REVIEW OF THE PRODUCT DEVELOPMENT PROCESS AND INFORMATION FLOW IN THE MANUFACTURING INDUSTRY: PROBLEMS AND A POSSIBLE WAY FORWARD

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This article evaluates the product development process and information flow in the manufacturing industry. Numerous concepts, methods, and prototype software tools for supporting various product development activities have been developed and tested. Only a handful of the developed concepts, methods and software tools are used in the industry. Extensive research has been on creation of computer-based concepts and methods to support various product development functions. A completely computer-based integrated product development function is not yet in place. This is partly due to the problem of lack of a mechanism to facilitate a two-way data transfer between dependent systems and lack of information structure to sufficiently satisfy the information demands of the life cycle activities. The last part of the paper presents the preliminary results of the research undertaken as an attempt to come-up with a process planning procedure that ensures that each product development task is provided with manufacturing information it requires in time. The goal is to reduce the number of rework cycles, particularly in the early phases of the product development process.

Keywords: *Integrated product development, design, process planning, manufacturing information management.*

INTRODUCTION

The uncertainty of the market and constant change of customers' needs have always been stimulating the need for development and commercialization of new product development concepts and methods. Today, numerous commercial and prototype computer aided tools supporting design, process planning, manufacturing, testing and quality assurance, mostly in mechanical engineering, electronics and industrial design engineering are available. As an example to show the scale of the influx of software concepts in the manufacturing industry, Kiritis (1995) reviewed fifty-two knowledge based process planning systems representing a wide range of methods and software concepts. Among the major reasons for the frequent need of new concepts, methods, and sometimes-dedicated computer-aided tools has been the dynamic nature of the products' market domain (e.g. continuous change of market demands in terms of complexity of design objects, shorter time-to-market, need for improved quality, globalization of the economy, etc.). Furthermore, new trends in design and production (for instance, the arrival of concepts such as Computer Integrated Manufacturing - CIM, integrated product development, concurrent engineering and collaborative engineering) and the introduction of new practices in the manufacturing industry such as co-engineering, out-sourcing and global manufacturing have also been inspiring researchers to develop new product development and production concepts.

This paper briefly reviews literature related to the product development process in the manufacturing industry. It critically evaluates the concepts, methods and software tools applied in the life cycle activities of design, modeling, process planning and manufacturing; and highlights the main deficiencies. The paper also reviews the current product development trends, research and practices; and proposes a possible way forward. Since there are numerous publications on this topic, completeness in the sense that all literature is reviewed is not covered; rather, the main issues are highlighted.

METHODOLOGY AND TOOLS

This section contains review of methodology and tools applied in the product development activities of design, modeling, process planning, and tool `management. It also evaluates the methods used to transfer information between design and manufacturing.

Design Process

Design can be described as the process of transforming an engineering problem (i.e. requirements and ideas about the product) into a solution (i.e. a decision on materials to be used and how exactly the final product should function and look like). The design process consists of several sub-phases, which often differs according to the framework under consideration, but generally the sub-phases range from analysis of the problem to generation of a final design model for use in downstream activities such as manufacturing and assembly. The design sub-phase may further be decomposed into sets of interrelated activities in order to gain control over the total duration of the design process. The decomposition also helps to attain a proper utilization of resources during planning and execution of design activities and as a result the total cost is minimized (Pahl and Beitz, 1988). The starting point of the design process is the customer requirements, which are translated by designers to technical specification before being translated and eventually transferred into Computer Aided Design (CAD) systems. Most choices related to product quality as well as to product cost are made by the designer. According to the literature (see e.g. TNO, 1996), the designer determines an estimated 80% and 70% of choices related to product quality and cost respectively.

Models of product design guide design processes. They provide a structured approach in the execution of the design tasks. There is an overwhelming literature on design process models (see e.g. Tichem (1997); Evbuomwan et. al. (1996); Blessing (1994); and Finger and Dixon (1989); Eder (2004)). Generally, design models fall under three categories, namely, *elementary activities models, phased models* and *domain models*. Elementary model outlines activities that are traditionally repeated many times in design process. Activities are executed by reasoning, starting from the design problem up to a final solution. Roosenburg and Eekels (1995) describe elementary activities in the basic design cycle. The details of each function are available in Tichem (1997) and in Roosenburg and Eekels (1995). Although division into phases seems to suggest a sequential product development process, usually in practice there is back and forth execution of activities.

Phased models are characterized by staged design process. The whole design process is split in a number of phases. In each phase, a specific product data is generated. Phase models are also characterized by a sequential flow of execution of activities between phases, and often one phase is bound to be finished first before the next one is started. An example of phased model is that described by Pahl and Beitz (1993). Many other phase models exist, but they often resemble (Roozenburg and Eekels (1995); Blesssing (1994)). Often only minor differences exist, particularly in terms of the nomenclature used and the number of phases. A domain model uses description of types of designs referred to as domains. The design process proceeds in a zigzag fashion between the different model domains, to 'fill' the product model defined by domains. Examples of domain models include those described by Erens (1996), Suh (1995), Andreasen (1992), and Andreasen and Hein (1987).

Product Modeling and Representation

Various techniques are used to describe engineering parts or products. These include the use of natural languages, symbolic representation, free hand sketches, engineering drawings, group technology-based representations, physical models and CAD models. Of these description methods, CAD models are the most effective method in terms of integration of the design functionality with downstream life cycle activities within the concepts such as CIM and integrated product development. The output of the CAD system is a product model or in other words, a framework for representing the technological information i.e. geometric and non-geometric information in design and in other downstream activities.

Advances in programming techniques have enabled objects to be represented in a variety of ways. Common representations are two-dimensional (2D), two and half-dimensional (2.5D)[1] and three-dimensional (3D) representations. The three ways commonly used to represent 3D geometry in the existing CAD systems are by using wire frame models[2], surface models[3], and solid models[4].

