design for X (DFX); Swift and Brown (2003) emphasised on implementation *approaches* for DFM; QingMing, Geng, and Hongjun (2008) proposed a DFM assessment system in design stage based on feedback information of part manufacturing; Belay (2009) investigated various product development techniques particularly on DFM and concurrent engineering; Lu, Zhao, and Yu (2012) proposed an optimisation algorithm to achieve concurrent tolerance DFM and DFA with a game theoretic approach, etc.

On the other hand, in the area of manufacturing feature based design system, interfacing of CAD & CAM in uniform software system had been developed by Chang, Wysk, and David (1982). Then in 1987s, (Yoshikawa & Ando, 1987) a prototype was built that integrates CAD and process planning. Same researcher in 1989s introduced new methodology called automatic generation of manufacturing information (Ando & Yoshikawa, 1989). However, the most general preference in the existing prototype systems called design-by-manufacturing-feature approach was 1st developed by Mantyla, Opas, and Puhakka (1989). The system is called HutCAPP system, where a facility for changing the feature specification of the part by means of feature relaxation was given. The major complexity of the system was that it had no capability of evaluating whether a change in a feature was functionally acceptable and also a human user was required to recognize the proposed changes. Another system called First-Cut system (Cutkosky & Tenenbaum, 1990) was also implemented for simultaneous part and process planning. The system assumes that there is no need of conversion, mapping, or extraction of manufacturing features. Accordingly, designer can design a part model directly in terms of manufacturing features. The difficulty of this system was that it is extra burden for designer to remember all manufacturing operations. Afterwards, Owusu-oFori (1994) described a methodology by passing geometric parameters to the modelling systems for instantiations. Accordingly, designer can apply tolerance and surface finishing value to derive manufacturing implications for review the design. The deficiency of the system was that design process is fully geometry driven. Just then, another system called an object-oriented feature-based design system for integrating computer-aided-design and computer-aided-process-planning had been developed by providing an intelligent interface between a CSG based geometric modeller and the process planning functions (Wong & Wong, 1995). The system also incorporates a knowledge-based system for the generation of process plans in accordance with the design features. However, the process-dependent geometric model had been developed by Dissinger and Magrab (1996). The approach was for the cold die compaction of powdered metal consists of a set of fundamental three dimensional manufacturable entities like plates, blind cavities and through cavities, all of arbitrary shape. Later on, Wang and Bourne (1997) started to work with sheet metal parts where features are automatically generated and after that automatic process planning system uses the feature for bending system. At the same time, Lin, Lin, and Cheng (1997) started to build the CAD interface on the ground of design oriented feature models. The approach can be directly used to drive the automatic generation of process information.

Recently (after 2000) a lot of investments have been made in research community as well as industrial sector to develop appropriate technology of actual manufacturing information in product design all over the world. Various approaches and algorithms have been proposed by many researchers. A summary of these approaches are shown in Table 1.

Currently, some smart CAD/CAM systems include feature-based design at a basic level. In those systems, most features contain less

Table 1
Some studies on actual manufacturing information in product design.

Authors/developer	Research nature	Remarks
Brunetti and Golob (2000)	Feature based conceptual design system	The system can capture the relevant product semantics of the early design phase which allows reusing this information in manufacturing phase
Choi et al. (2001)	Feature based modelling system software for generating set-up and machining sequence	The system required to integrating the encapsulate system and machining system into one automated system
Öztürk and Öztürk (2001)	Neural network based feature recognition approach	The approach does not consider the machining requirements of each component
Zhao, Ridway, and Al-Ahmari (2002)	Concept of turning operation for the integration of a CAD system and knowledge based system	This concept is only capable for the selection of cutting tools and conditions
Zha and Du (2002)	STEP-based method for concurrent integrated design and assembly planning	The model facilitates the exchange of product model data in standardized format
Subrahmanyam (2002)	Finding machining and fixturing feature from the design feature	Maximum forces and moments generated are primary used to find fixturing features for drilling and milling processes
Butdee (2002)	Hybrid feature modelling concept	The concept is only for spot shoe sole design to reduce design lead time
Fu, Ong, Lu, Lee, and Nee (2003)	Identify design and manufacturing features from a data exchanged part model	The feature panorama is briefly expressed from the viewpoint of product design and manufacturing to assist feature identification and extraction
Chen, Wen, and Hob (2003)	Extraction of geometric characteristics in feature-based manufacturability assessment	They focus on evaluating a design and modifying or re-designing it into one that is functionally acceptable and compatible with a selected manufacturing process of separate parts with highlighting on a net shape Process—injection moulding
Howard and Lewis (2003)	Developed an expert system which is linked into a 3D design package	The system provides an analysis of alternate methods of manufacture for producing the design
Muljadi, Ando, Takeda, and Kanamaru (2004)	Development of feature library of a process planning system	Further works required to be through on how the extracted manufacturing information to produce manufacturing features
Muljadi, Takeda, and Ando (2006, 2007a, 2007b)	Semantic Wiki for the development of the feature library	The library consists of the function feature ontology, the manufacturing feature ontology and the manufacturing information
Molcho et al. (2008)	CAM analysis tools	It has only facilities for modification, capture and implementation of manufacturing knowledge in the design stage
Riou and Mascle (2009)	Product dynamic model and design for X solution	It is a data structure based on the B-rep model topology
Marchetta and Forradellas (2010)	Hybrid procedural/knowledge-based approach	This feature recognition system has some limitations
Kerbrat, Mognol, and Hascoët (2011)	Integration of manufacturing entities at design stage	The system is used for reducing time and cost; improving quality and flexibility
Li and Li (2011)	Part information model based on manufacturing feature	This model is created on the basis of geometric model
PoboŜniak (2012)	Object database of manufacturing feature oriented part model	It represents the work-piece on the logic level of the database in the form of simple and complex manufacturing features
Boothroyd and Dewhurst (1992)	Commercially developed DFM and assembly DFMA methodology	It focuses on eliminating inefficiency in design, simplifying the structure, reducing cutting costs and quantifying improvements
SIGMAXIM (online)	Developed the Smart Library software for Creo	Only design features are used
Tebis (online)	Develops CAD/CAM systems for tool, die and mould manufacturing	Lack of manufacturing information like DFM, DFA, and DF

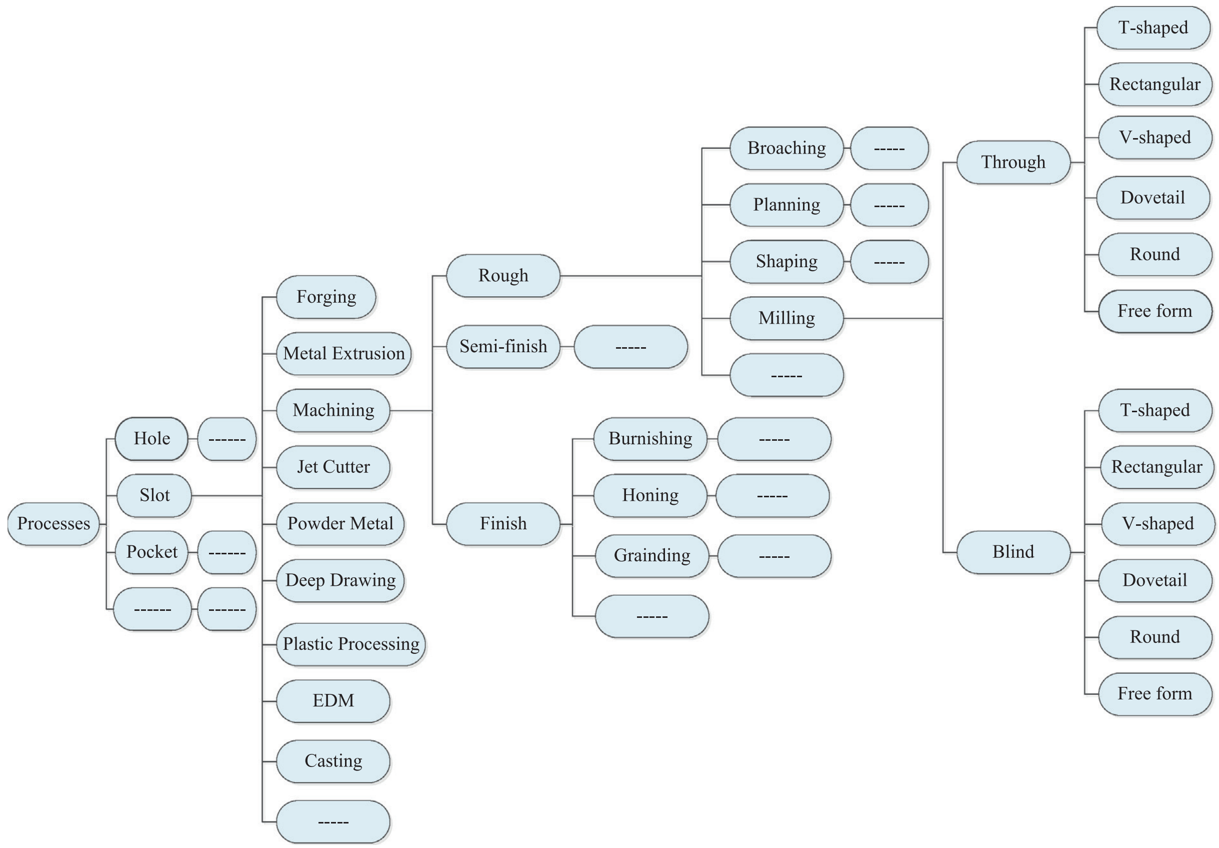


Fig. 2. Combined hierarchical manufacturing process and geometric classification of features.

