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DESIGN FOR MANUFACTURABILITY IN VIRTUAL ENVIRONMENT USING KNOWLEDGE ENGINEERING

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Abstract
Design for manufacturing (DFM) strategies help companies to develop new products that are feasible to manufacture. In the early stages of design all engineering activities are initiated in computer aided systems. When the design is finished, the process of manufacturing and production planning begins. Issues often occur at this point because two teams, designers and manufacturers, have been working separately. The resulting question is: 'how can Knowledge Engineering (KE) be used effectively to enhance manufacturability during early design?' Even if the most complex geometrical product can be realized using today's technologies such as rapid prototyping it is only true in unit production. In lot and mass production where CNC machines are used, complex geometry causes a number of difficulties. So it is important to investigate the project carefully in the early design stage from the point of view of whether it will be possible to manufacture.

Keywords
design for manufacturing, knowledge engineering, virtual manufacturing.

Introduction

Design for manufacturability or design for manufacturing in general, is connected with a methodology that involves engineers designing with the intent to minimize the cost of production and time-to-market without compromising on the quality of the product. The idea of design for manufacturability and its application are not new. The first person who engaged in design for manufacturability was Eli Whitney over 200 years before use of the term became widespread [1]. Awareness of the importance of designing products for easy manufacture and low cost has existed in leading design and manufacturing engineers since product design and manufacturing activities originated but use of the term DFM, recognition of it as a worthwhile engineering approach and development of an organized DFM methodology are more recent – becoming popular only around 1985.

A number of studies have proven that an error identified and removed during the design stage costs almost a hundred to thousand times less than when removed during the manufacturing or exploitation stages [2–4]. Many researchers state that near 70% of the product cost is committed during the design stage with production decisions such as process planning, or machine tool selection making up only 20%. As such, it is important to resolve as many manufacturing problems as possible during the design stage, because all problems accruing in the manufacturing stage generate not only cost but have a great impact on time and quality, Fig. 1. for example designing holes or pockets which cannot be machined with standard tools (e.g. reamer) will result in increased cost. Even though it is an obvious problem for advanced designers, beginners would not be aware of it. Much more difficult problems arise when a complex geometrical shape is taken into account. There is still a lack of publications in which shape interrogation for computer aided manufacturing are considered.

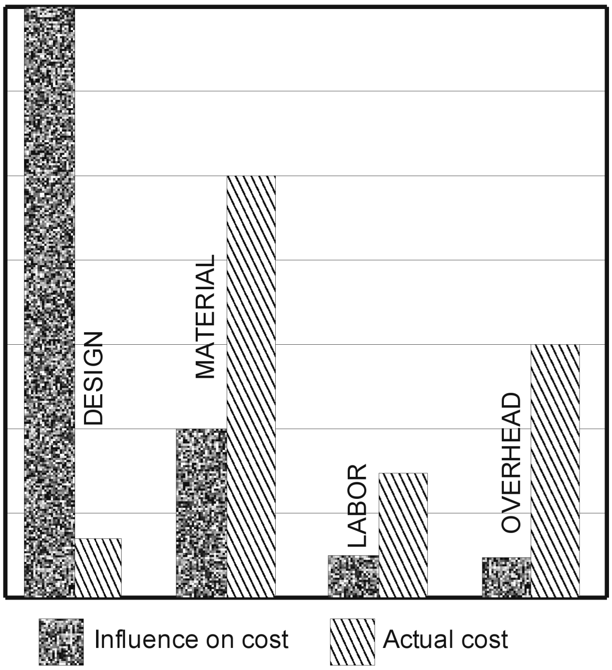

Fig. 1. Design impact.

The design engineer should ensure that the design is suitable for production. The heart of any design for manufacturing system is a group of design principles or guidelines that are structured to help the designer reduce the cost and difficulty of manufacturing an item. Listed below are these rules [4, 5]:

- reduce the total number of parts,
- develop a modular design,
- use of standard components,
- design part to be multi-functional,
- design parts for multi-use,
- design for ease of fabrication,
- avoid separate fasteners,
- minimize assembly direction,
- maximize compliance,
- minimize handling.

It is worth noticing that these rules are much more suitable for DFA (Design for assembly). You can find further information on principles of DFA in [6, 7]. Current approach to DFM defines it as a process of proactively designing products to optimize all manufacturing functions: fabrication, assembly, test procurement, shipping, delivery, service, repair and assuring the best cost, quality, reliability, regulatory compliance, safety, time to market and customer satisfaction. DFM encourages standardisation of parts, maximum use of purchased parts, modular design and standard design features [8, 9].