There are several schemes used in organizing and storing geometric data in solid modelers. These schemes differ in the range of objects that can be modeled, consumption of CPU time and memory, ease of interrogation or manipulation of model, uniqueness (i.e., whether one object maps into one or more models within the representation scheme) and in easy of validity testing (i.e., how easy or feasible tests on a model can be conducted). The commonly used schemes are Constructive Solid Geometry (CSG) and Boundary Representation (B. Rep.). CSG modelers describe the geometry in terms of solid shapes, half-spaces, pre-defined or user-defined shapes called primitives. Primitives are basic solids such as spheres, blocks, cylinders, cones and cuboids; which can be combined in several ways to form objects. A binary tree of geometric primitives, transformations, and Boolean operators is the representation method of the CSG model. By using Boolean operators (i.e. union, difference and intersection) a component

[1] 2D and 2.5 D (i.e. a 2D model plus some depth information) models describe parts with 'lines' rather than a 'model' of the product being described. 2D and 2.5D CAD systems have several limitations, e.g. they have neither the capability to check if the corresponding views of a part are compatible nor provide knowledge on the space that the 2D lines represent. Examples of applications requiring 2.5D representation include electrical wiring schematics, printed circuits board designs, design of control networks, pipe layout designs, and NC programming for processes like flame cutting, end milling and drilling. (2D or 2.5D model provides the basic data for generation of NC programs for these manufacturing processes.)

[2] 3D wire frame models describe an object using a frame of lines (or wires), which represents the edges of the object and a set of 3D coordinates, which represents the endpoints of the lines in space. 3D wire frame models are generally very difficult to work with because their representation scheme simply consist of lines of 3D space with no information on surfaces between the lines or volume within those surfaces. Any manipulation made in a wire frame modeler makes direct reference to lines. For example, sectioning of a 3D wireframe model typically reveals only points or lines, which are rather meaningless.

[3] Surface modelers describe objects in terms of points, edges (i.e. lines between points), and faces (i.e. area bounded by those lines). They provide no volumetric information. Surface models are regarded as the best and possibly the only way of representing free-form surfaces. They are largely used in the design of molds and dies, household appliances, plastic injection molded parts, and in aerospace and automotive industries where there is a need to model complex surfaces for technical purposes (e.g. wind resistance) and/or styling purposes (e.g. visual appearance of cars). The existing CAD surface modelers generate different kinds of surface models. However, most of the present CAD systems base their modeling systems on Non-Uniform Rational B-Splines (NURBS), in which curves are generated based on parametric functions, which can be manipulated by changing the control points. Typical surfaces that can be represented with such surface modelers include flat, analytical, swept and free form surfaces. Free-form surfaces are based on the algorithms developed by Bezier (see Bezier, 1966) or by de Boor (i.e. B-Splines). Free-form surfaces generated by surface modelers can generally be manufactured (e.g. by using 3-axis ball-end milling or 5-axis milling process and EDM techniques). The major drawback of surface models is that they are not reliable in dealing with mass properties (e.g. volume, etc.), sectioning and hidden lines removal.

[4] A solid model holds a complete description of an object in terms of space it occupies and allows points in space to be classified as either inside, outside or on the surface of the object. Typical software utilities in solid modelers include those for producing realistic shaded images, hidden surfaces, line drawings, calculation of mass properties, clash detection between objects, and generation of data for NC programming and finite element analysis. Since a solid modeler stores complete geometric model of an object, it can potentially provide a geometric database for design and downstream tasks.

can be built interactively through a text or a graphical editor dialogue. The structure used to represent CSG models is a tree, with operations as its nodes and primitives as its terminals. Most of the existing CSG modelers have some limitations on their capabilities. For instance, in order to discover faces, edges and vertices of an object, the CSG modeler must first undergo a process known as 'boundary evaluation', which is quite expensive in terms of CPU time. Furthermore, interactive editing of local geometry on a CSG model is not possible - modifications can only be done in the input model. When a need for modification arise the user must go back to the input model, as no topographical or geometrical information is readily available. Also, the underlying mathematics of the representation seem to dictate that the surfaces used must be half spaces, making it difficult to widen the domains of CSG models.

The description of an object in a B.Rep model is held in terms of the boundaries, faces, edges and vertices of the solid object. These entities are held in a tree structure whose connections indicate the way in which the entities are connected in the object. Most B.rep Modelers use redundant data structure in which each entity has many pointers to other related entities. These extra pointers serve to reduce the amount of searching when traversing the model in order to modify or interrogate it. The main drawback of a B.rep model is that it requires large memory space because of large amount of explicit data stored in it.

The concept of features[5] and the virtual reality (VR) technology have also been incorporated in some modeling systems. It is generally agreed that the concept of features is central to the integration of the life cycle activities of design and process planning (Maraghy, 1993). Significant research efforts have in recent times been directed towards feature-based modeling, which is considered to offer a better connection of the CAD data to process planning and manufacturing data. Features are seen as a major vehicle in improving the link between CAD and CAPP/CAM[6]. In feature-based systems, CAD geometric models stored in databases are examined and form features (e.g. holes, slots, pockets, bosses, etc.) are extracted from low-level entities (i.e. points, faces, edges, vertices and primitive solids) (Joshi and Chang, 1988)[7]. One of the limitations of feature technology is that only a limited number of features can be recognized. Also, technological information and data are traditionally added manually. One of the problems is that often the number of possible features on a given part model is virtually infinite and the 'feature library' can be extended indefinitely. Also, feature recognition techniques are not yet optimized. The prevailing techniques are difficult to apply for complicated parts and they sometimes require human intervention because of their complexity.

VR tools equipped with features such as real-time shadows, reflections and collision detection; with which designers can evaluate their designs are available; from advanced high-end development systems to PC-based systems. With VR tools-generated digital prototypes, designers can navigate e.g. through the interior of their design and observe their design in action. Some applications can also be distributed, letting the designers work together regardless of their geographical location. VR tools provide the means to ensure that suppliers and customers can share a complete understanding of the design and functionality of prototypes and provide feedback

[5] Features are shape elements that have some engineering significance. The definition of features is not agreed among researchers and practitioners, and it can be confusing. It is, however, important to understand that this nomenclature has different meaning in different life cycle activities. For example, 'design or functional features' constructed using CSG or B.Rep modelers' based geometric primitives are not necessarily the 'manufacturing features' needed in process planning.

