

Computer-aided Concurrent Environment for Manufacturing Education*

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Undergraduate education in manufacturing engineering is undergoing constant change to satisfy the level of competence expected from the graduate engineers by manufacturing industry. Apart from a need to integrate the different strands of course material, more emphasis needs to be placed on computer-aided concurrent manufacturing. One way to respond to these needs is to introduce practical examples into the curriculum. The case study presented herein considers one such example. The product around which the case study was developed, is simple yet flexible enough so that the lecturer can tie in a number of manufacturing-related topics, such as computer-aided design, computer-aided process planning, computer-aided manufacturing, concurrent engineering and manufacturability of a product. The computer-aided design and manufacturing software used in the case study is identical to that used in several manufacturing engineering companies. The case study could be considered as a simulation of some of the common practices found in these companies.

INTRODUCTION

THE INCREASING industrial need for skilled engineers in manufacturing engineering is to be met with graduates who have the knowledge and passion in the field. To a certain extent, the prosperity and viability of a manufacturing company are dependent on the successful recruitment of quality manufacturing engineering graduates. These graduates are typically trained in a manufacturing or mechanical engineering department of a tertiary institution. The manufacturing engineering curriculum in these institutions have been subjected to fundamental changes over the last half century, particularly since computers have become more and more intimately involved in almost every single aspect of manufacturing business. Traditional undergraduate programmes on manufacturing placed considerable emphasis on processes, primarily with respect to their manufacturing capabilities and the basic science of manufacturing. While there has been no shortage of recognition of the importance of manufacturing subjects, the relevant courses have in the past been taught with little reference to other subjects such as design. Recently, the traditional divide between manufacturing and all the other related activities such as design and prototyping in a company has disappeared. Today, there is an urgency of striving for integration and concurrence in a manufacturing company. The endeavour of engineering institutions to incorporate these aspects into their courses now means that manufacturing-related courses can no longer be taught in isolation.

Computer-based engineering methods have

come a long way to assist the development of concurrent engineering environments in manufacturing companies. There is even a plan to get computer-aided design and manufacturing (CAD/CAM) software into every secondary school in England [1, 2]. In the tertiary sector however, the teaching and practice of some of these methods have now been incorporated into different engineering courses to such an extent that these institutions now provide the same technologies and software systems as those used by many manufacturing companies. The vehicle for the above practice is no doubt a host of well-defined, industry-based teaching programs and/or projects. There have been a number of case studies reported in the literature. Academics in the Gippsland School of Engineering at Monash University, Australia have developed a training program in industrial automation [3]. At the Department of Industrial Management and Engineering of Technical University of Denmark, a learning system called 'Ruler Factory' has been developed [4]. Another example is a product-based teaching programme developed by the Department of Manufacturing Engineering at Loughborough University of Technology in conjunction with a number of industrial partners [5]. Lamancusa *et al.* present an approach to integrate design and manufacturing in the engineering curriculum [6]. Tavakoli *et al.* proposed an approach utilising a multi-track teaching style that allows for concurrent teaching of engineering design, analysis and manufacturing [7]. An integrated approach is also taken by the University of Texas at Dallas for graduate education in manufacturing systems [8].

For centuries, many aspects of the business in a manufacturing company have been run in a

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sequential manner, that is, the various functions such as design, manufacturing and customer service have been treated separately. Hence, the information flow from one phase to another is in succession. Introduction of computers into industry has helped by promoting more effective information management within a department, as well as between departments. For example, computer-aided 2-D drafting software has significantly improved the product design process. Various computer-aided part programming tools such as APT (Automatically Programmed Tools) have helped to alleviate the NC programmer's job, which used to be tedious and error-prone. The commercial introduction of CAM tools around the mid-1980's provided more user-friendly features such as allowing operators to graphically create an NC program directly from a CAD model. Not until recently did these CAM tool/systems serve as a means of achieving automation and productivity in an isolated manner, resulting in so-called automation islands being formed within the factory. This type of disjointed environment in manufacturing industry resembles the similar scenario in the education sector in that different topic areas of manufacturing have been introduced through separate courses and more often than not by different academics. Course improvement and rationalisation are only carried out within the individual courses.