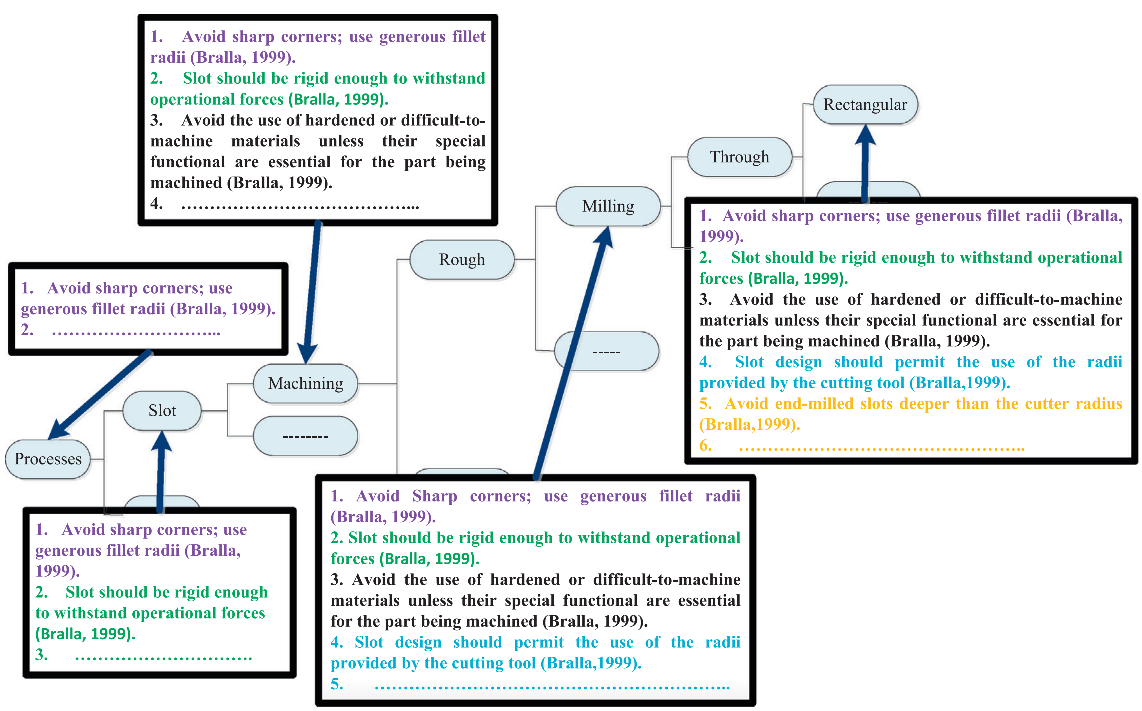


Fig. 3. Pointing hierarchical DFM guidelines at manufacturing features.

useful manufacturing information. In most cases, they can only provide geometric data which may not be the major concern of process engineers. Therefore, essential efforts have been determined on the development of fully automatic manufacturing feature based systems in the last two decades. However, relatively a small number of systems have been developed to deal with the

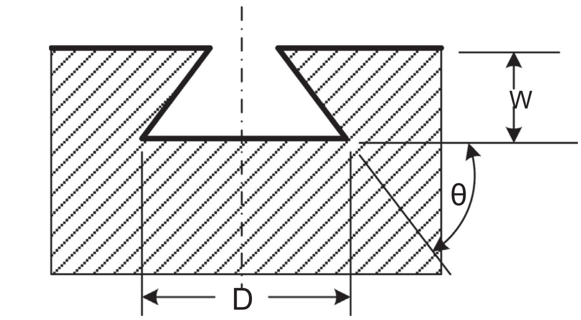
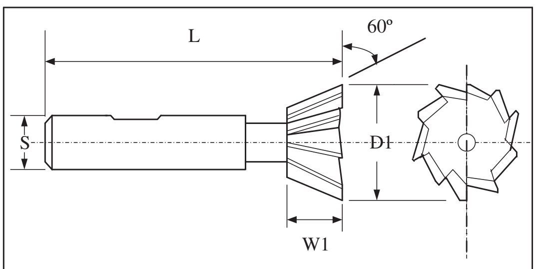


Fig. 4. Parameterised dovetail slot feature.

Table 2
ANSI 60° single-angle milling cutter (Oberg, Jones, Horton, & Ryffel, 2004).



Dia., D1	S	W1	L
19.05	9.53	7.94	53.98
34.93	15.88	14.29	73.03
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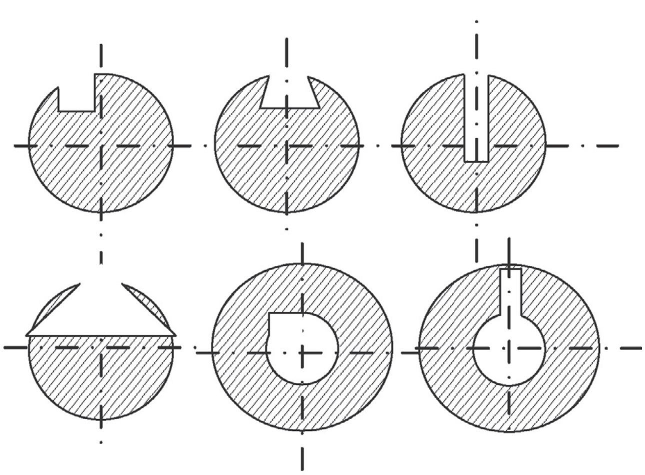

Fig. 5. Violation of DFM and DF guidelines for key-way features.

topic of manufacturing feature, how the design intent from a CAD part model is created in a heterogeneous product design environment, and in standard data exchange formats. On the other hand, several papers about DFM have been published for the last few years and also a large number of DFM/DFA & DF guidelines have been developed. But still now no standard formats are available for organising them. Thus, a systematic and standard DFM/DFA & DF guidelines structure is essential. Hierarchical DFM/DFA & DF system is one of them.

From literature review, we can conclude that manufacturing feature-based techniques can maintain a much more effective design environment. They have the capability of choosing the types of manufacturing process and determining the information (cutting tools, DFM/DFA guidelines, DF guidelines, recommended tolerance and surface finishing values, relative cost estimation, etc.) which are required for the execution of the operations. As a result, it is therefore necessary to perform more research to develop an application oriented approach for the library of manufacturing features with hierarchical DFM/ DFA & DF evaluation system for an integrated product design and manufacturing system. This paper presents integrated manufacturing features and DFM guidelines for reducing product cost under CAD/CAM environment.

3. Methodology

3.1. Structure of the manufacturing feature library

Features have been manufactured by using a large number of manufacturing processes. Therefore, in a manufacturing feature-based design system, features are required to organise in a systematic manner in order to avoid conflict. One of the best ways is that the features are arranged hierarchically inside the feature library. Therefore, in this research, Manufacturing Feature Library (MFL) has been developed by organising the features hierarchically based on geometrical and manufacturing process classification system, as illustrated in Fig. 2. The MFL consists of hierarchical DFM and DF guidelines for feature, standard cutting tools parameter, cutting conditions, cutting fluids, recommended dimensional tolerances and surface finish values, etc.

Large numbers of DFM guidelines are required to be arranged systematically inside the MFL. Inside MFL, all DFM guidelines have been organised hierarchically because of avoiding repetition (when applying the guidelines). Thus, the hierarchical structure enables to reduce the number of guidelines. It also makes the guideline system easier, and gives a much clear structure and standard format. The extension of the hierarchical systems is relatively simple; no alteration of existing system, but only expanded, i.e. new guidelines and process are added to the hierarchical trees without changing the remaining structure. In hierarchical systems for more generic manufacturing features, guidelines at the higher level of hierarchy are applied, and for more detailed features more specific guidelines are applied. Therefore, guidelines at lower levels of the hierarchy (children) inherit the characteristics of their parent guidelines as shown in Fig. 3.

