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Digital enterprise technology—defining perspectives and research priorities

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Abstract. The majority of research and commercial efforts in computer-based methods for design and manufacture relate to applications in Computer Aided Design (CAD), whilst research in Computer-Automated Process Planning (CAPP) has substantially enriched the design knowledge domain with concepts that originated in the manufacturing domain. The development of isolated computer applications was recognized as a potential problem, leading to the definition of the Computer Integrated Manufacturing (CIM) concept, seeking to achieve the local integration of systems. The introduction and development of the internet have since provided a decisive advancement in the communications infrastructure. We can now capitalize on recent advances in computer graphic visualization and distributed information management systems, in order to positively impact product development and realization and to develop objective risk mitigation strategies on a global basis. In this context, Digital Enterprise Technology (DET) can be defined as 'the collection of systems and methods for the digital modelling of the global product development and realization process, in the context of lifecycle management'. This paper introduces the concept of DET and reviews the status of the design and manufacturing planning integration that is fundamental for the definition and development of DET methods and systems.

1. Introduction

Major elements of competitiveness for the manufacturing industry are methods for rapid product and process realization, early integration of design with manufacturing operations and the technical integration of the supply chain (Maropoulos 1995a, 2002a, 2002b). In order for such integration efforts to be effective, they should be focused on the early stages of product development, where the majority of product lifecycle cost is decided (Boothroyd *et al.* 1994). The question of dealing with the communication and coordination of the 'various islands' of computer automation is not new, with initial efforts carried out under the Computer Integrated Manufacturing (CIM) umbrella (Maropoulos 1999, Rembold *et al.* 1993). Such systems have largely served as technology demonstrators for large corporations, as their industrial implementation was inhibited by their high complexity, high cost and lack of infrastructure support. Consequently, effective integration methods for the various product and process development phases are not available at present, particularly for complex products, resulting in lengthy product development periods, uncompetitive manufacturing operations and increased lifecycle costs (Bedworth *et al.* 1991). The global trend for reduced product lifecycle and increased product variety places additional strain on the integration of design with distributed manufacturing operations.

Concurrent Engineering (CE) systems aim to achieve the parallel development of the product and of the manufacturing processes (Sohlenius 1992). The traditional objective for CE was the reduction of the 'time to market' through a simultaneous approach to product and process design (Sohlenius 1992, Pham and Dimov 1998), the two main activities required to realize a product. Successful early planning implementations have been reported using decomposition of CAD models into critical areas (Krause *et al.* 1997). A key technology for CE is 'computer automated process planning' (CAPP), allowing the selection of production methods based upon process capability and production economics through the automatic interpretation of design data (Alting and Zhang 1989). The current generation prototype and commercial CAPP systems use design and manufacturing features from solid models to generate tool paths and perform tool selection for NC applications (Salomons *et al.* 1993). The level of detail required before CAPP systems can run their 'micro planning' algorithms is relatively high, as the product model must usually be fully specified in

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terms of geometry, dimensioning and tolerancing (GD&T), materials and production volumes. These requirements make current CAPP systems rather unsuitable for use at the conceptual and embodiment design stages, which are critical for life-cycle cost control.

Design for specific goals (DFX) methods are also usefully employed to improve manufacturing realization, such as assembly and disassembly (Boothroyd and Alting 1992), within the product life cycle (Jovane *et al.* 1993). Design for manufacture (DFM) and assembly (DFA) methods have long been recognized as critical to concurrent engineering strategy, promoting the manufacturability assessment of discrete parts and fabrications, the reduction of part-count of assemblies (Boothroyd and Alting 1992, Boothroyd *et al.* 1994) and the calculation of assembly times using motion studies and algorithms. Currently, DFM/DFA methods are not well integrated with design tools, although research is underway to develop computer tools that link design characteristics to assembly process models (Laguda and Maropoulos 1999). It has also been argued that DFA does not provide sufficient feedback on design cost or resource availability (Liebers and Kals 1997). Although the principles of CE are sound, the natural cycle of design means that, paradoxically, process planning, which has a significant impact upon life-cycle cost, cannot take place until the majority of design specifications have been decided upon (Yao *et al.* 1998a). It is also recognized that, in DFM, most effort is concentrated on the application of methodologies rather than the synthesis of process models (Lenau 1996). It is important to overcome the incompatibilities in data granularity between conceptual design and process planning through the use of process models that can function using partial design information. This will result in integrated product and process development and producibility analysis, which are recognized as the most significant elements for achieving manufacturing responsiveness in the aerospace industry (Gindy 1999).