The impediments of sequential engineering and the isolated automation islands have now been widely recognised. The inability and inefficiency of inter-department coordination in a factory can lead to poor product quality, high costs and longer lead-time. It is evident that there is a need for concurrent engineering and synergetic integration of the various manufacturing activities. Software developers have been quick to respond to this need. Software systems start to play an indispensable role in the day-to-day business of product oriented manufacturing companies. These software systems include Parametric Technology Corporation (PTC)'s Flagship system Pro/ENGINEER WILDFIRE, Dassault Systems' CATIA and EDS's Unigraphics NX and I-Deas CAD/CAM systems. The commonality among these software products is their integrated suite of applications covering all aspects of product development: computer-aided design, computer-aided engineering and computer-aided manufacturing, whether by providing the necessary functionality to support collaborative product development, or by enabling the seamless integration that allows full support of company processes.

A concurrent engineering environment in particular is also a must for a product-centric company. Product-centric companies are those that make a corporate-wide commitment to creating competitive products and embody this commitment throughout their organizations, including product development, engineering, manufacturing, finance, purchasing, sales, marketing, and after-market

support. To support this commitment, these companies need a technology infrastructure that allows them to effectively manage their products throughout their lifecycles.

Based on the manufacturing practice of a local company, this article presents a case study which emphasises the features of a concurrent environment for a manufacturing company. The main objective is to showcase a real-life, computer-integrated manufacturing scenario and bring together some of the fundamental manufacturing engineering topics that are traditionally covered in different courses. This case study adopts the project-based learning approach, which has been used successfully for a number of courses in the Mechanical Engineering Department at the University of Auckland. The product-centric strategy that has been adopted helps to address the essential issues in a product-centred organisation [9].

BRING INDUSTRY EXPERIENCES INTO CLASSROOM TEACHING

In the last quarter of the twentieth century, software suppliers have developed a number of integration solutions, i.e. CAD/CAM systems, which have helped companies embrace concurrent engineering and integrated manufacturing. These systems are now in place in almost every major manufacturing company. Tertiary institutions responsible for educating manufacturing engineers have an obligation to reflect the current industry situation in the curriculum of manufacturing engineering. Separation of design from manufacturing in the curriculum or vice versa is no longer acceptable [5, 10, 11]. Traditional classroom-based teaching of manufacturing topics is inadequate to keep up with industry reality. Therefore, the two issues that tertiary institutions have to address are the integration of course materials and the introduction of industry-based projects/case studies.

The case study presented in this article has been developed based on the experiences of a leading whiteware manufacturer in New Zealand. Both the company and University are using the same CAD/CAM system, i.e. PTC's Pro/ENGINEER WILDFIRE. Little modification has been made so that the case study follows a much closer representation of the industry practice. The focus though is not on the complexity of a manufacturing system, but rather on the inter-connections among different manufacturing activities effectively co-ordinated by the CAD/CAM system.

An industry-based case study

One of the mainstream products in the company is a household refrigerator. One configuration of the product sees it mounted inside a cupboard. To allow for correct placement and adjustment, two foot integration parts are fixed on the floor of the cupboard, into which the front levelling feet of the