DF is another additional key concern for a designer where a designed product can be rejected due to only functionality problems. However, it is much easier to implement in feature-based design systems. Generally, feature-based design functionality concern with the concepts of higher level of abstraction. The major aim of using them is to guarantee that a design can perform according to the concept of the feature with its underlying geometry. Conventionally, DF contains: parameterised geometry as demonstrated in Fig. 4, datum surfaces that are to be linked to existing surface in the design and functionality guidelines. Consider a dovetail cutter ground with a negative angle that produces the undercut on the edge of the slot (Fox Valley Technical College, online). The insert strip is cut out using a profiling cut that has an angle called negative angle required to match with a standard dovetail cutter. Otherwise, manufacturing costs will increases or the designed product will be rejected due to the functionality problems of the design. In Fig. 4, where the datum surfaces of the dovetail slot are related to surfaces of already inserted objects, and values are assigned to the parameterised dimensions such as W, θ and D. If D is smaller than standard cutter, then a smaller, special cutting

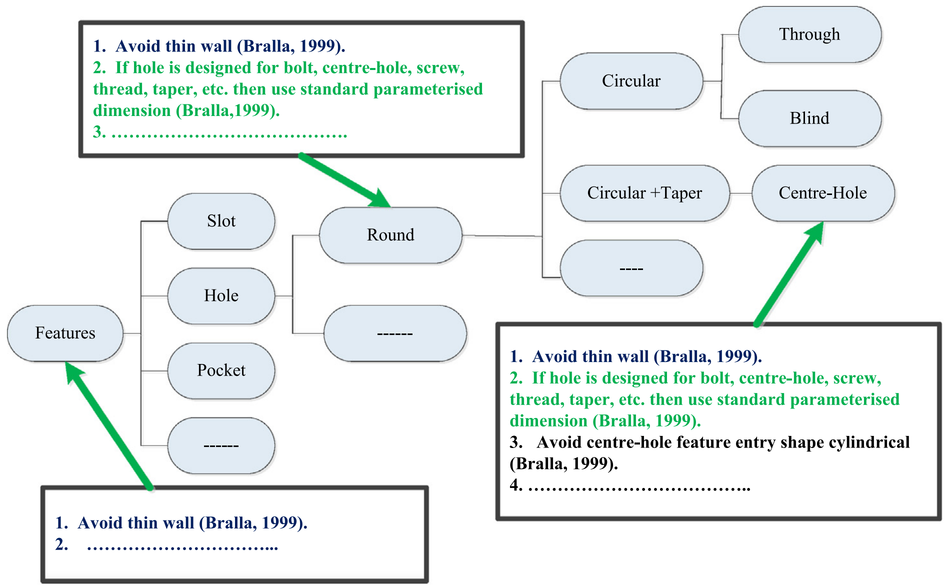

Fig. 6. Pointing hierarchical DF guidelines.

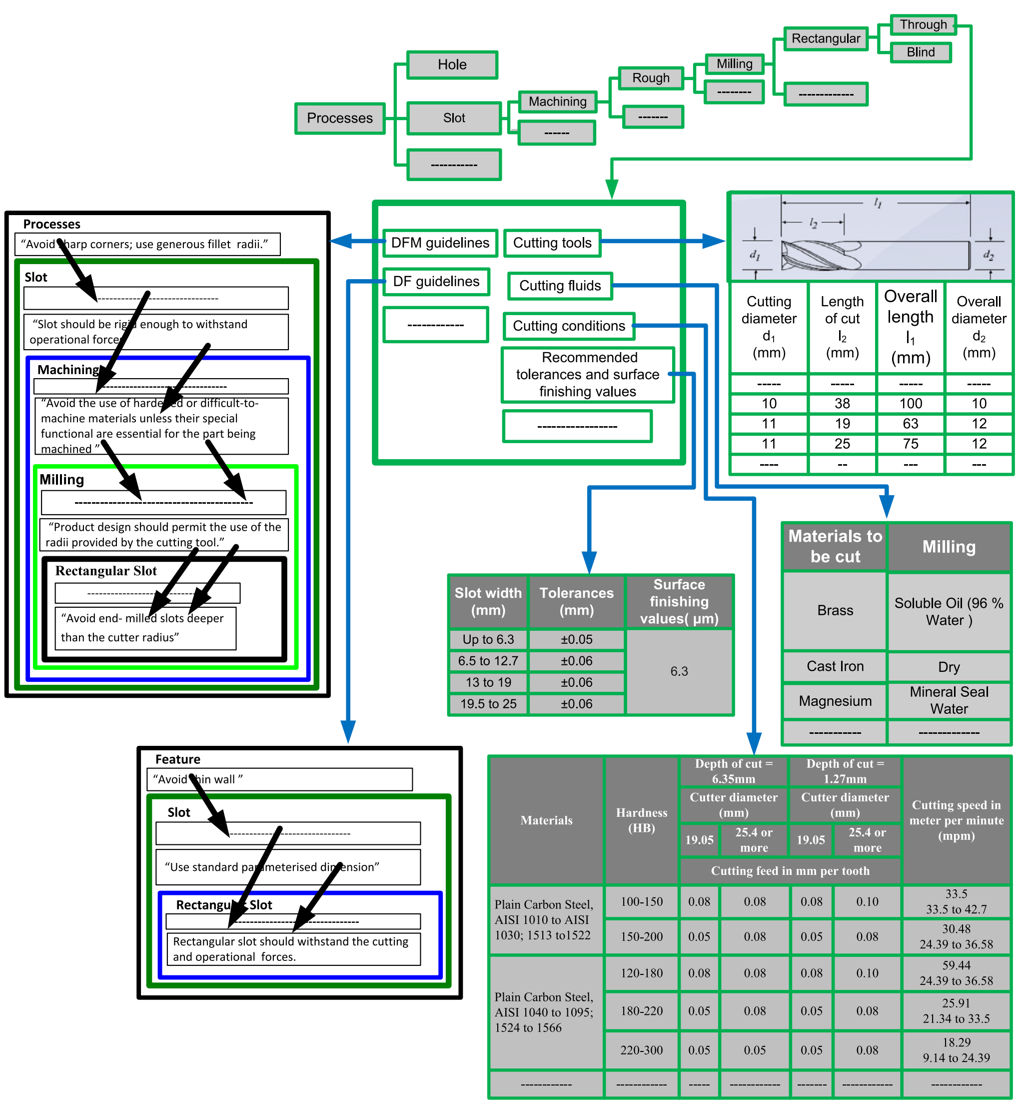

Fig. 7. Hierarchical manufacturing feature structure.

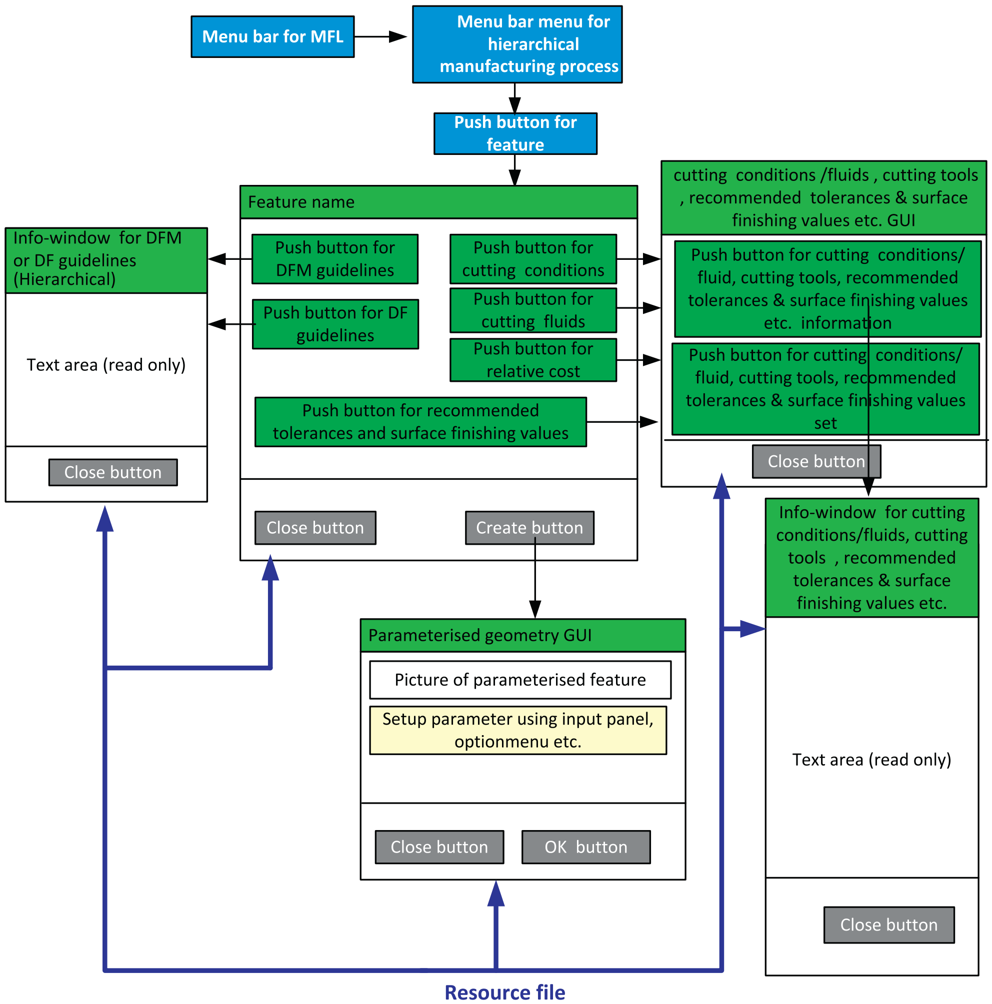

Fig. 8. Architecture of the user interface components for the MFL.

tool has been required to produce the slot feature. To solve this type of problem, a design engineer/technician requires using standard cutting tool parameter from Table 2 for milling operations. Another one of key-way feature as illustrated in Fig. 5 causes manufacturing problem because of violating DF guidelines of the feature. Although, the parts can be manufactured and assembled with another part, however it is impossible to work appropriately. Therefore, manufacturing features inside the MFL is based on process and DF guidelines of feature which reflect the concept of the feature. On the other hand, DF guidelines independent on the underlying manufacturing process, but based on a hierarchical geometric classification system as shown in Fig. 6.