Dr. David Anderson, after more than 20 years of theoretical and empirical investigations has formulated the myths and realities of product development.

Myths of product development [10]:

1. To develop products quicker, get going soon on the detail design and software coding and then enforce deadlines to keep design release and first-customer-ship on schedule.
2. To achieve quality, find out what's wrong and fix it.
3. To customize products, take all orders and use an ad hoc "fire drill" approach.
4. Cost can be reduced by cost reduction efforts.

Realities of product development [10]:

1. The most important measure of time-to-market is the time to stable, trouble-free production and that depends on getting the design right the first time.
2. The most effective way to achieve quality is to design it in and then built it in.
3. The most effective way to customise products is by the concurrent design of versatile product families and flexible processes. This is known as mass customization.
4. Cost is designed into the product, especially by early concept decisions and is difficult to remove later.

These realities are similar to the Toyota philosophy: "*The cost of a product is largely determined at the planning and design stage. Not much in the way of cost improvement can be expected once full-scale production begins. Skilful improvement at the planning and design stage are ten times more effective that at the manufacturing stage*".

Principles of designing for manufacturability

As stated before, design for manufacturability is the process of proactively designing products, the following principles are applicable to virtually all manufacturing processes and will aid in specifying components and products that can be manufactured at minimum cost [11]:

- simplicity,
- standard material and components,
- standardized design of the product itself,
- liberal tolerances, Fig. 2 illustrates the range of surface finishes obtainable with a number of machining processes and how substantially the process time for each method can increase if a particularly smooth surface finish must be provided,
- use of the most processible materials,

- teamwork with manufacturing personnel,
- avoidance of secondary operations,
- design appropriate to the expected level of production,
- utilizing special process characteristics,
- avoiding process restrictiveness.

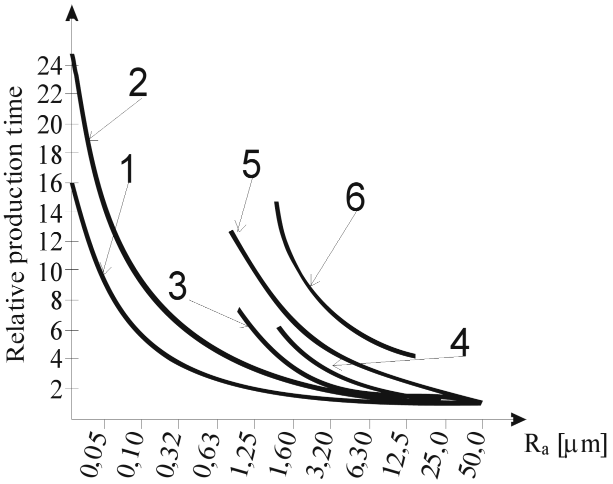

Fig. 2. Some typical relationships of productive time and roughness (R_a) for chosen machining processes: 1 – cylindrical grinding, 2 – finishing grinding, 3 – turning, 4 – drilling, 5 – finish milling, 6 – reaming [10].

These days DFM is used for three main activities:

- as the basis for concurrent engineering studies to provide guidance to the design team in simplifying the product structure, to reduce manufacturing operation and cost, and to quantity the improvement,
- as a benchmarking tool to study competitors' products and quantify manufacturing difficulties,
- as a should-cost tool to help negotiate suppliers' contracts.

In product development activities DFA (Design for Assembly) is credited to be the first step. The aim of DFA analysis is simplification of the product structure. The second step in an analysis is DFM. Particularly when estimating the cost of each set of machining features, it is important not only to know the total estimated manufacturing cost of an item but to know the cost of providing the various features. Figure 3 shows the typical steps which are usually considered during DFM analysis.

The geometry of the part is first classified according to its size, shape, cross section and features [12–14].

The geometrical classification of a part is concerned with the following characteristics:

- the overall size,
- the basic shape,
- the accuracy and surface finish,
- the cross section,
- functional features.