[6] Feature technique provides interfaces between Computer Aided Design (CAD) and Computer Aided Process Planning (CAPP)/Computer Aided Manufacturing (CAM) systems.

[7] It is important to note, however, that features are not the only elements of importance in product development, because other elements such as assembly models and tolerances are also important due to their influence in both manufacturing and functioning of the product.

in the early stages of product development. VR also include methods with which parts can be designed by simulating manufacturing operations on the screen. In this case, the designer generates the manufacturing specifications as they design. The design solutions are specified in terms of manufacturing data, which are captured through an interactive VR simulation of manufacturing processes. Most of the VR tools are compatible with existing engineering tools, thus giving the users the power of being even more productive. Also, typically there are commercial links that translate commercial CAD models into real-time graphics visualization simulation environments for rapid visual prototyping of designs. This greatly reduces lead times in the prototyping process[8]. The use of digital mockups instead of physical prototypes or clay models in the product development make it possible to keep multiple concepts alive longer in the development process. Reduced lead times, fewer physical prototypes, lower costs, increased understanding and shorter time-to-market are some of the benefits gained from VR technology.

In conclusion, this section reviewed various methods and tools used in design, drafting and prototyping. It can be said that:

- There is a need for a comprehensive data structure that will address the issue of timely availability of information for both upstream and downstream activities. Data carried by geometric models generated by traditional CAD systems is tailored mainly for tasks that require graphical information, and is typically not intended for use in downstream processes which require much more information than just product geometry.
- Often the process planning activities (such as process selection and identification of manufacturing resources) starts after the design tasks have been completed. This frequently leads to iterations in the design process, which e.g. can result into production delays.
- The designers have no means for obtaining manufacturability and capacity planning information in time. Typically, decisions on e.g. part's surface finish, tolerances and fits; which dictate the selection of manufacturing processes; machine tools; tools and fixtures are often not optimized. A wrong choice of these manufacturing related design parameters can be very costly, e.g. may eventually lead to the need for special tools, fixtures, expertise or even machines.
- In the conventional drafting systems, key manufacturing data such as tolerances and fits are typically not represented readily for use in manufacturing.
- In the design process, the designer normally generates many ideas and solutions, analyses and evaluates them, and eventually selects the most suitable solution. The knowledge and skills they use has not been made available in CAD systems.

Process planning

Process planning is the act of preparing detailed processing documentation for the manufacture of an engineering part or assembly (see e.g. Kiritsis, 1995). It is strongly based on the expertise and experience of the process planner who is involved in the art of preparing process plans. According the literature (see e.g. Chang (1990); Juri *et al* (1990); Kiritsis (1995); Pande and Walvekar (1990)), process planning include process, machine tool and tooling (i.e. jigs, fixtures and cutting tools) selection, process sequencing, process parameter selection, determination of machining times and cost, generation of tool paths and NC program; and generation of the process plans document (see Table 1). These process planning functions are largely dependent. However, the order of conducting these functions is universally not agreed, but in most case process and machine tool selection are the initial tasks. The initial input information to process planning is the total description of the component, which includes dimensions, dimensional and form tolerances,

[8] An example of such links is *Clarus* CAD real-time link software (see www.clarus.se, 2004) used to import and convert CAD engineering data files produced using commercial CAD/CAM systems such as ProEngineer and CATIA.

number of parts to be produced, blank information, surface quality data and materials specifications. Typically, process planning starts with the interpretation of the product model. A process planner uses hand-prepared drawings or CAD models from the design department, which consists of geometric data, including information about a component's tolerance and surface finish. The ultimate goal is to obtain a final component that satisfies technical requirements. For example, according to Zhao (1995), apart from dimensional, surface roughness and tolerance requirements, final machined part should fulfill circularity, flatness, straightness, parallelism and perpendicularity requirements, depending on part configuration. Technical requirements must be obtained at a minimum cost, within a certain time span; and often by utilizing available manufacturing resources (i.e. equipment, manpower and consumables). Most often process planning deals with conflicting goals that must ultimately be achieved within the context of overall goal.

Computers can support some of the process planning activities. Computer Aided Process Planning (CAPP) can be anything between computed assisted system to fully automated function linking CAD and CAM (Vin, 1995). There are several ways to categorize the existing CAPP tools. For example, Teicholz (1987) and Vin (1993) categorized the existing process planning systems as either generative[9] or variant[10]. Other authors, for example, Kiritsis (1995) and Chang (1990) described the existing systems as either knowledge based or analytical.

The existing process planning procedure and software tools have been applied successfully in the industry. However, it can be said that:

- The prevailing process planning procedure does not adequately support up-stream life cycle activities. Traditionally, process planning follows the design process. It is, however, evident that process planning information is required in activities such as feasibility analysis and design that precede process planning. With the arrival of concepts such integrated product development and collaborative engineering, there is a need of decentralization of process planning, with the goal of adequately supporting all product development cycle activities. For instance, there is a need of conducting some of the process planning activities before or during design, and some locally at the machine shop level.

[9] Generative computer aided process planning systems attempt to capture the knowledge, expertise and sometimes practice used by manual process planners. New process plans are developed from scratch. Manufacturing data and manufacturing resources information are stored into the computing system and computer program generates completely new process plan based on this information and on stored decision logic. These systems vary significantly by approach, scope and level of sophistication in using the knowledge and data stored within the systems. At one end of spectrum there are those which use AI techniques and try to emulate the expertise which an experience process planner uses to prepare process plans, while at the other end, others use algorithms and technological constraints in generation of process plans. However, a fully generative process planning system is not yet available. This partly is due to the problems associated with product representation and the complexity of identifying, extracting and understanding the logic of human decisions in process planning. Most of the present systems can generally be described as of 'semi-generic type', with some steps of the process planning performed interactively.