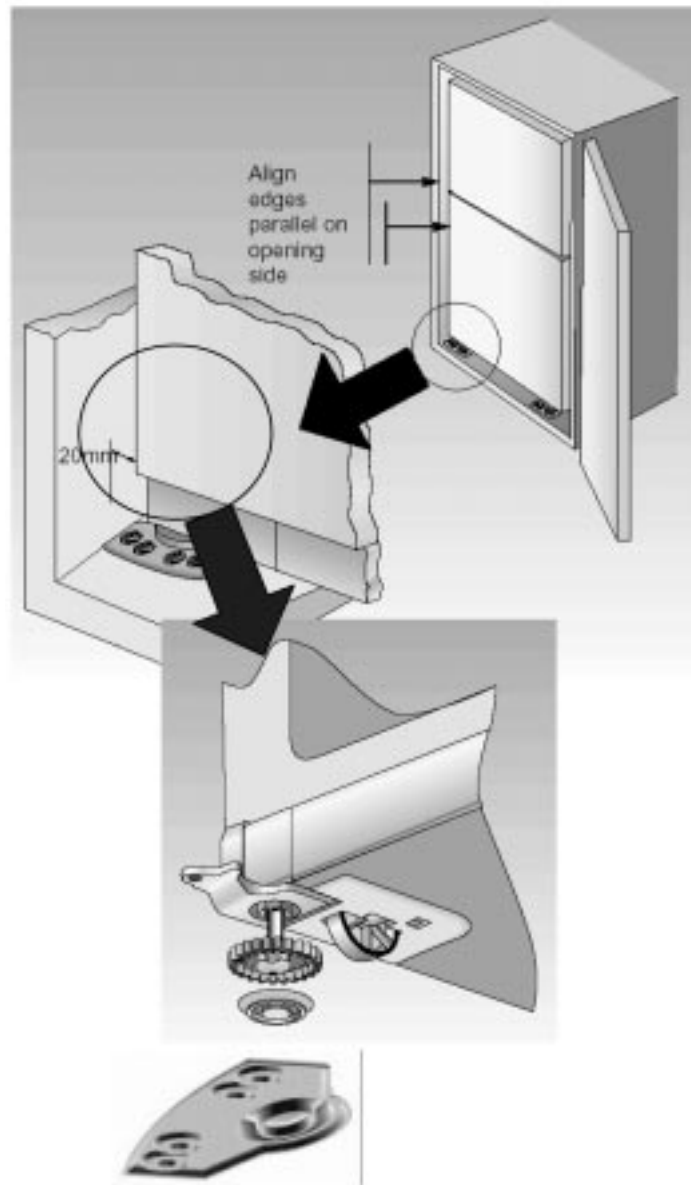


Fig. 1. The built-in type of refrigerator and its levelling assembly.

refrigerator sit (Fig. 1). The case study starts from designing this part to all the down-stream activities related to the manufacture of the part.

The foot integration part is designed using a 3D CAD/CAM system, i.e. Pro/ENGINEER WILD-FIRE. Being a thermoplastic product, the foot integration is mass-produced using the injection moulding process. Tooling therefore becomes an important part of the entire manufacturing process. Design of the tooling is also carried out within the same CAD/CAM system, but using an additional module called Pro/MOLDESIGN. The complete tooling model consists of the mould bases, insert core, insert cavity (within the top mould base), foot integration part and a number of small inserts (Fig. 2). Most of the tooling components are machined on a CNC milling

machine. The process planning and NC code generation are carried out within Pro/NC, another integrated module of Pro/ENGINEER WILD-FIRE.

A narrow deep circular slot, which corresponds to a small circular protrusion on the foot integration part (Fig. 3) requires an Electrical Discharge Machine (EDM) to produce. The tool used on the EDM machine is an electrode as shown in Fig. 3, and is usually made from highly conductive materials such as graphite and copper.

Once again, the electrode design is carried out in the same CAD/CAM system. The geometrical modelling of the electrode part is done with reference to the corresponding faces on the insert core. This reference is deemed important as will be demonstrated later for the provision of