Selection of proper cutting tools, cutting conditions, cutting fluids, recommended tolerances and surface finishing values, etc. are a sub-function of process planning and also a complex task. It needs significant skill and knowledge. The objectives of any tool selection exercise are to select the best tool holder(s) and insert(s) from available standard cutting tool stock, and to determine the optimum cutting conditions, cutting fluids, recommended tolerances and surface finishing values (Arezoo, Ridgway, & Al-Ahmari, 2000). This means that selection of standard cutting tools, appropriate cutting fluids; recommended tolerances and surface finishing values are easier. Designing through machining features using standard cutting tool parameters help the designer to avoid the violation of parameterisation problems of features and to avoid feature functionality and manufacturing problems. It tends to reduce production cost because of availability of standard tools in marketplace and cheaper. Tool life depends on three main factors comprises: the cutting speed, the feed rate, and the depth of cut are called cutting conditions. When cutting speed or feed is increased tool life is reduced. Another factor is the selection of cutting fluids depends on many complex interactions including the machinability of the metal, the severity of the operation, cutting tool material, metallurgical, chemical, human computation, fluid properties, reliability and stability. Cutting fluids differ for different work piece materials with different processes used for the same feature. Tolerance and surface finishing values play a significant task as a relationship between the product functional requirements and the manufacturing cost. Unnecessarily tight tolerances lead to higher manufacturing cost but loose tolerances may lead to large variability in assembly output characteristics. Low values of surface roughness improve fatigue life, decrease the coefficient of friction and wear rates, and improve erosion resistance. At the same time, tight surface roughness values increase manufacturing cost.

Therefore, hierarchical DFM, hierarchical DF, standard cutting tools parameter, cutting conditions, cutting fluids, recommended tolerances and surface finishing values, etc. have been used hierarchically inside the database system of MFL in order to avoid functionality and manufacturing problems of feature which is shown in

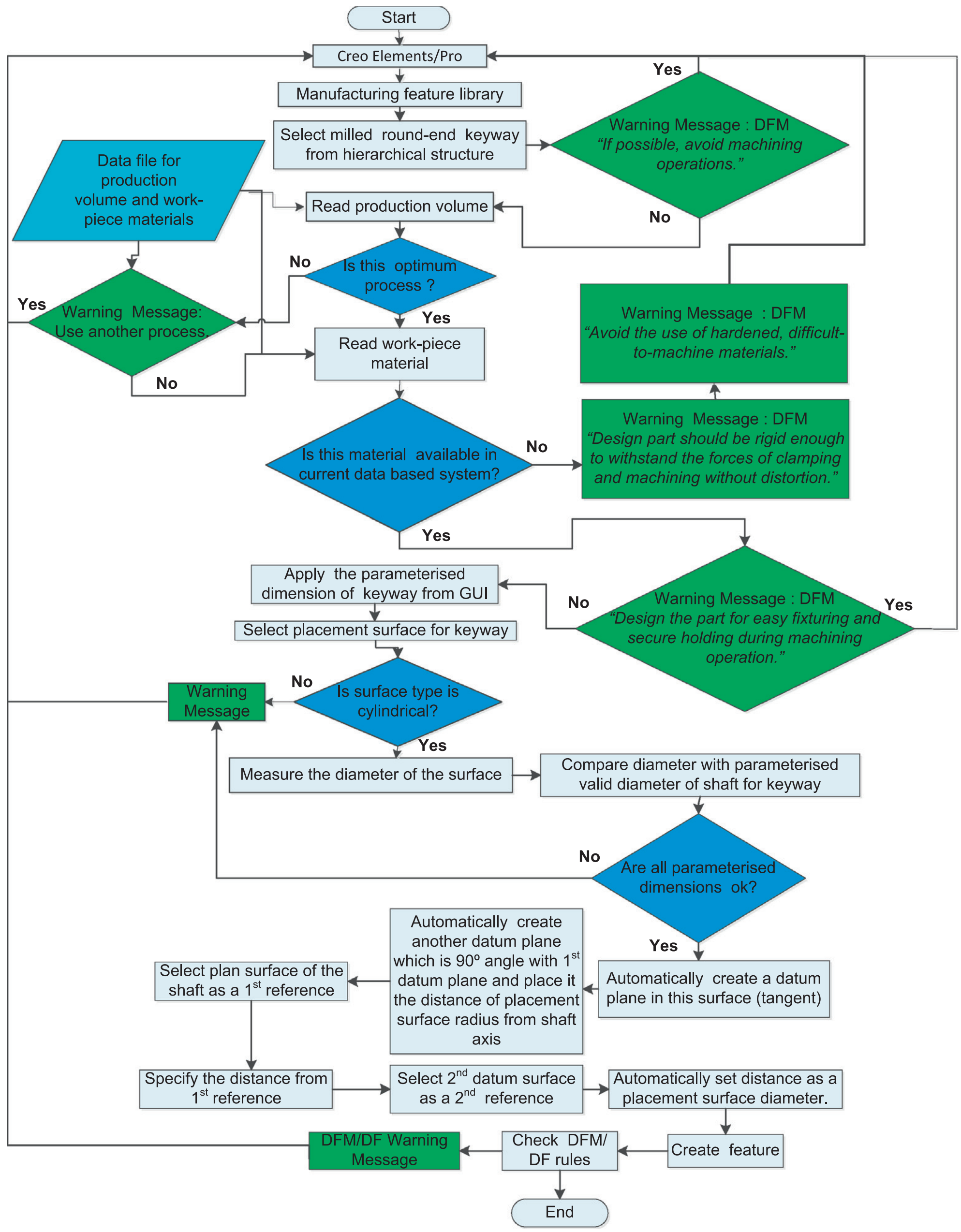

Fig. 9. Development architecture for creating the external key-way feature.

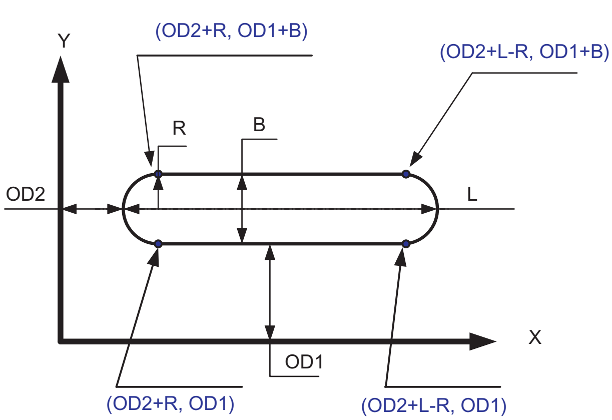

Fig. 10. Template for external key-way features.

Fig. 7. Designer can design a part with considering those as well as check the parameters from Graphical User Interface (GUI) of the MFL.

3.2. Software architecture

The MFL, developed in this research, is an external application of Creo Elements/Pro (Parametric Technology Corporation, online), which was developed by using Creo Elements/Pro toolkit functions (written in C/C++). The MFL has a menu-driven capability where the user is first guided by a set of introductory screens explaining its capabilities. The menu-driven system allows the designer to select appropriate processes from the hierarchical process structure. Then the designer is prompted for the values of the properties of the components object like dialog components, different value sets, read help information like hierarchical DFM guidelines, hierarchical DF guidelines, cutting conditions, etc. The warning messages