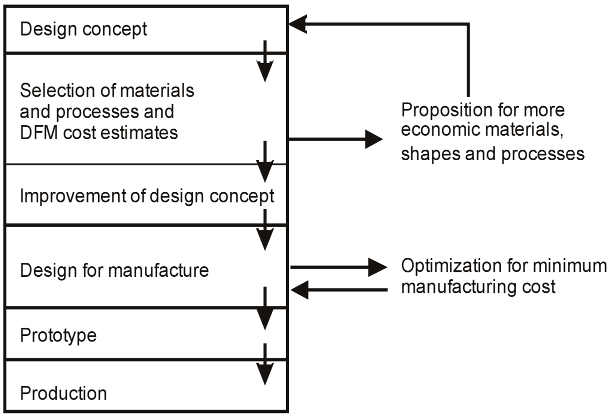

Fig. 3. Steps taken in DFM study in concurrent engineering.

Processes are classified as either primary, secondary or tertiary to take advantage of the natural order of processes in a sequence. Rules, formulated from engineering knowledge about processes are used to select the sequence of operations for part manufacture. Operations are selected using a pattern matching expert system and rules of the form:

```
if ...
    condition 1, constraint 1
    ...
    condition n, constraint n
            then ....
            operation 1
            ...
            operation n
```

For primary selection, the conditions are restrictions on the size of the enclosing envelope, the size and shape of the fundamental envelope, and the cross-section of the part. If analysis satisfies the restriction, the process could be stated as a candidate to be a primary process. In this stage all conditions and rules should be stated for all features of the part but the boundaries of a process' capabilities are not well defined. Therefore, the process selection rules are better formulated with fuzzy logic membership function to model the progressive transition from "easy" to difficult or impossible to manufacture by the selected process [15]. In the next step, the material database is searched for the primary process selection in the same way as described for primary process selection. Secondary and next processes are selected in similar manner to form any features of the part that cannot be formed by the primary process. Next step is connected with feature and shape analysis and interrogation. In the last step, tertiary processes are selected to fulfil all requirements. Figure 4 shows this selection graphically.

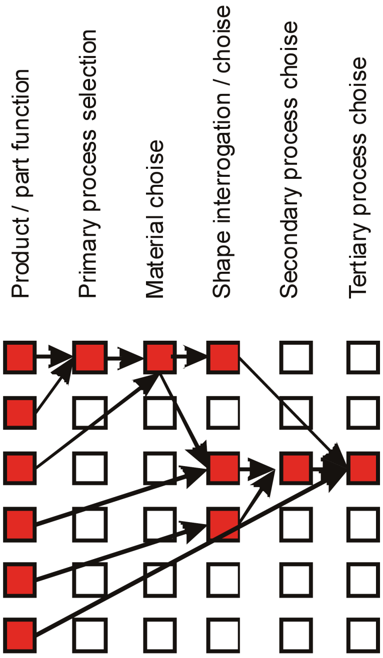

Fig. 4. Sequence for processing selection.

Knowledge engineering for manufacturability

Knowledge engineering is a methodology which is used to create knowledge-based systems and enables reuse of results from earlier projects. However, results and experiences obtained during project work in major cases are not documented for reuse. So many companies try to write in CAD/CAM system knowledge which could be reused in the future. Some of them base this on guiding rules given in STEP norm, others on knowledge-base engineering, case based reasoning and programming. But it is still not transparent how KE can be used to support engineering design in early stages of a project and the question remains: how to use knowledge engineering to enhance manufacturability during early stages of product development while having a lifecycle view.

Product development and product life cycle management

PLM – Product Lifecycle Management is a systematic approach for managing the life cycle of a product, from its design and development to its ultimate disposal. Usually PLM is divided into the following three stages:

- BOL: Beginning of Life, which includes new product development and the design process,
- MOL: Middle of Life, which includes collaboration with suppliers, product data management (PDM) and warranty management,
- EOL: End of Life, when the product is discontinued, recycled or disposed of

PLM provides a framework for all of the information that might affect a product and also provides tools for formal communication between product stakeholders. The main goal of PLM is to eliminate waste and improve efficiency. The success of any company depends on its ability to supply products of the right quality, in the right quantity, at the right time and for the right price. To meet these demands, engineers should take into consideration: the right product design and tolerances, the right material, the right equipment, the right tooling and a motivated, knowledgeable workforce.

PLM is usually closely connected with product development in a virtual manufacturing system defined as an integrated, synthetic manufacturing environment. It is developed using information technology tools to enhance all levels of decision and control. PLM uses a computer to simulate a product's performance and the processes involved in its fabrication. Simulation technology enables companies to optimize key factors directly affecting the profitability of their manufactured products [16].