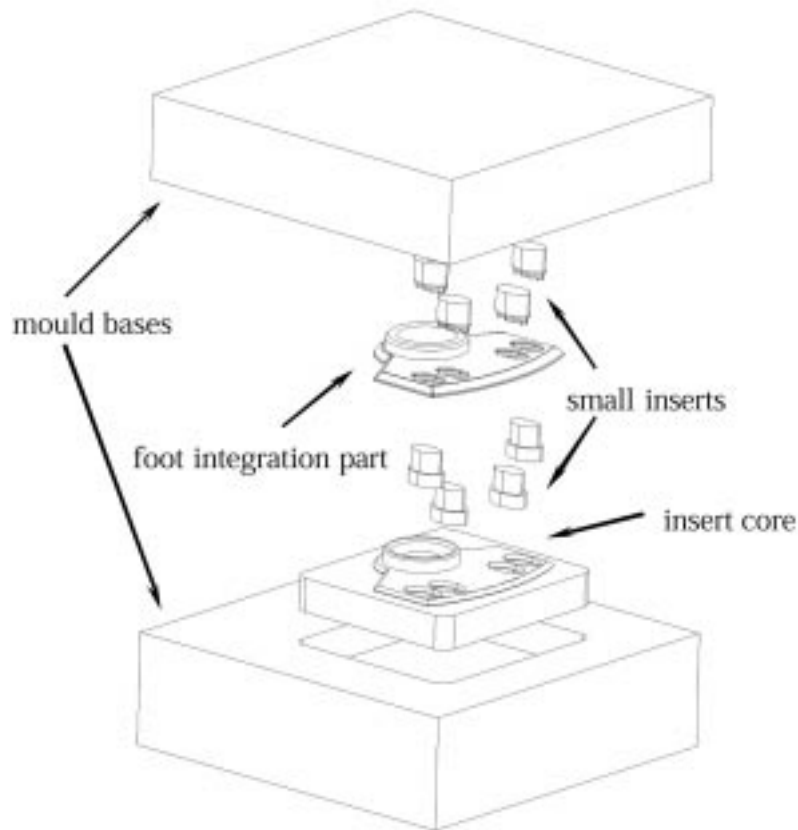


Fig. 2. The tooling assembly.

a concurrent engineering environment. Electrode manufacturing is carried out on another CNC mill and its process planning and NC programming are also carried out in the Pro/NC module.

A bird's-eye view of the case study

Figure 4 shows an overview of the entire manufacturing process concerning the production of the

foot integration part. The three highlighted routes are (1) production; (2) design information and (3) manufacturing information. The production route illustrates a sequence of different manufacturing activities on the shop floor for the final production of the foot integration part. The design information route describes the design activities for the foot integration part, tooling and the electrode, whereby both Pro/ENGINEER WILDFIRE and Pro/MOULDESIGN are used. The information flow from design to manufacturing follows the manufacturing information route, primarily managed by the Pro/NC module. It is worth noting that both design and manufacturing information is effectively managed by the same CAD/CAM system on a single database. Hence, the associativity among the different design and manufacturing models is guaranteed, which enables a concurrent environment.

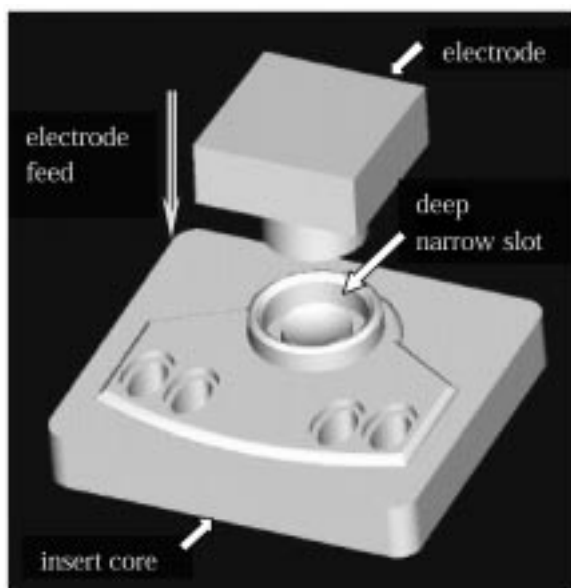


Fig. 3. Mould insert core and the required electrode.

Manufacturing processes and technology put into context

The case study mentioned above links together a host of topics specific to manufacturing processes and technologies, as well as some common types of machine tools. These manufacturing processes involve the use of injection moulding machines, CNC milling machines, high-speed machine tools and EDM machines. Not only did the students better understand these processes and equipment, but they also appreciated the inter-connections