The specification and realization of 'intelligent and resource aware' distributed enterprises require substantial development of the underpinning modelling, information management (Lutters *et al.* 2001) and knowledge retrieval, representation and classification technologies (Thannhuber *et al.* 2001, Bramall *et al.* 2001). This is a very large, and still largely ill-defined technical area and, as such, it is a fertile domain for the application of 'emergent synthesis methodologies' (Ueda *et al.* 2001), in order to consolidate recent advances in life-cycle management and distributed, cooperative systems that employ virtual and augmented reality technologies (Lu *et al.* 1999). This paper deals with the definition of the 'digital enterprise technology' (DET) concept and the detailing of key functionality of the main cornerstones of DET. The DET functionality is put into context by analysing industrial needs and identifying research priorities.

2. Industrial trends and requirements

Industry is undergoing a rapid transformation internationally, characterized by the liberalization of global markets, increased mobility of people and capital and the constant requirement for exploiting the enabling capability of the internet to rapidly add value to products and services. Increased competition has also led to the gradual consolidation of sectors as companies adopt corporate alliances and mergers in order to manage their spiralling R&D and marketing costs across different markets. Currently, the defence and aerospace sectors are largely consolidated on both sides of the Atlantic and the same is true for the automotive, pharmaceuticals and chemicals industries.

Globalization and enterprise consolidation amplify the effects of socio-economic events and market requirements in industries and economies of the industrialized world, in much more direct and immediate ways than previously. These conditions create the need for:

- Highly agile and innovative corporations that can seize and exploit market opportunities, worldwide.
- Effective management of corporate revenue streams across major technology development phases.
- Formation of dynamic supply networks and development of flexible manufacturing capabilities within the extended enterprise, based on the sound management of the product's life cycle.

2.1. *Requirements per industry sector*

It is now widely accepted that industry is changing via the integration of services throughout the life cycle of products and the enabling capability of the internet. A large proportion of manufacturing industries can be classified into the following four generic categories (Maropoulos 2002a), whose characteristics and requirements are shown in table 1.

Category 1. *High value/complexity product integrators.* This category includes large and complex products that have high value-added, are highly customizable and can be

Table 1. Key industrial characteristics and technology requirements, adapted from Maropoulos (2002a).

Key industrial characteristics	Category 1	Category 2	Category 3	Category 4
Importance of product & service customisation	Critical Business Requirement	Average/low, but Increasing	Average/low, but increasing	Applicable to 'niche' products
Mass customisation–manufacture in a unit of one	Usual & Critical Requirement	Long-term need	Long-term target for automotive Usual for precision components	Applicable to niche items, in the longer-term
Life cycle	Short (in relation to complexity)	Average and reducing	Average and reducing	Short and reducing
Importance of life-cycle management	Critical Business Requirement	High, but not well understood	Very high for automotive Lower for precision components	High for niche products Low for commodity items
Capability of a typical supply chain	Usually limited both in terms of logistics and technology	Limited in terms of technology, Below average logistics	Critical Business Requirement, Well developed for Automotive	Limited in terms of technology, Average logistics
Potential for high added-value manufacture	Very High	High to Average	Average to Low	Low to Very Low
Technology requirements				
Importance of early manufacturability (QCD) evaluation of designs	Critical for risk mitigation of design options at distributed sites	Very high for process and routing evaluation and make-or-buy	Very high for process and logistics optimization	High for factory line design and optimization
Importance of early evaluation of advanced manufacturing technology	Very high, for the introduction of flexible automation and laser metrology for 'module' production	Very high, for the introduction of robotic automation for fabrication and assembly, with integrated process measurement	Critical Business Requirement for Automotive Very high benefits for high precision	High for flexible cells for niche parts and high volume flow lines for mass produced items
Importance of '3D digital manufacturing & assembly' modelling and analysis	Critical for the improvement of key assembly and fabrication processes	Very high, for the improvement of key processes and factory/ cell design	Very high, for the optimization of processes & lines/cells	Average to high, for optimal manufacturing system/cell design
Importance of early supply chain design and evaluation	Critical for the control of inventory, process quality, and the reduction in design and production lead times	High for the control of inventory and increased system responsiveness	Very high for logistics optimization and cost control Benefits will increase with higher customization	High, for niche customisable items Lower for mass produced commodities