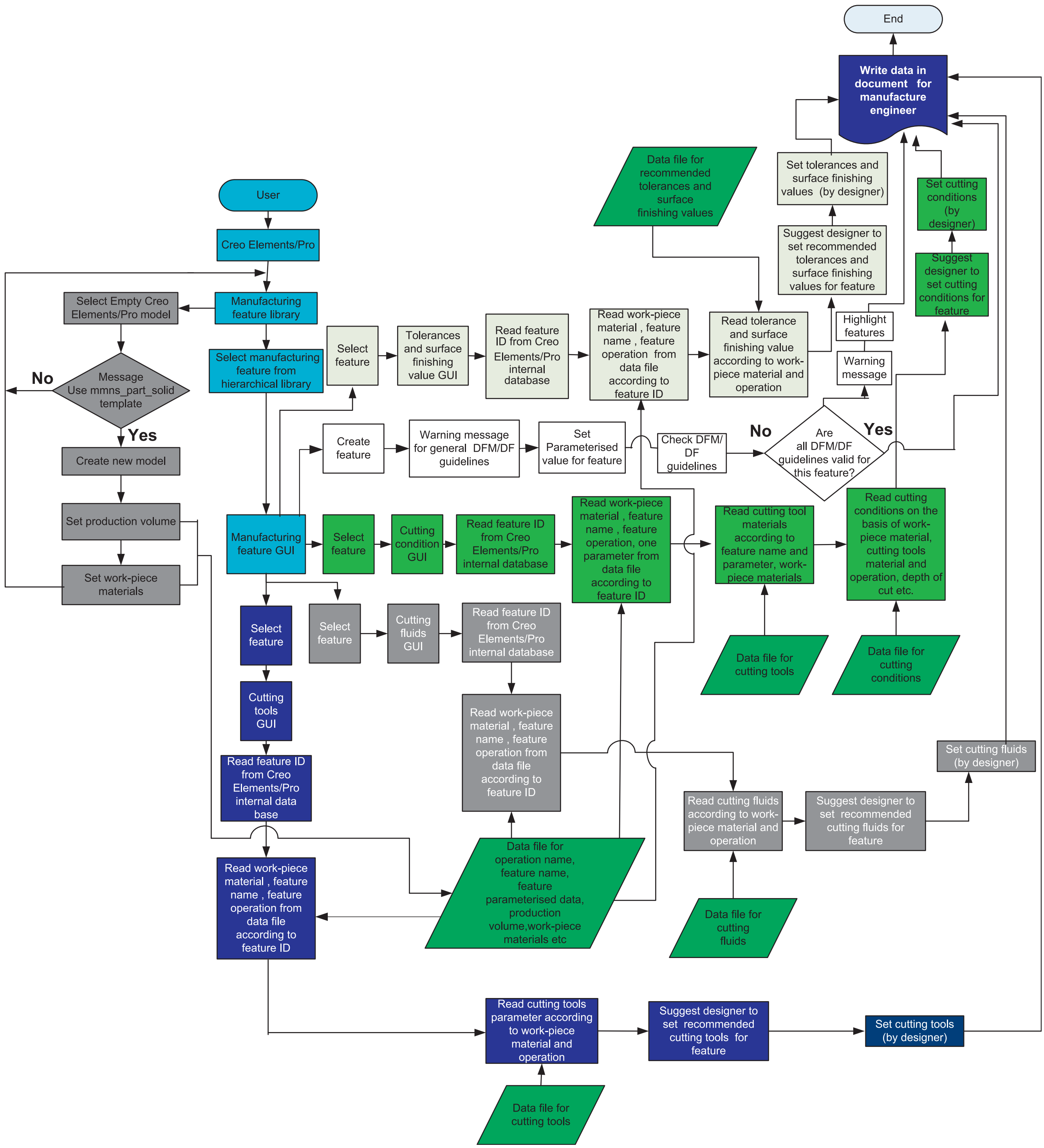

Fig. 11. The development architecture of MFL.

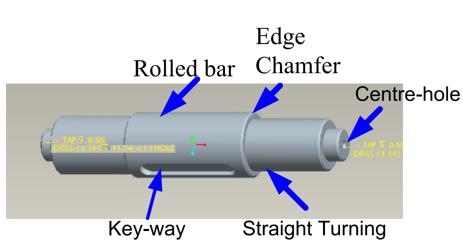

Fig. 12. Manufacturable test part (rotational).

from the system are displayed on separate screens with details of violation of DFM and DF guidelines. The interaction between the system and the user is entirely through menu-driven options and the user is prompted for data inputs whenever numerical values are required as shown in Fig. 8. The MFL is divided into two groups: one is an empty Creo Elements/Pro model and another is a manufacturing feature.

A DFM guideline varies on production volume and materials. So, those parameters are required to set-up before starting the design a part by using MFL. Designer will open one empty Creo Elements/

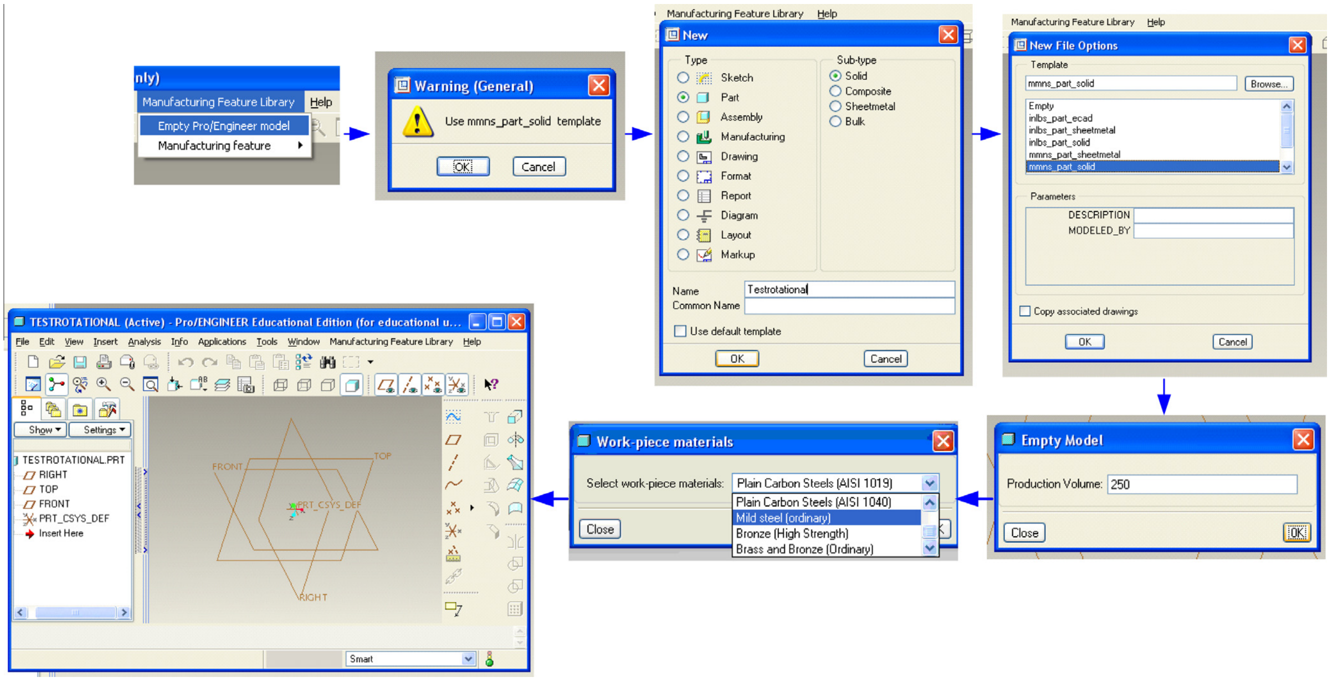

Fig. 13. Empty model (*Testrotational*) developed by the MFL.

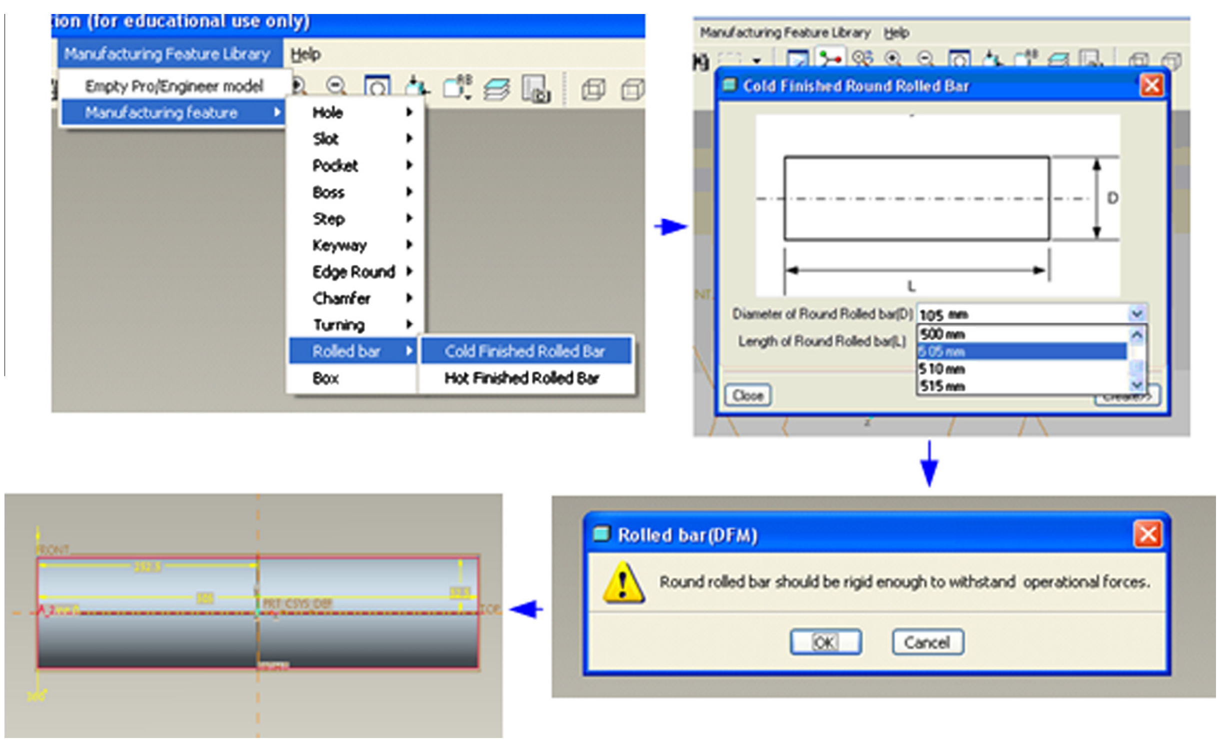

Fig. 14. Design process of rolled bar by the MFL.