More of today's companies try to work together on projects aimed at enhancing the efficiency, flexibility and "life" of a product. In recent years, several new systems which use DFM technology have appeared on the market [17]. Such systems are equipped with automated tools that support several common DFM guidelines for machining. This helps to produce parts economically, to a better quality, in reduced time using readily available machining tools.

Figures 5 and 6 depict examples of some guidelines for machining. Drills should enter and exit the surfaces that are perpendicular to the centerline of the hole. If they do not, the tip of the drill will wander on the surface and exit burrs will be uneven around the circumference of the exit hole, making burr removal difficult.

A similar situation occurs when blind holes are designed. A flat bottom should be avoided because it will cause problems with subsequent operations. A better solution is a hole with a conical bottom. More examples of machining features for DFM are given in [18–20].

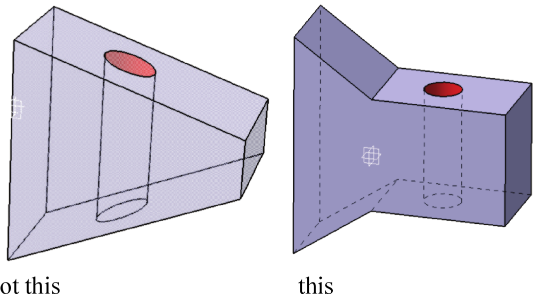

Fig. 5. Entry and exit surface of the hole should be perpendicular to axis.

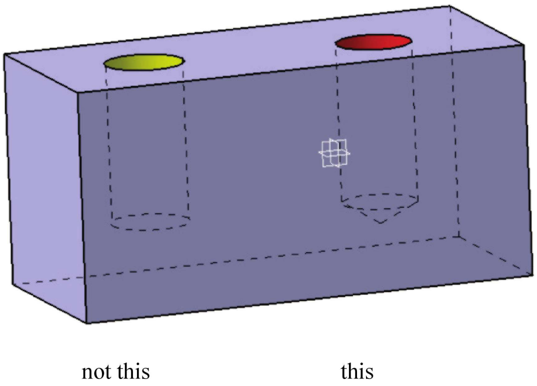

Fig. 6. Designers should avoid flat bottomed holes.

But the majority of these systems work only with simple features. Problems occurs when shape and geometry of the product are complex.

An example of designing for manufacturability for lower cost in virtual manufacturing environment

Manufacturing cost is the most complete measure of manufacturability. It can be expressed as a total cost for the product or component. Total cost includes cost of all features to be manufactured.

In this paper an example of a milling machine process is considered in DFM aspects. Milling is an effective means of removing a large amount of material and an efficient method of producing highly precise contours and slots. Milling cutting is classified by two principal cutting actions: those which remove material by cutting on the side and those whose cutting action may be described as cutting in addition to side cutting.

More than 80% of all mechanical parts which are manufactured by milling machines can be cut by NC pocket machining. This is based on the fact that most mechanical parts consist of faces parallel or normal to a single plane, and that free-form objects are usually produced from a raw stock by $2^1/_2$ D roughing and 3-D or 5-D finishing.

The success of NC milling depends on the availability of efficient algorithms for defining tool paths. Generally, the cutter motion for machining a part consist of roughing, semi-roughing and finishing and should be considered separately, Fig. 7.

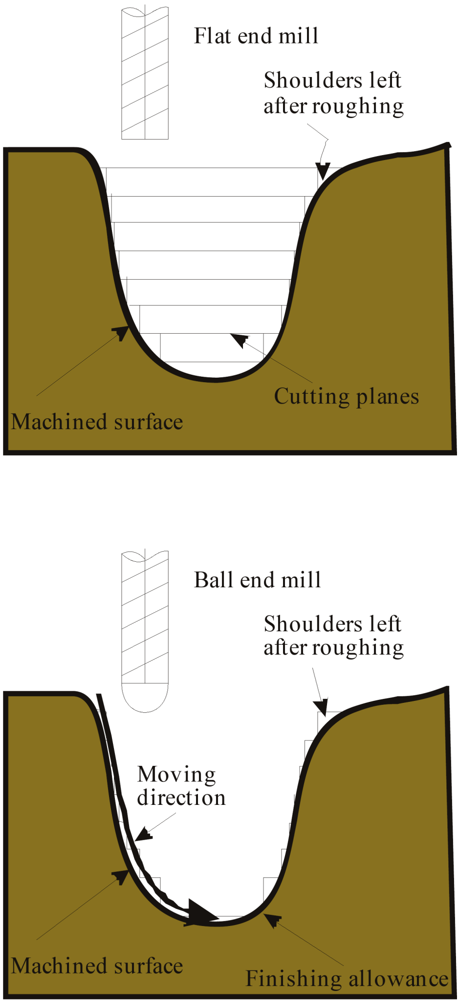

Fig. 7. Pocket machining with flat-end mill in roughing and semi-roughing with ball-end mill.