produced at a unit of one. Typical examples include satellites, aerospace, shipbuilding and offshore platforms for the oil and gas industry.

Category 2. *Smaller scale, heavy engineering products.* This category includes smaller scale engineering products that are manufactured at higher volumes, including heavy engineering defence products, land transport systems, articulated trucks and excavators.

Category 3. *Automotive and high precision products.* This category includes high precision products and components for defence and aerospace applications as well as the automotive industry, which has introduced several benchmark practices in terms of industrialization.

Category 4. *Lower complexity/higher volume products and electronics.* This category includes manufacturers of home appliances, mass-produced lightweight products for domestic or industrial use and electronic components manufacture.

From table 1 it is clear that the conditions of Category 1 are predicted to become gradually the de-facto prevailing conditions across most future manufacturing sectors with key characteristics being; unit of one, high customization, life-cycle-based manufacture.

3. The theoretical cornerstones of DET

Industry and research organizations can now capitalize on recent advances in computer modelling, graphic visualization and distributed information management, in order to positively impact product development and realization and to develop objective risk mitigation strategies on a global basis.

DET can be defined as 'the collection of systems and methods for the digital modelling of the global product development and realization process, in the context of life-cycle management'. DET is implemented by the synthesis of technologies and systems from five main technical areas, the DET 'cornerstones', corresponding