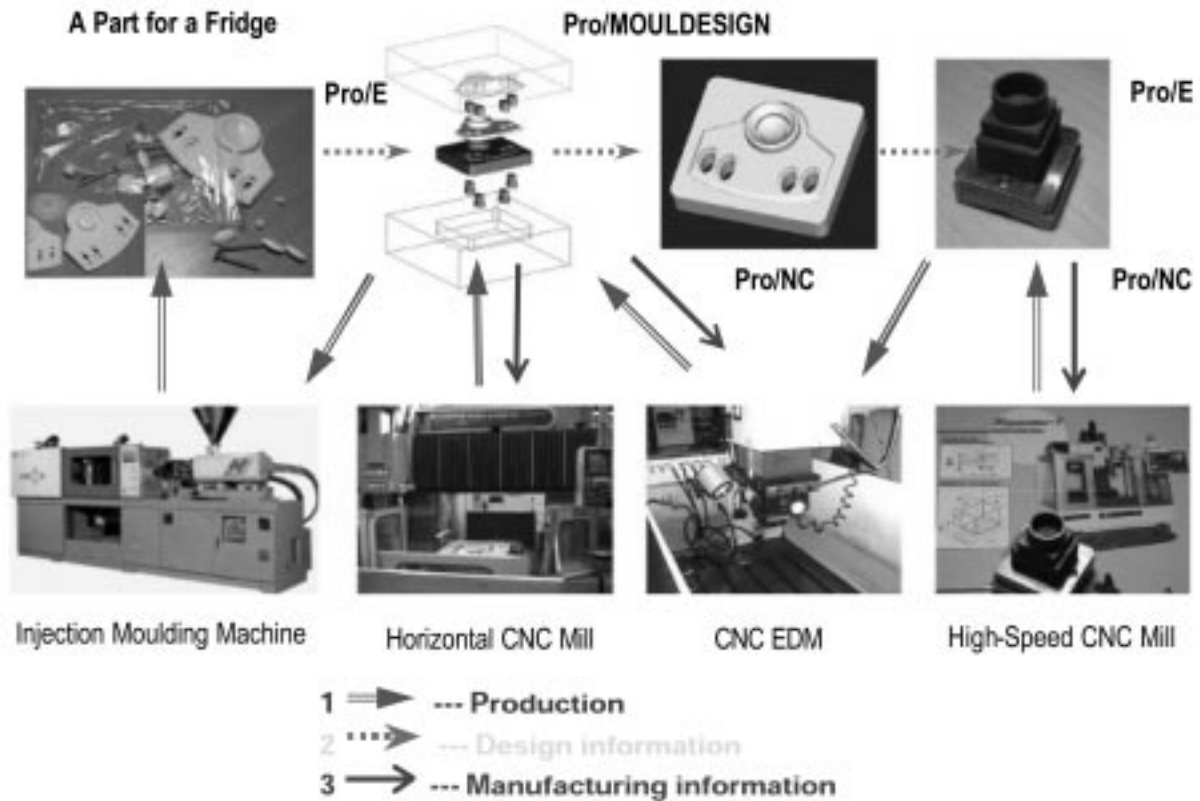


Fig. 4. Design and manufacturing information flow.

between different processes, and the rationale behind the selection of these manufacturing processes. While the injection moulding process seems to be a more than obvious choice for manufacturing a thermoplastic component, the necessity of using a high-speed CNC milling machine for the machining of an electrode made of graphite leads to a new group of topics. For example, issues such as cutting force, chip handling and use of coolant are addressed from a totally different angle for the case of high-speed machining. The EDM process gains little attention when introduced on its own. However, students can now better appreciate the process, as they have to design the electrode and plan the process for the EDM operation. When designing the electrode, issues such as spark gap and surface finish have to be taken into consideration.

AN INTEGRATED ENVIRONMENT VIA A CAD/CAM SYSTEM

Computer-aided design and manufacturing software plays a key role in integrating various manufacturing activities in an engineering company. This is demonstrated in the case study in two different aspects. First of all, the CAD/CAM software manages the information for various manufacturing activities in a single database. Secondly, it helps to improve the manufacturing process

through user-friendly interfaces and imbedded technologies.

CAD/CAM enabling a concurrent environment

Since design and manufacturing information resides in a common database, changes can be managed easily and quickly. Furthermore, these changes are bi-directional. A change made to the design part by the designer, for example, the diameter of the seat on the foot integration part, can be propagated throughout the whole model chain all the way to the NC commands generated for mould manufacturing, the design model of the electrode part, the NC commands generated for electrode machining on a high-speed CNC mill etc., etc. This is made possible thanks to the associativity feature in the system.