[10] Variant process planning is based on Group Technology (GT), and can be regarded as a computer-assisted extension of manual process planning. Parts are classified into families, usually using GT coding system and template process plans are drawn up for each family (Teicholz, 1987) and stored in digital form in databases. The process planner selects a template process plan and adapts it to suit the requirements of the new design. The process planner controls the planning task and the success depends on the ability to identify similarity of a new part to an old part, for which a plan already exists. The use of this technique and computer tools leads to shorter process planning time and lower costs. Variant process planning is, however, inadequate in the context of automated process planning. Template process plans are rather too general, and quality of the process plans largely depends on the skills and experience of the process planner. For parts that do not match the existing families templates, process plans must be prepared manually, from scratch. One of the drawbacks of variant CAPP tools is that they are equipped only with general manufacturing knowledge. Key parameters in the selection of set-ups such as surface quality and tolerance cannot be retrieved from template process plans.

- Most of the present CAPP systems architectures do not support functional integration with other computer-based systems used in product development.
- Most process planning research focus on metal cutting processes. Very little has been done on other manufacturing processes.

Table 1:Process planning functions

Function	Description
Process selection	Literature (see e.g. Kristensen and Lenau (1993); Maragy (1995); Merhar et al. (1994); Esawi (1994); Kiritsis (1995); Tichem (1997)), indicate that process selection is performed based on shape information, material, tolerances, fits, surface quality, time-to-market, production rate and batch or order size. It involves investigation of the relationships between the design characteristics and the available manufacturing resources, the goal being to produce the part according to its design. In most cases a part is manufactured in a number of operations or chain of processes, which Faris and Knight (1992), and Esawi (1994) categorized as primary, secondary and tertiary processes. Primary processes are the basic shapes giving processes (e.g. casting, powder metallurgy etc.) while secondary processes are final shape-giving operations such as turning, drilling and milling. Tertiary processes are essentially finishing processes such as surface and heat treatment.
Machining operations and fixture selection	The selection of machining operations to produce a given profile or surface is made based on rules following geometric, surface quality and tolerance consideration. Grouping of operation is also performed based on features, technological criteria (such as tolerance and surface roughness) and fixturing capabilities. A sound selection of fixtures leads to reduction of product costs (reduction of machining time) and assists in achieving the desired accuracies (i.e. tolerance, fits and surface quality).
Sequencing of operations	The order in which a series of manufacturing operations should be executed is an important decision that the process planner has to make. Sequencing of operations ensures precedence relationships, which are determined by technological and geometric considerations. A proper operations sequence avoids geometric complications in manufacturing of product, and reduces manufacturing costs.
Machine tools selection	The process planner considers machine specifications such as the drive capacity (e.g. available power, pressure, etc.) and dimensional capacity of the machines (e.g. swing and center to center distances for lathe machine, maximum stroke, etc.) in making decisions on which machine tool to use. In most existing software tools, analytical and AI techniques are used, and information required and experience of the process planner is built into the computing system.
Tool selection	Tool selection in process planning is made based on the constraints on either tool or machine tool. When constrains on the tool are used, all tools in the shop floor can be candidates for tool selection. Only the technical and logistic constraints are considered (Boogert, 1994). Examples of technical constraints include power requirement, work holding, chip-breaking, work piece deflection, detection of tool failure, tool breakage and tool wear. The advantage here is that many tools are considered (instead of standard tools only). However, this approach is expensive, as it requires that every kind of tool must be available in stock. Machine tool constrained tool selection is based on a choice of the right tools from a fixed standard tool set designed for specific machine tools (Boogert, 1994). This approach requires up-to-date information with respect to the storage, allocation and availability of tooling. The use of standard tooling (i) ensures availability of the selected tools before the job starts; (ii) lowers tooling costs, as it is based on tool standardization; and reduces tool preparation time and consequently avoids production delays. The draw back of this approach is that non-standard tools are overlooked. Several tool selection prototype and commercial software tools (e.g. EXCAP by Wright et al. (1987); PRICAPP by Pande and Walvekar (1990); KAPPS by Nau and Luce (1987); MICROPLAN by Phillips et al. (1987)), based on either analytical, AI or combination of the two techniques, are available.
Determination of machining conditions	Techniques used in optimization of machining conditions take into the consideration technological and economic criteria. Economic algorithms are used to optimize machining conditions in order to minimize machining costs and time. Typical technical considerations include process know-how, tooling technology, machining data, material properties and machine tools capacity. In generative processes such as turning and milling, procedures for selection of optimum number of passes are available while in non-generative processes such as extrusion and deep drawing, process simulation systems are used in determination of steps required.
Determination of processing time and costs	Processing time and costs are among criteria used in choosing a process plan to use among several alternative process plans. These criteria are also important in other decision-making processes (e.g. in choosing an alternative machine tool to use in case of unexpected machine breakdown) and in scheduling manufacturing activities.
Generation of NC program	Most CAD/CAM systems comprise software tools that process planners or machine operators can use to generate NC programs interactively. A CAD model is the starting point in the process of generation of tool paths. The generated tool paths can be verified and edited (i.e. check for collision, new data added, or modified) as required.

Tool Management

Tool management is one of the key activities that support other the product development process such as design, process planning, purchase, production planning, shop floor control, and manufacturing. According to Boogert (1994), tool management helps to minimize disturbances in the progress of the production process, improves utilization of tooling resources, minimizes numbers of rejects and reduces the overall tooling costs through standardization and rationalizations. It deals with technical, logistic and strategic aspects with respect to the usage of tooling resources. Technical aspects of tool management involve activities such as selection of tools, jigs and fixtures; and ensure usage of right tools and machining conditions. The logistic aspects of tool management ensure the availability of tooling resources at the right place and in the planned time. The key issue in logistic planning is preparation and storage of physical tooling resources (i.e. tools, holders and assemblies) and also their information. Most of the existing computerized tool management systems can be regarded as databases, and are primarily used for handling tooling information. One of the deficiencies of the existing computer based tool management systems is that they are typically used in isolation as storage and retrieval systems. Data cannot be transferred to other software tools, for instance, to CAD/CAM systems.