Pro model and setup the production volume and materials first. Production volume and materials help for the selection of optimum process. Consider a part will be manufactured by casting operation. In case of small scale production, it is better to use sand mould casting rather than die casting. However, for larger production volume die casting will be the appropriate solution. Consider another manufacturing feature named round-end machines keyways, which is cut along the axis of the cylindrical surface of shafts. Fig. 9 shows the development architecture (external keyway). In order to apply different values for the parameters of external keyway features from the GUI, a static template has been used which is shown in Fig. 10.

In the MFL, recommended cutting conditions, cutting fluids, tolerances and surface finishing values are arranged in such a way that the designer can automatically select them in order to make suggestions for manufacturing engineers. For example, to calculate

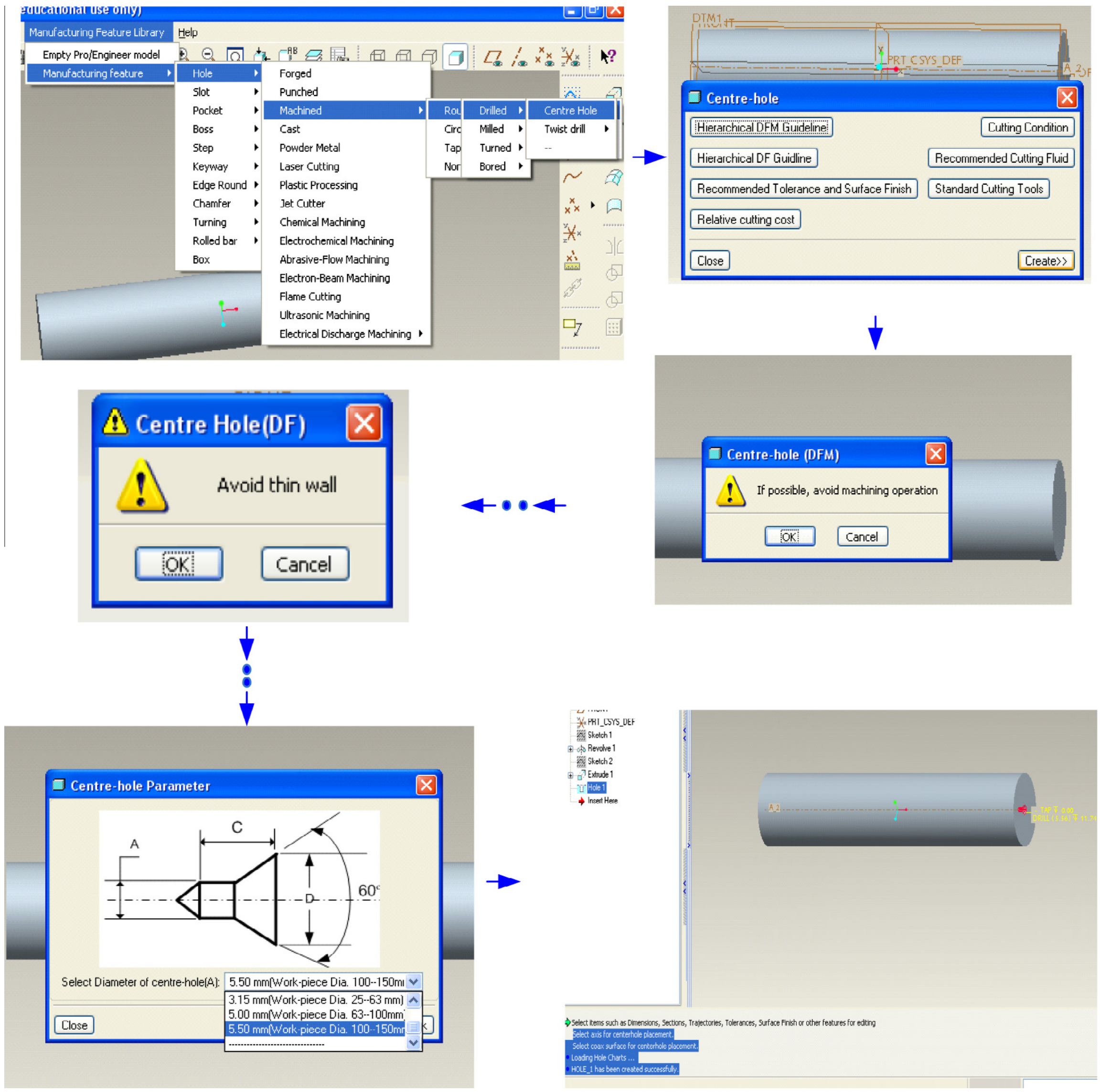

Fig. 15. Design process of a centre-hole feature by the MFL.

the appropriate rpm rate for centre-holes, the appropriate cutting speed is required. Centre drills will break if they are run too slowly. The development architecture of MFL is shown in Fig. 11.

4. Results and discussion

In order to validate this new DFM system, several manufacturing parts have been studied. One of them is rotational part as shown in Fig. 12. It has been composed through MFL. The sequence of creating the features corresponds to the normal manufacturing sequence of the part. In many cases, this might seem somewhat limiting for design engineers, especially if their expertise in manufacturing engineering is not comprehensive. Before adding those features hierarchically from MFL, one Empty Creo Elements/Pro model named "*Testrotational.part*" has been created from the library which is shown in Fig. 13.

Now from MFL, a standard round rolled bar parameters has been selected. Commercially available round rolled bar data for MFL have been taken from Parker Steel Company (online). The system will ensure its proper manufacturing ability by showing DFM warning message "*Rolled bar should be rigid enough to withstand operational forces*" (Bralla, 1999) when the length-to-diameter ratio is not less than 3:1. Fig. 14. shows the procedure to create the rolled bar feature by using the MFL.

Rolled bar piece was separated from a large size by using band saw, and subjected to rough surface finish. So, facing feature is required for producing a flat surface. During designing, general DFM or DF guidelines for facing will alert the designer to consider those guidelines. In a lathe machine, generally a support is required from tail-stock centre for rotational work-piece during turning operation. So, centre-holes are used to support from the tail-stock centre. Centre-holes size depends on the size of the work-piece and required to coordinate the size of the centre-hole feature with the overall dimensions. Fig. 15 shows the implementation method of centre-hole feature for the *Testrotational* part.

Now, turning is a kind of machining operation where surface metal is removed from the rotating cylindrical work-piece. Several external straight turnings are required in order to get the specified diameter of the work-piece. In MFL, to avoid the inconsistency of the design with this DFM guideline "*Radii, unless critical for the part's functions, should be large and conform to standard tool nose-radius*

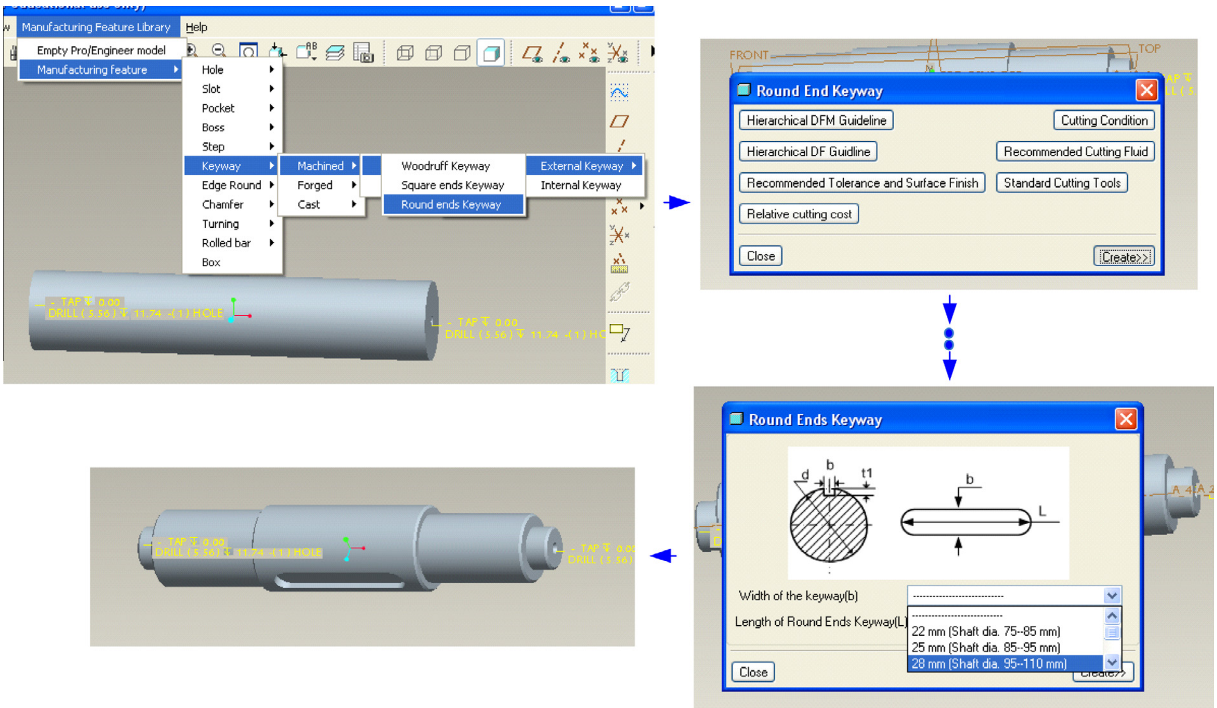

Fig. 16. Implementation method for a key-way feature.