Associativity or relationships in the model can be built in different ways. Making intended reference to an existing part is one way. When the electrode part is being modelled, it is desirable that links be established between the features in the tooling and those of the electrode. A correct way of doing this is to create a 'quilt' feature based on the faces belonging to the mould and then use the quilt to define the protrusion feature on the electrode (Fig. 5). Another important link is between the foot integration part and the moulds. In Pro/MOULDESIGN, the shape of the moulds is directly generated from a 'reference' part that is effectively a duplicate of the foot integration part. Therefore, changes to the foot

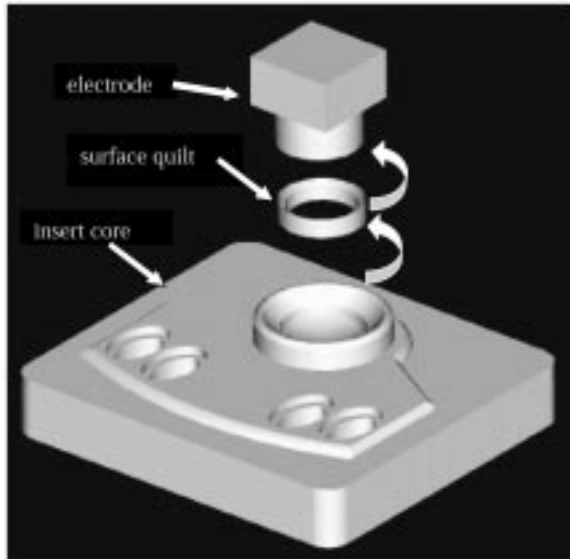


Fig. 5. Associativity between the mould and the electrode.

integration part, will be propagated through to the subsequent models and NC programs, i.e. the geometry on the moulds, electrode part and the NC programs for machining the moulds and the electrode part. Students are able to take this advantage into another block of lectures and assignments where cost analysis and concepts of Design-for-X such as design for manufacturing were introduced, enabling them to re-design the part, in an assignment for example, so that the cost of the part could be brought down. One obvious change to make is to modify or widen the circular protrusion on the part so as to eliminate the necessity of the EDM process and achieve a significant reduction in cost. Because of the associativity feature in the system, there is little revision work to carry out other than 're-generating' all the subsequent models based on the re-designed product model.

In brief, associativity makes it possible for different activities concerning the manufacture of a part to happen simultaneously instead of sequentially. Tooling and electrode design, and process planning for tooling and electrodes can all commence at the early stage of the part design. Hence, the product development cycle time can be shortened. Furthermore, product re-design at a later stage can be made less arduous and error-free. The whole set of design and manufacturing models can also be easily re-used for another similar product.

CAD/CAM system as an enabling tool for process planning

CAD/CAM systems nowadays have all adopted the three-dimensional representation scheme. This makes the design model more complete and convenient to work with. But more importantly, CAD/CAM systems serve as a vehicle for introducing some of the contemporary technologies and enabling tools for product development. For an

injection-moulded part, Plastic Advisor in Pro/ENGINEER WILDFIRE allows students to check manufacturability of the part without the need for expertise in plastics processing. This is done by on-screen animations of mould filling.

Pro/MOLDESIGN provides some common tools for creating, modifying and analysing the mould components and assemblies, and also quickly updating them to the changes in the design model. Shrinkage can be applied corresponding to the design part material, geometry and moulding conditions. Once the basic mould assembly is completed, it can be populated with standard components such as the mould base, ejector pins, sprue bushings, screws, fittings and other components creating corresponding clearance holes. The system teaches students how to define feasible parting surface(s) and then split the workpiece using these surfaces. The module can also check interference of components during mould opening.

To manufacture the moulds, insert core and electrode, Pro/NC is used for process planning and NC machine data generation. Figure 6 summarises a logical sequence of steps to progress from a design model to process planning and CL data files which can then be post-processed into NC machine data.