Information Transfer and Sharing

As all product designs are ultimately destined for manufacturing, transfer of information between design and manufacturing is a critical productivity consideration. Geometric entities such as arcs, circles, curves and splines are typically represented in an incompatible form in various CAD/CAM systems, which often use different mathematical representation techniques. The incompatibilities among entity representations greatly complicate the exchange of data among CAD/CAM systems. The data exchange problem is complicated even further by the complexity of CAD/CAM systems, varying information requirements in organizations and the rapid pace of technological change. The approaches used to tackle the problem of CAD/CAM data exchange include the use of neutral file formats, common database and direct conversion programs.

A solution provided by the method of transferring data via a neutral file format is to construct an 'international' second language (called neutral format) so that CAD and CAM systems exchange data via it. The widely used neutral file formats include Initial Graphics Exchange Specification (IGES)[11] and Standard for the Exchange of Product Model (STEP)[12]. Other known standards are DXF and CALS (see e.g. McMahon and Browne (1998); Lee (1999)). With such standards, entities such as lines, arcs, circles and curves can be transferred.

Database is the central element in the implementation of integration through a common database in which product data is stored in a universal and neutral way. The database acts as a reference source and a controlling element for functions in an integrated computer supported engineering system. Single common databases provide substantial reduction in human error and significantly shorten time required when looking for product's information. The main obstacle, however, is tediousness and subjectivity of the representation and interpretation of data generated by CAD/CAM systems. Engineering components are typically defined by low-level information such as points, lines, curves, surfaces and primitive solids. Such component definition is generally not of great

[11] IGES is one of the most widely used formats for data exchange, particularly in the transfer of data from CAD-to-CAD system. IGES graphic standards were essentially designed for use in transfer of geometric data between CAD-to-CAD system rather than CAD-to-CAPP/CAM system (Gulesin, 1996).

[12] STEP is a neutral graphics standard used in representing both geometric and technological data (Gulesin, 1996). Recent developments have involved incorporation of feature definition techniques, which has made STEP even more universal. Typical engineering part information that can be represented using STEP includes geometry, topology, form features, tolerances and material (Smith (1990); Dong and Wozny (1990)). STEP supports exchange of data between different systems, e.g. CAD-to-CAD systems and CAD-to-CAM systems.

use in the subsequent CAPP/CAM system, which requires manufacturing features (e.g. holes, slots, pockets and bosses) as well as information on e.g. tolerances, surface finishes and hardness requirements (Gulesin, 1996). As for direct translators, these are dedicated translation programs (written by users or computer service companies that specialize in CAD/CAM database conversion), which link a system pair. Often two translators are needed to transfer data between two systems. This method is suitable for a dedicated set of applications pair and is inadequate for commercial information transfer and sharing.

REQUIREMENTS FOR TODAY'S PRODUCT DEVELOPMENT PROCESSES AND NEW CONSIDERATIONS

Based on the current state of product development practice presented in the previous Section, it is proposed that the following issues be addressed:

- A thought should be given to the present changes in the market place such as an increase of demand of variant products, need for shorter innovation cycles and increased need for quality products.
- Product development research should be placed in the context of the emerging concepts, methods and technologies such as collaborative engineering, global product development and feature technology.
- Computer based methods should imitate the practice that people follow during the product development and production process. For example, in the context of intelligent product development, it would be advantageous to explore and emulate the superior human's intelligence, expertise and ability into the software tools used. Software applications must be flexible and adaptable to the company's environment (i.e. products, procedures and practices) and should provide an opportunity for adjustment to suit planning scenarios and managerial goals.
- There is a need for a comprehensive and transparent data structure that will take into account the overall needs of the product development process. Product information must be available at the right time for each process, e.g. designers and manufacturing personnel should be provided with proper information. Also, there should be a possibility to generate and transfer information produced, e.g., by a CAD system to software tools used in the upstream processes. In addition, the departments in the firm should be provided with information (e.g., on manufacturing resources (i.e. tooling and production machines), human resources, suppliers and customers) in an appropriate format.
- Consideration should be placed in achieving the basic technical requirements such as dimensions, material, tolerances, surface roughness, flatness, perpendicularity, parallelism and circularity as specified in designs, while keeping costs lower in the entire product development interval.
- There is a need for various departments of a manufacturing firm to work as a team. For instance, a production engineer should at any time be able to work as a designer and vice versa; engineers of different disciplines should work together and understand each other's activities, etc. Such interactions can be very beneficial as the designers would be acquainted to manufacturing knowledge, which is also essential input in their traditional tasks. Also, activities such as design should be performed cooperatively in teams consisting of members representing various product development disciplines.
- A software tool supporting any product development activity must be part of firm's integrated information and communication system. Absence of integration typically leads to higher product development costs and may seriously impede the efforts towards early product delivery.

Table 2: Proposed semi-autonomous phases of process planning

Name	**Activities**	**Supported product development processes**
Global Product Planning (Global-PP)	Identification of manufacturing processes given details of the order.	Feasibility analysis; global decision-making.
Conceptual Process Planning (Conceptual-PP)	Preliminary identification of production resources and cost estimation.	Conceptual and detail design
Macro Process Planning (Macro-PP)	Selection of set-ups, i.e. machining operations, grouping of operations, sequencing of machining operations.	Manufacturing
Micro Process Planning (Micro-PP)	Planning within one set-up, i.e. selection/design of fixtures, tools, machining conditions/machining data, calculation of machining time and costs, selection of clamping forces and document generation.	Manufacturing
NC Programming	Generation of NC program and simulation.	Manufacturing
Fine-tuning and preparation of manufacturing resources	Fine-tuning of the process plan (i.e. a final quick check of the process planning document by an experienced process planner) and preparation of the production machines, including checking if the machines are acceptance tests compiant.	Manufacturing; assembly

- Rework cycles in the product development process should be avoided or kept minimal. One of the possibilities to achieve this is to create two-way information and communication support tools. For example, software that can assists designers to make manufacturing related design decisions early on would substantially reduce design iterations.
- Software tools used in the product development process should address the iterative nature of the design process, e.g. should provide feedback data and in real time.
- Considerations should be given to the new trends and practices in design and manufacturing such as outsourcing, in which suppliers are becoming key players at some stages of the product development process, for instance during process planning.