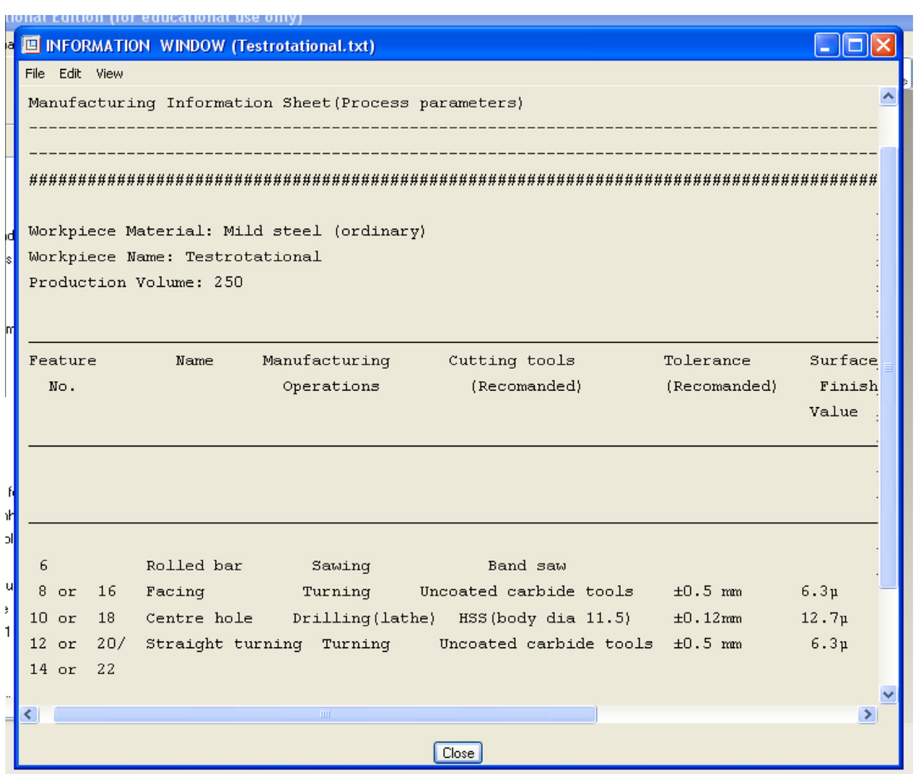

Fig. 17. Information window of rotational part for manufacturing engineers.

specifications" (Bralla, 1999), an extrude cut feature and a fillet feature are implemented together.

Chamfer features are used to conform to an important general guideline "*Avoid Sharp Corners*" (Bralla, 1999) and also for easy assembly operations. Due to the absence of DFM guidelines in the Creo Elements/Pro, the designer will create a chamfer feature from the MFL, after getting an info window message (in the main window) "*please select edge for chamfer and specify the DxD value*".

Now designer will add external key-way feature. External key-way feature parameters depend on the surface of the placement

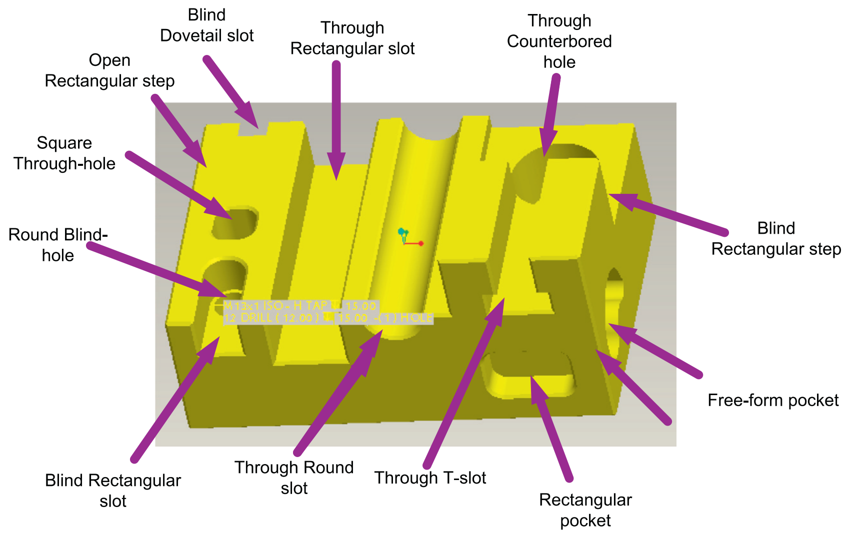

Fig. 18. Non-rotational part with manufacturing features.

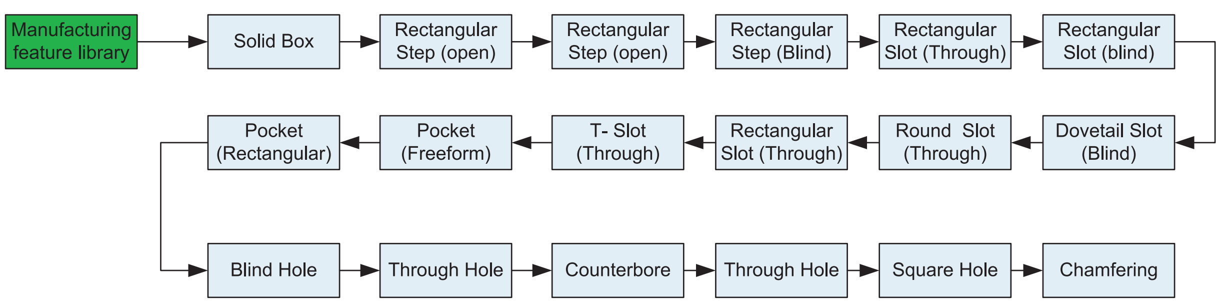

Fig. 19. Order of creating the manufacturing features.

diameter. The standard key-way sizes have been already entered inside the database system of MFL according to the placement diameter. So, designer will add the width and length from the GUI. Fig. 16. shows the implementation method for a key-way feature.

Process parameters like cutting conditions, feeds, fluids, etc., directly influence the machining processes and play vital roles for optimising productivity. So, information is required to keep record for manufacturing engineer. Standard cutting tools, cutting conditions, cutting fluids, recommended tolerance and surface finishing values were applied for the *Testrotational* part during designing. Fig. 17 shows information windows of this part.

The non-rotational part chosen for this demonstration is shown in Fig. 18. This part was also developed by using the MFL. There are twelve manufacturing features involved in this design. For the case study of the non-rotational part, an empty part named *"Testnonrotational.part"* was created. The production volume is specified as 2500 and the work-piece material is aluminium. In order to develop this part the designer needs to design a solid box first. Suppose the solid box will be manufactured by casting for this case study. Designer will select the box feature from the manufacturing feature library and will apply the parameters for the solid box. Since most of the features are on the same face, thus it will be economical to use a vertical milling centre for medium production volume. The feature structure is shown in Fig. 19 which was created step by step by using the MFL. One example of this part is blind-hole feature. The creation method of this feature is shown in Fig. 20.

Cutting tools, cutting conditions, cutting fluids, recommended tolerance and surface finishing values for this part are selected and an info window is created as shown in Fig. 21. The designer will alert by getting a warning message from the system during the time creating or placing the feature in improper way. Consider the centre-hole feature for rotational part where the designer will get a warning message when the placement surface for the feature is not perpendicular to its axis which is shown in Fig. 22. Another example for non-rotational parts is shown in Fig. 23 where the designer will alert by getting a warning message for through hole feature when violating DFM guideline *"Avoid the design of open hole"* (Bralla, 1999).