Of course rough machining should be as simple as possible and preferably consist of a linear type motion in order to minimize machining time. So, the cutter path should be as short as possible and the depth of cut and feederate should be as large as possible.

At the first stage when choosing a material it should be carefully considered due to the fact that there can be significant differences in the cost and lead time of acquiring different forms. In many cases choosing aluminium alloys instead of steel can have better performance and significantly improve machinability. For further interrogation let us consider the geometry of a part presented in Fig. 8, which shows examples of features: the part is interpreted in terms of hole, slots and pocket. In CAD systems surface features are distinguished and converted into machining features (volumetric). Next, a sequenced set of instructions used to manufacture the part are generated. Manufacturing features are recognized directly from a solid model built in Catia system.

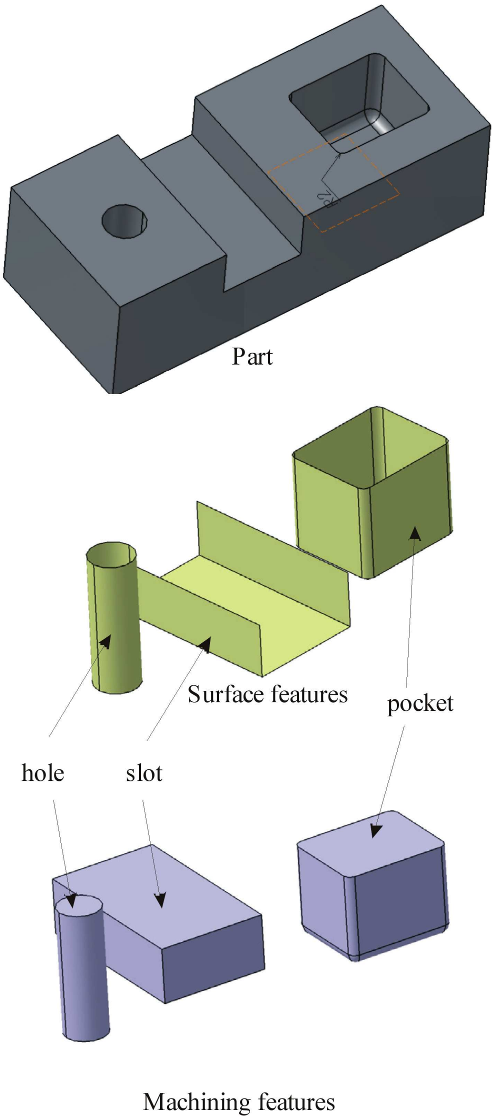

Fig. 8. An example of part and its surface and machining features: hole, slot, pocket.

For the purpose of this paper let's consider only one feature "pocket". All simulation and time calculations were realized in Catia system in machining module.

The first simulation was done using three tools to machine, with diameters $\phi 10$, $\phi 6$, $\phi 4$, Fig. 9. These tools were used due to design requirements.

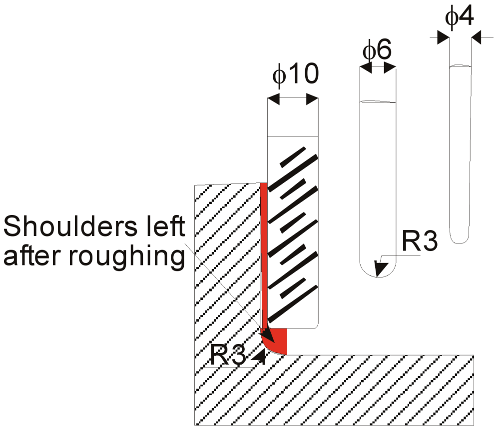

Fig. 9. Tools used in first simulation in Catia.

From NC code times of each operation were read. Total time to machine feature "pocket" is near 12.2 min., Table 1.

Table 1
Time calculation for machining feature pocket.