DELIVERY OF THE CASE STUDY

The case study is incorporated in a third year, second semester course named 'Manufacturing Systems' as part of the four-year Bachelor of Engineering program. The course accounts for one seventh of the total semester credits. The students enrolled in the course would have had two-and-a-half-year experience with the Pro/DESKTOP system (a sister product of Pro/ENGINEER WILDFIRE) for 3D conceptual design and one-year experience with the Pro/ENGINEER WILDFIRE system for mechanical design and simple kinematics analysis. However, the students only have a limited knowledge of manufacturing systems and processes.

The case study accounts for 25% of the course content and it is delivered as a combination of a company visit, classroom lecturing, CAD/CAM tutorials, CAD/CAM clinics, written assignment(s) and assessment on computer (Fig. 7). The case study starts with a company visit (2 hours) which exposes the students to some tangible industry practices. This is followed by a set of 6-hour lectures that covers basic topics concerning the case study and also introduces the case study and assignment. Before commencing the assignment, the students are assigned to different groups, attending two 2-hour tutorials on Pro/NC. One of the assignments that have been fully developed is 'Computer-Aided Process Planning in Reality'. It carries 20% of the total course mark. The assignment features a real-life exercise of developing a process plan based on a commercial CAD/CAM

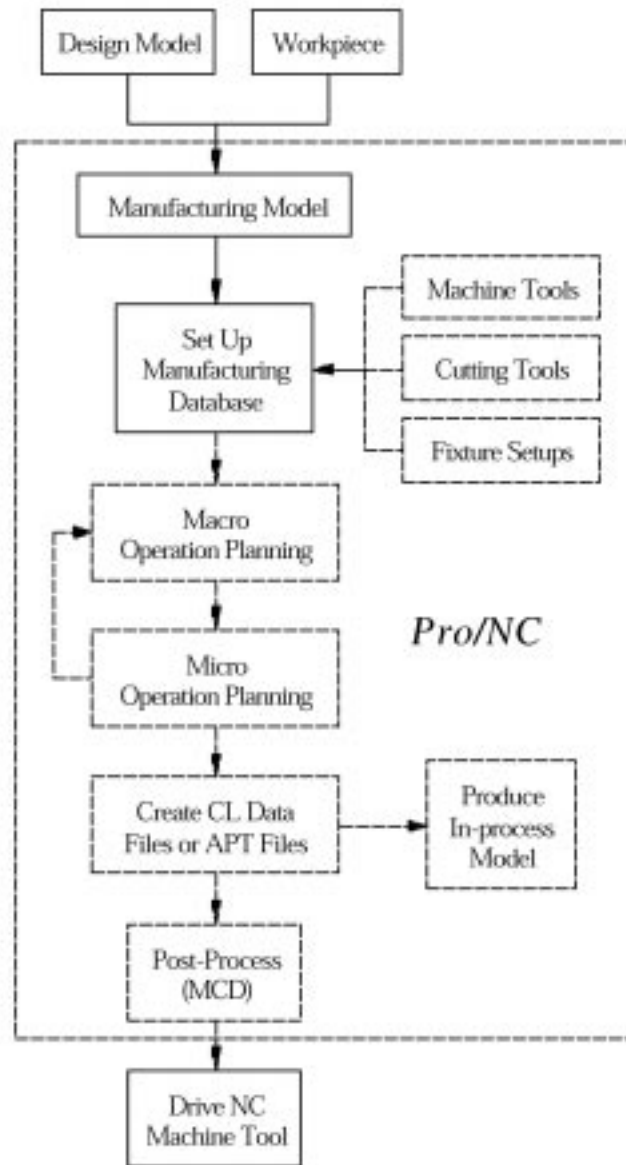


Fig. 6. Process planning and NC code generation.

system, i.e. Pro/ENGINEER WILDFIRE. The product family, for which the process plan is developed, is the electrode parts used for EDM operations on tooling parts. The electrode, made of graphite material in this case, is machined on a high-speed CNC mill. The shape of the electrode has an intrinsic link to the final product, i.e. foot integration pad, through the tooling parts. The NC commands (G-code program) used for high-speed machining are generated by Pro/NC, and they are based on the shape of the electrode part. Thanks to the associativity feature of the Pro/ENGINEER WILDFIRE system, a change when initiated at the product level can be quickly propagated through the tooling, electrode part and then to the NC commands. Hence engineering changes are automatically managed and a concurrent engineering environment is created. The assignment is an individual assignment, lasting for four to five

weeks. Pro/ENGINEER WILDFIRE models of all the components including the tooling and electrode are all given.