Two examples showed the step-by-step process of creating parts from manufacturing features. It needs to be noted that optimised process selection depends not only on the cutting cost per unit but also on production volume. Consider case study of rotational part, where for larger production volume the selected processes would not be optimal. For economical production the part would be forged first and then profile turning would be used. The feature-based system enables to take into consideration the production volume. Features that are not feasible for a certain production volume are not shown in the menu (thus the designer cannot select improper processes), or at least the designer is warned that a particular feature is not appropriate for the production volume. It also needs to be noted that in order to compose parts from manufacturing features designers need to have a deeper knowledge in process engineering. Since a design now includes

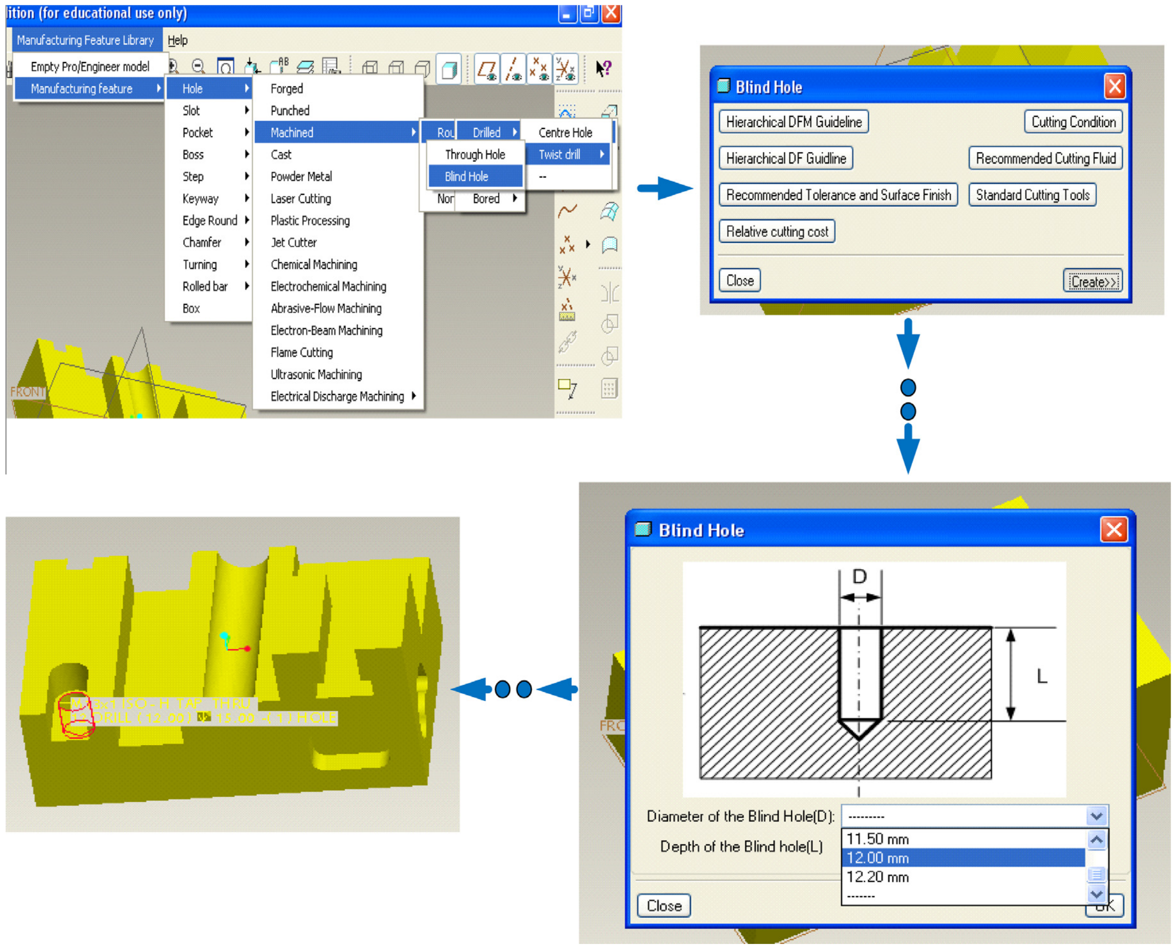

Fig. 20. Implementation method of blind hole feature.

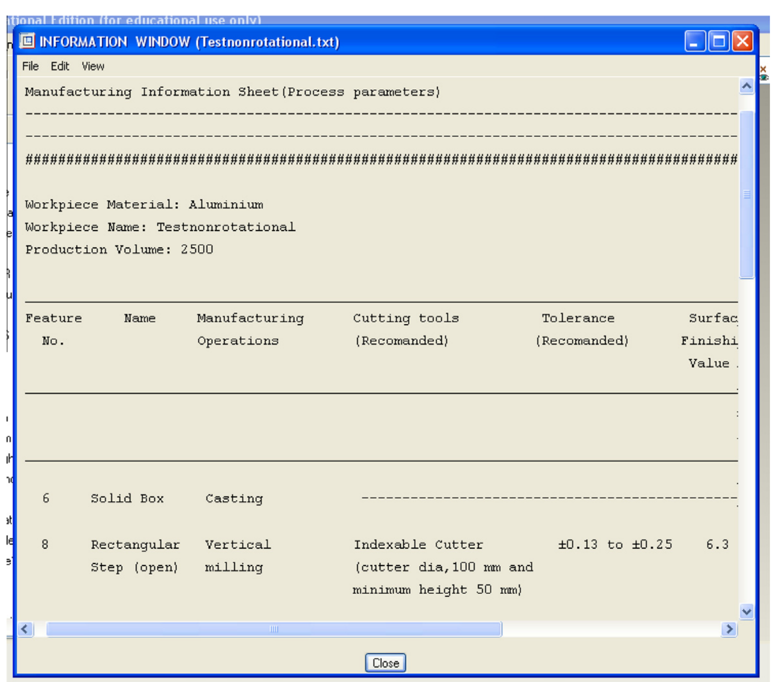

Fig. 21. Info window for non-rotational part.

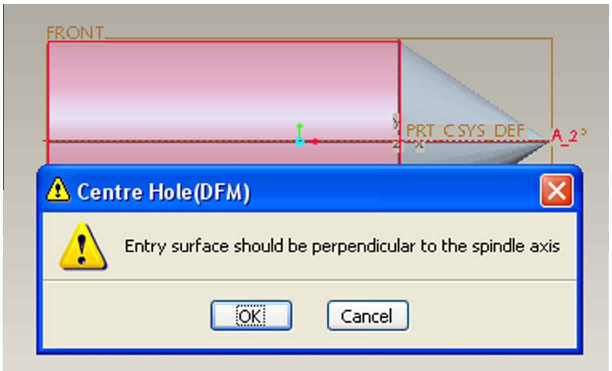

Fig. 22. DFM warning message for rotational part.

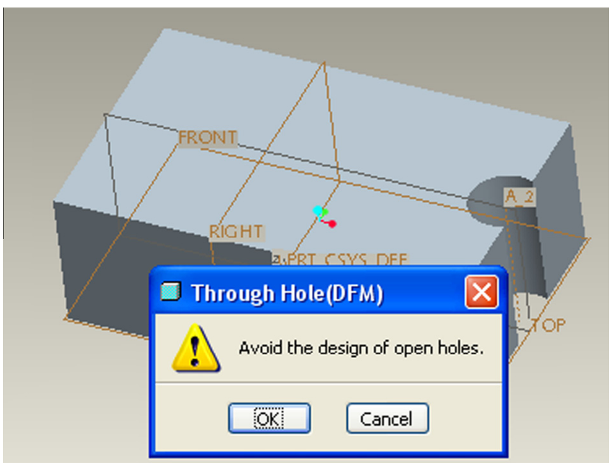

Fig. 23. DFM warning message for non-rotational part.

manufacturing data, improperly selected features may unduly restrict the choices of process engineers.

Since material selection affects the manufacturing processes, before inserting any manufacturing feature the material of the part has to be defined by the designer himself. However, the design feature part of the manufacturing feature can warn about functionality problems if the selected material is not consistent with the functionality of the feature. However, material selection is primary as no single manufacturing feature has the complete information about the purpose and functionality of the whole part.

5. Conclusions and future works

An extensive literature survey was carried out to show the capabilities and limitations of commercially available CAD/CAM systems and to explore the state-of-the-art and current trends in integrating design with other activities of the product life cycle. The paper presented a new approach of composing a part entirely from entities of higher level of abstraction than geometric primitives and their combination. Developed hierarchical MFL was implemented in a software component using the toolkit application programming interface which is easy to use by designers. It is possible to alert by getting the violation warning from the developed warning massage system. An advice system also developed where the system advices designers how to select cutting tools, machine tools, cutting conditions, cutting fluids, etc. Finally, two parts were designed considering the manufacturability by using the developed system. Since the MFL is based on international standard cutting tool parameters, manufacturing firms do not need special tools to develop their products and moreover the complex one.

The current system is restricted to machining features; however, using the same techniques and algorithms, features of other manufacturing processes can be added to the system. The hierarchical structure of the feature library ensures that such an extension can be made with relatively little effort. The developed feature templates enable to ease the feature parameter modification and consistency check. The developed graphical user interface makes the feature easy and intuitive to implement the MFL for both simple and complex designs. A detailed relative manufacturing cost database should be developed for each manufacturing feature. The manufacturing data for each feature can be expanded with more information on fixtures, standard cutting tools, cutting conditions and cutting fluids, etc. In a full-scale feature-based CAD/CAM system, rules/guidelines of other stages (like assembly, inspection, maintenance, safety, etc.) of the product life cycle can be added.

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