In the following sub section, a phased procedure for execution of process planning activities is introduced. The idea is to ensure that the process planning functions are conducted timely in order to adequately support other product development activities within the concepts such as integrated product development and collaborative engineering.

New Process Planning Procedure

Table 2 outlines the proposed semi-autonomous phases of process planning. Global process planning (Global-PP) is intended to support decision-making process in the initial stages of the product development process by furnishing the decision makers with manufacturing knowledge. Conceptual process planning (Conceptual-PP) on the other hand supports product designers. In these two phases, process planning is conducted preliminarily, based on uncertain product definition (i.e. based on information on e.g. customer requirements, technical specifications and working principles). Manufacturing processes and manufacturing resources (i.e. machines, tools and fixtures) are identified. These are vital to the designers and to the decision makers in the early stages of the product development process. Macro process planning (Macro-PP) and Micro process planning (Micro-PP) detail the set-up and planning within one set-up respectively, based on the previously identified process and manufacturing resources. NC program is subsequently prepared. In fine-tuning and preparation of manufacturing resources, humans (i.e. experienced process planner, machine operator and quality assurance personnel) assess the process plans and manufacturing resources. This new approach brings the following advantages:

- It adequately supports the initial decision making process as well as the design process. Global-PP supports decision making on whether or not to accept an order early on, in the beginning of the product development process. This avoids the possibility of proceeding shortsightedly with jobs without knowing, e.g. if or if not they can in fact be accomplished. Conceptual-PP on the other hand furnishes the designer with manufacturing information needed during the design process. These phases have in principle been created as an attempt to facilitate thorough assessment of the manufacturability of job orders and design proposals early on.
- Increases flexibility. In this approach, micro process planning activities have been shifted closer to manufacturing. This allows more autonomy for the initial process planning activities (i.e. global, conceptual and macro-process planning activities). On the other hand, with modern machining centers and CNC machines (which have sophisticated controllers and powerful CPU and programming capability), NC programming can be performed even at the machine shop.
- This approach reduces rework cycles. For example, the designers are provided with manufacturability data early on, which allows them to know and accommodate manufacturability constraints early on. This leads to reduction of the design iterations arising from lack of manufacturability information.
- Phased process planning procedure facilitates portability of process planning knowledge among different departments of a manufacturing organization.

Integrating the New Process Planning Procedure into the Product Development Process

Figure 1 shows how the new process planning procedure is incorporated into the product development process. The sources of information for this product development process architecture include not only the organization's databases and knowledge bases, but also include external information sources such as the Internet[13] and CD-ROMs[14]. The organization's databases and knowledge bases consists of a wide range of information, e.g. on engineering product development technology and rules, manufacturing resources (e.g. technical specifications and availability of production machines, tools, jigs and fixtures), humans resources, products, orders (including previous orders) suppliers and customers. The advent and progress of web-based tools is beneficial to product development. Today, Internet contains an increasingly expanding spectrum of product development information sources and is also an important communication means.

[13] The Internet serves as a major source of information. Typical product development information available on the worldwide web sites includes data on materials and suppliers. Such information is usually provided by educational and research institutions, manufacturers, suppliers, professional societies, standards organizations and trade associations. Also, the Internet provides means of communication between company and the customer; product development teams and suppliers; and between the enterprise and the world. It is thus an important consideration in the implementation of concepts such as global manufacturing, integrated product design, and collaborative engineering; and a valuable support tool for activities such as requirements engineering, design and marketing of products and services.

[14] CD-ROMs are available for some dedicated subject areas and they contain specialist information about a relatively narrow range of entities. They may contain large quantity of data that can be very detailed and of high precision. The information may be in the form of text, graphs, tables, photographs, video clips or computer programs.

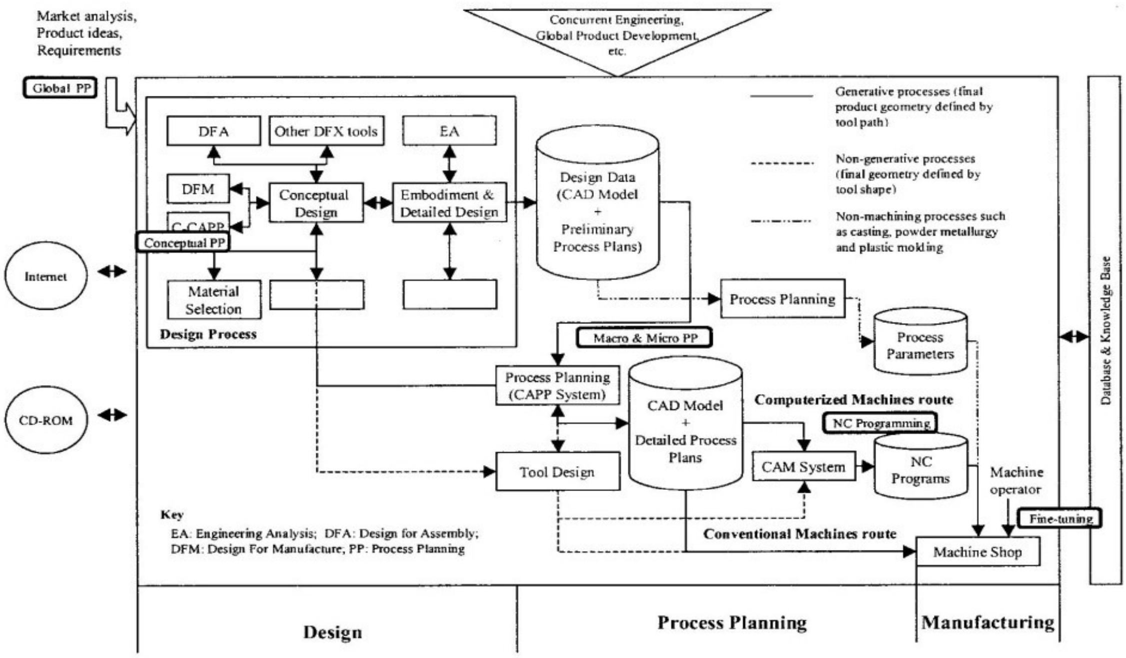

Figure 1: Interfacing the new process planning procedure with product development process

DISCUSSION

Product development and production is a multi-task process, which involves a wide spectrum of concepts, methods and technologies. It is characterized by a continuous change of market demands and frequent changes of technologies. The ultimate goal of the product developer is to produce products that comply with technical specifications and quality requirements at the lowest possible cost. Significant research progress has been made as an attempt to meet new needs in the manufacturing industry and in the markets. Currently, there are numerous research programmes focusing on the development of new concepts, methods and technologies, and a lot have been achieved.