Tool diameter	Machining time [min]	Changing tool time [min]
Φ10	6.3	
Φ6	1.2	0.2
Φ4	4.3	0.2
Total	11.8	0.4

But it occurs that it is hard to remove material from the corner, Fig. 10. In such case a rule based on KE should be introduced:

```
if
    the radii of floor and wall are different
then
    "warning" this feature will be difficult to machine, try to change radii
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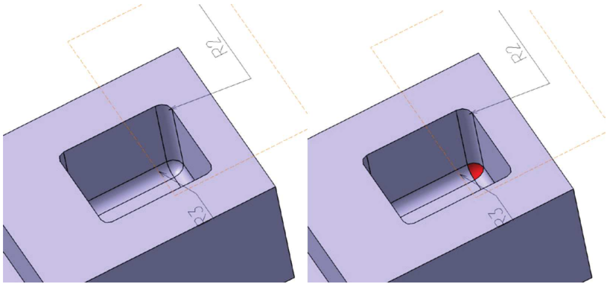

Fig. 10. Material which is hard to remove (in red).

But this condition doesn't means that the two radius should be the same. Usually engineers in design process use "apply all round" or fillet feature in CAD systems, the easiest thing to do is to select both the floor and wall intersection and apply the same radius to all those. Even if it saves some time to have one feature, this can cause difficulties in machining and cost a lot of money in the long run. Sometimes it cost 5 to 10 times more. But if the design requirements are not so rigid we can use a tool with ball end which machines both wall and floor radii, Fig. 11.

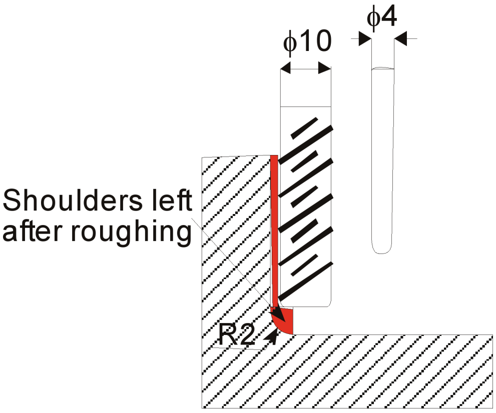

Fig. 11. Changing R3 into R2.

To make the right decisions at the early stage of design, cost estimations is required. Such estimation could be done from a model and knowledge of time machining. Activity-based costing could be apply to calculate cost and can be applied to product development. ABC usually has the following steps: identify and choose activities, applay costs to each activities (machining time), calculate product cost.

Table 2
Time calculation for machining feature pocket (after changing R3 into R2).

Tool diameter	Machining time [min]	Changing tool time [min]
Φ10	6.3	
Φ4	4.6	0.2
Total	10.9	0.2

In this case the machining time was decreased from 12.2 to 11.1 min (near 9%).

But even it is possible to machine in a manufacturing environment some aspects of the rigidity and strength of the cutting tool ($\phi 4$) were not considered. The depth of the pocket is 25 mm, so the proportion between tool diameter and depth is: $4/24 = 0.16$, Fig. 12. As the length of the wall increases, the length of the tool increases. This means that the tool should be fed much more slowly, increasing the cost. For strength the proportion should be greater than 1/3. In the considered feature it means that federates should be much slower.

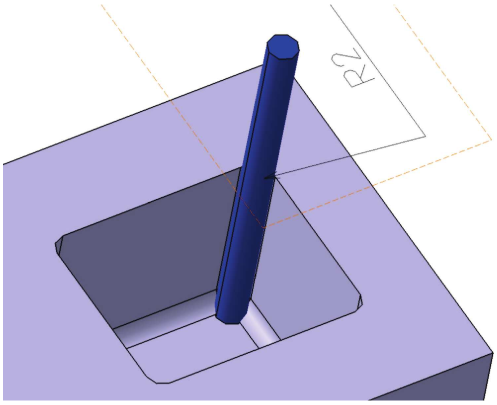

Fig. 12. Proportion between pocket depth and tool length.

Such rules are very difficult to attach into CAD systems and so, a lot of researchers and companies develop guidelines, which when used can significant reduce the cost of machining.

Conclusions

Design for manufacturing is not a fixed system. DFM is continually being developed, both in university research projects, within companies and by a number of consultants. DFM has been accepted by industry as a valid element in the product design process. Effective DFM encompass two aspects: analysis of the complete product in order to simplify its design and analysis of each individual part and feature to maximize its manufacturability.

Another advantage is that DFM provides a systematic procedure for analyzing a proposed design from the point of view of manufacturing.

However, effective CAD/CAM integration has been elusive, and extensive human intervention is still necessary to move ideas and design between CAD and CAM in most manufacturing domains.

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