The Clinics provide the venues for students to ask questions about the assignment. The assessment is composed of three parts, Questions on Pro/NC Tutorials (6/20), a written CAPP User Guide (6/20) and Demonstration of the CAPP model in Pro/ENGINEER WILDFIRE (8/20). The questions on the Pro/NC tutorials are designed to assist the students' understanding of the system. The CAPP User Guide resembles a procedure/operation documentation exercise in a manufacturing company. Assessment on computer is deemed necessary and effective as it is almost impossible to assess some aspects of the CAPP model developed, e.g. user-friendliness of the model and clarification of some of the doubts found in the User Guide.

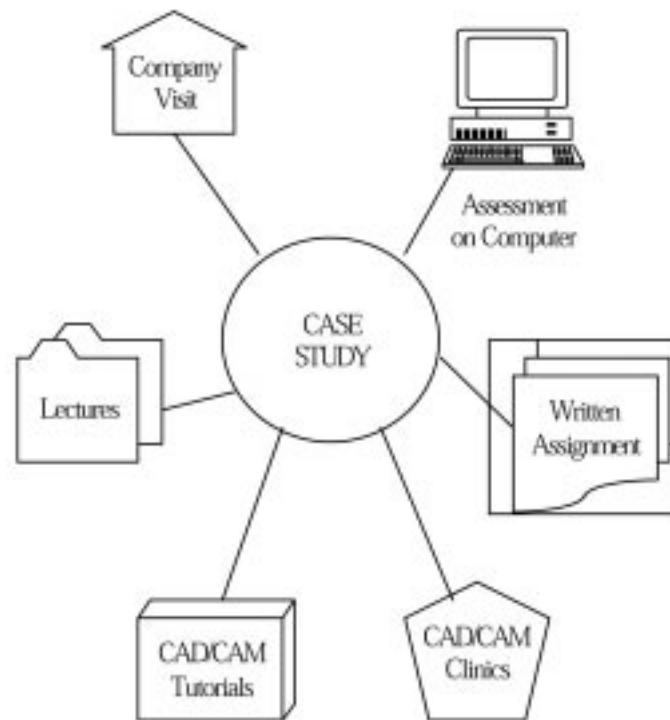


Fig. 7. Delivery of the case study.

CONCLUSIONS

The manufacturing engineering discipline differs from many others in that it has a strong and direct connection with the day-to-day running of manufacturing industry. The curriculum of manufacturing engineering in a tertiary institution should therefore reflect this nature. The case study presented here responds to this need. It is based on a realistic example from a local manufacturing company. It is a simple manufacturing case, yet covers broad areas of manufacturing engineering. Therefore, the case study also serves as a common thread for introducing a number of topics under the same roof, giving the course a more coherent structure and holistic approach. Another useful feature of this case study is that the students gained an extensive appreciation of the use of computers, in particular with regard to the professional suite of integrated CAD/CAM software. The software helps streamline the engineering process in a manufacturing company from conceptual design to tooling and manufacturing by allowing different people in the factory to have access to native bi-directional associativity throughout the entire product development process. This is showcased in the case study with little modification to a practical situation.

The case study also demonstrated to the

students the role that concurrent engineering plays in a modern manufacturing company which is product-centric and multi-dimensional. Through completing the case study and the assignment, students gained experiences of:

- working concurrently with a single product model so that product design changes can be automatically incorporated;
- seamless data exchange and collaboration in mould design and tooling process;
- flexible NC programming environment for all machining technology, including high speed machining.

Using professional CAD/CAM software, some of the manufacturing related concepts can be easily amalgamated and interconnected to one another, such as computer-aided design, computer-aided process planning, computer-aided manufacturing, manufacturability of the design, manufacturing cost analysis, etc., etc. It has to be pointed out that Pro/ENGINEER WILDFIRE is only one of the many CAD/CAM software systems that can fulfill the task.

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