Today, many methods, techniques and software concepts are available commercially or as prototypes. In some cases, even the nomenclature that implies the same concept, method or technology is very diverse. In fact, even recent developments such as the evolution of concurrent engineering, collaborative engineering and human centered engineering concepts; new practices such as global product development and outsourcing; and research developments in intelligent manufacturing and introduction of modern CNC machines equipped with large memory space, powerful CPU and higher programming capability call for new concepts, methods and technologies.

Due to the present state of influx of concepts, methods and technologies, the selection of a concept, method or technology to use in a particular task has emerged as a new issue of concern. Wrong choice of a concept, a method or a technology may become very costly, e.g. can result into costly process of developing products or even in disruption of the product development process. The key issues in the form of actions to be taken and factors to be considered when selecting a concept, a method or a technology include establishment of formal selection criteria and thorough examination of the available concepts, methods or technologies. Manufacturing industries should analyze their specific needs, devise selection criteria and draw-up appropriate requirements in order to make sensible choices. A number of issues should be considered in the selection process, including the steady changes in related technologies.

As far as data management and communication in the product development process is concerned, it can be said that availability of right, reliable and objective product information in all phases of the product development process is currently a major obstacle. Some product data e.g. key product characteristics such tolerance and surface quality are typically available in an unusable format. It is also difficult to utilize directly e.g. design data in upstream phases. A comprehensive information system (e.g. with a two-way communication capability) can reduce the number of rework cycles and the product development time, and can also provide interface between various product development activities.

Process planning is seen as a strategic activity in linking design and manufacturing, and in supporting the up-stream product development activities such as design and feasibility analysis. The notion of phased process planning introduced in this paper can be regarded as a contribution towards putting concepts such as collaborative engineering and integrated product development into practice. With the decentralization scheme introduced in this paper, process planning activities such as process selection and identification of manufacturing resources (i.e. machine tools, tools and fixtures) would be performed in the early stages of the product development process while set-up and detailed process planning would be deferred, and some activities conducted even just before manufacturing. In this way, the designer will be furnished with the required manufacturing information, and would therefore be able to make reliable designs quickly. Also, by shifting micro-process planning activities nearer to manufacturing, more flexibility would be introduced into the product development process. The availability of CNC machine tools equipped with powerful CPU and programming capability makes it possible for NC programming to be performed even on the machine tool.

CONCLUSION

A critical evaluation of the product development process has been presented. While improvement of performance in the product development process due to recent advancements of technologies is obvious, there are however many research challenges that need to be overcome. These include the challenges posed by lack of true two-way data transfer between pairs of life cycle activities, and lack of adequate architectures and information system to support concepts such as integrated product development. As an attempt to partly support integrated product development, a new way of execution of process planning activities has been proposed in this paper. It ensures availability of manufacturability information early on, and therefore reduces the number of rework cycles in the early phases of the product development process. The ongoing research focuses on industrial case studies on the application of the new process planning procedure.

ACKNOWLEDGEMENT

This research was supported in part by Jan Tinbergen Scholarship Program.

REFERENCES

1. Andreasen, *M. M., Hein, L.,* Integrated Product Development, IFS Publications, Ltd/Springer-verlag, Bedford, UK. 1987.
2. Andreasen, M. M., *Designing on a Designers Workbench DWB*, 9th WDK Workshop, Rigi, 1992.
3. Bezier, P., *Definition numerique des courbes et des surfaces*, Automatisme, Vol. 11 pp. 625-632, 1966.
4. Blessing, L. T. M., *A Process-Based Approach to Computer-Supported Engineering Design*, Ph.D. Thesis, University of Twente, Enschede, Netherlands,1994.
5. Boogert, R. M., *Tool Management in Computer Aided Process Planning*, Ph.D. Thesis, University of Twente, Enschede, Netherlands,1994.
6. Chang, T. C., *Expert Process Planning for Manufacturing*, Addison-Wesley, 1990.

7. Dong, X., Wozny, M. J. *Managing Feature Type Dependence in a Feature Based Modeling System*, Proc. of ASME, International Computers in Engineering Conf., Boston, MA. pp. 125-130, 1990.

8. El Maraghy, H. A., *Evolution and Future Perspectives of CAPP*, Annals of the CIRP, Vol. 42 No. 2, pp. 739 – 751, 1993.

9. Erens, F. J., *The Synthesis of Variety*, Ph.D. Thesis, Eindhoven University of Technology, Eindhoven, Netherlands, 1996.

10. Esawi, A. M. K., *Systematic Process Selection in Mechanical Design*, Ph.D. Thesis, Cambridge University, Cambridge, United Kingdom, 1994.

11. Evbuomwan, N. F. O., Sivaloganathan, S., Jebb, A., *A Survey of Design Philosophies, Models, Methods and Systems*, Imech 1996, Proc. of the Institution of Mechanical Engineers, Vol. 210, 1996.

12. Farris J., Knight, W. A., *Design for Manufacture: Expert processing sequence selection for early product design*, Annals of the CIRP, Vol. 41 No. 1, pp. 481-484, 1992.

13. Finger, S., Dixon, J. R., *A Review of Research in Mechanical Engineering Design. Part I: Descriptive, prescriptive and Computer-based models of design processes*, Journal of Research in Engineering Design, Vol. 1 No. 1, pp 51-67, 1989.

14. Gulesin, M., *Finished Part Modeling in Computer Aided Process Planning System*, Journal of Intelligent Manufacturing, Vol. 7, pp 251-256, 1996.

15. Halevi, G., Weill R., *An Algorithm to Determine Number of Cuts in Machining Operations*, Manufacturing Systems Journal, Vol. 17, No 2, pp 105-133, 1988.

16. Houten, F. J. A. M. van, *PART: A Computer Aided Process Planning System*, Ph.D. Thesis, University of Twente, Enschede, Netherlands, 1991.

17. Jasperse, H. B., *A Macro Process Planning System for Machining Operations,* PhD Thesis, Delft University of Technology, Netherlands,1995.

18. Joshi S., Chang, T. C., *Graph Based Heuristics for Recognition of Machined Features from a 3D Solid Model*, International Computer Aided Design, Vol. 20, No. 2, pp. 58-66, 1988.

19. Juri, A. H., Saia, A., De Pennington, A., *Reasoning about Machining Operations using Feature-based Models*, International Journal of Production Research, Vol. 28 No. 1, pp 153-171, 1990.

20. Kiritsis, D., *A Review of Knowledge Based Expert System for Process Planning: Methods and Problems*, International Journal of Advanced Manufacturing Technology, Vol. 10 No. 5. pp 240-259, 1995.

21. Kristensen, L., Lenau, T., *MADED - An Information System for Manufacturing Processes*, Proc. of the 9th International Conf. on Engineering Design ICED93, Edition Heurista, Zurich, pp. 1093-1096, 1993.

22. Lee, K., *Principles of CAD/CAM/CAE Systems*, Addison-Wesley, 1999.

23. Maropoulos, P. G, *Review of Research in Tooling Technology and Process Planning Part I: Process Planning*, Computer Integrated Manufacturing Systems Journal, Vol. 8. No. 1, pp 13-20, 1995.

24. McMahon, C., Browne, J., *CAD/CAM: Principles, Practice and Manufacturing Management*, Addison-Wesley, 1998.

25. Merhar, C., Chong, C., Ishii, K., *Simultaneous Design for Manufacturing Process Selection of Engineering Plastics*, International Journal of Materials and Product Technology Vol. 9 1/2/3, pp. 61-78, 1994.

26. Nau, D.S., Luce, M., *Knowledge Representation and Reasoning Techniques for Process Planning: Extending SIPS to do Tool Selection*, 19th CIRP International Seminar on Manufacturing Systems, Penn State, pp 1-98, 1987.

27. Opiyo, E. Z., *Development of a Hybrid*

System for Product Development and Production - With a New Process Planning Procedure, Research Report, Vakgroep Ontwerp en Produktie, Sub-Faculty of Mechanical Engineering and Marine Technology, Delft University of Technology, Netherlands, 1998.

28. Pahl G., Beitz, W., *Design Konstruktionslehre - Methoden und Anwendug*, 3rd Edition, Springer-Verlag, Berlin, 1993.

29. Pande, S. S., Walvekar, M. G., PRICAPP: *A Computer Assisted Process Planning System for Prismatic Components,* International Journal of Production Research, Vol. 28 No. 2, pp. 279-292, 1990.

30. Phillips, R., Arunthavanathan, V., Shou, X. D., *An Integrated Intelligent Design and Process Planning System*, 19th CIRP International Seminar on Manufacturing Systems, Penn State, pp 17-22, 1987.

31. Roozenburg, N. F. M., Eekels, T. Product *Design: Fundamentals and Methods*, Wiley Series on Production Development: Planning, Designing, Engineering, John Wiley & Sons, 1995.

32. Ruland, D., Spindler, T., *Integration of Product and Design Data using Metadata - and a Rule Based Approach*, Computer Integrated Manufacturing Systems Journal, Vol. 8. No.3, pp 211-221, 1995.

33. Eder W. E, *Theory of Technical Systems – An Important Teaching Tool for life Cycle Engineering,* Proc. of the 5th Tool and Methods for Competitive Engineering TMCE Conf., April 12-17, Lausanne, Switzerland, Vol. 2 pp 1173-1174, 2004.

34. Smith, P., *Product Data Exchange:PDES Project Status and Objectives,* NISTIR 89-4165, US Department of Commerce, National Institute of Standards and Technology, pp. 1-9, 1990.

35. Suh, N. P., *Axiomatic Design of Mechanical Systems*, Transaction of the ASME, A Special Combined Issue of the Journal of Mechanical Design and the Journal of Vibration and Acoustics 117: 2-10, 1995.

36. Teicholz, E., Orr, J. N., *Computer Integrated Manufacturing Handbook* McGraw Hill International Editors, 1987.

37. Tichem, M., *A Design Coordination Approach to Design for X*, Ph.D. Thesis, Delft University of Technology, Netherlands, 1997.

38. TNO, Netherlands Organization for Applied Scientific Research - *Annual Report* - 1996.

39. Vin, L. J. de, Computer Aided Process Planning of the Bending of Sheet Metal Components, *Ph.D. Thesis,* University of Twente, Enschede, Netherlands1994.

40. Warwick, K., Gray, J., Roberts, D., *Virtual Reality in Engineering,* The Institution of Electrical Engineers, London, UK, 1993.

41. Wright, A.J., Darbyshire, I. L., Park. M. W., Davis, B. J., *EXCAP and ICAP: Knowledge Based Systems for Process Planning Components*, 19th CIRP International Seminar on Manufacturing Systems, Penn State, pp. 309-313, 1987.

42. Zeid, I., *CAD/CAM Theory and Practice,* McGraw-Hill Series in Mechanical Engineering McGraw-Hill Publishing Company, 1991.

43. Zhao, Z., *Process Planning with Multi-level Fuzzy Decision Making*, Computer Integrated Manufacturing Systems Journal, Vol. 8. No.4, pp. 245-254, 1995.