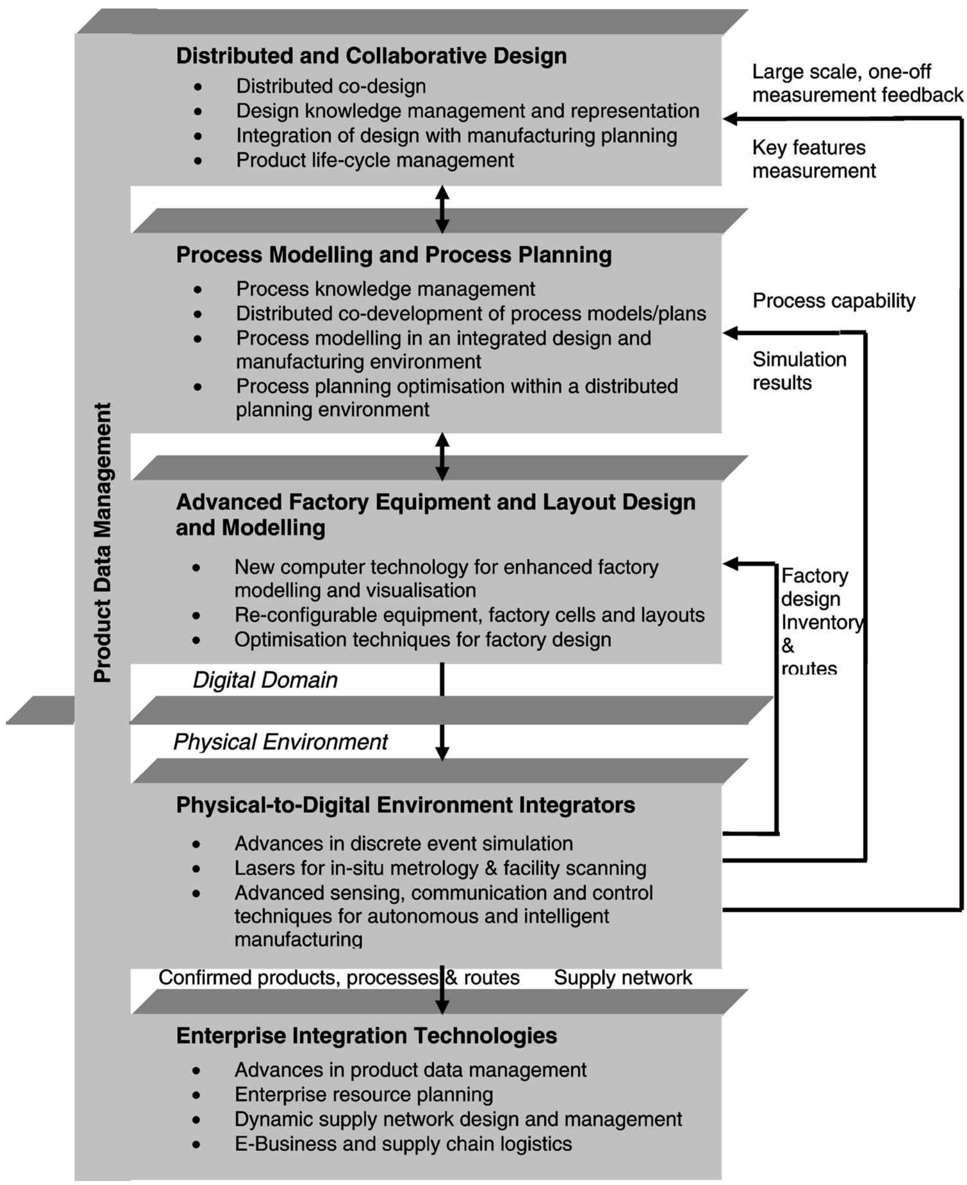

Figure 1. The five cornerstones of Digital Enterprise Technology (DET).

to the design of product, process, factory, technologies for ensuring the conformance of the digital with the real environment, and the design of the enterprise. Figure 1 shows the main theoretical elements of each one of the five cornerstones of DET and indicates the key feedback loops regarding the communication of results to distributed members of the product development and realization team.

The first three technical areas of DET can now be performed entirely in the digital domain, utilizing the enhanced graphics and computer processing technologies developed over the past five years as well as the communication infrastructure of the internet. The fourth category is of particular importance as it involves methods for the bi-directional integration of the digital and physical environments in order to achieve risk mitigation at product and system levels using shop-floor based metrology and discrete event simulation respectively. The fifth area of DET includes methods that are predominantly employed to manage physical resources when these have been released for manufacturing and as such are used when product realization has commenced. The fifth area also includes web-centric methods for product data management that are applicable from the very early stages of product development and span the five areas of DET.

DET has a flat, 'heterarchical structure', with functionality configured by the flexible, internet-based integration of data repositories, distributed systems and user sites, which reflect the particular product development and manufacture requirements. The internet is the backbone of DET, with standards for the communication and exchange of data being of primary importance, such as STEP and XML. The deployment of scalable and adjustable elements of DET can be configured to address the following industrial needs:

(a) Global product development and realization under increased (mass) customization and reduced product life-cycles.
(b) 'Life-cycle' product management and 'corporate agility' are key industrial requirements.
(c) The internet will revolutionize industry via e-manufacture and B2B applications.

The perceived industrial benefits from the industrial deployment of DET are:

(a) Minimization of risk in global product realization.
(b) Provision of analysis and computer support throughout the product's 'life cycle'
(c) Enabling 'digital manufacture and assembly' for complex products with short life cycles.
(d) Integrated feedback can be received by the digital environment regarding;
    - the status and programming of production machines,
    - the status of cells/plants, and
    - the capacity and logistics of the extended enterprise.
(e) High reconfigurability, to meet product complexity needs and production network characteristics.
(f) Low technology redundancy, as investment levels are linked to requirements and are distributed, facilitating renewal.

4. Discussion of key technical functions of DET

This section reviews the state-of-the-art functionality and development priorities of the main technical cornerstones of DET.

4.1. *Distributed and collaborative design*

Product design within a collaborative and distributed network is the first technical cornerstone of DET. Developments regarding the definition of product modelling methods have been continuous over the past 20 years, with feature-based methods forming the backbone of most formally defined models. The core product model of NIST is a generic (object-oriented and feature-based) method for representing a product in terms of its function, form, behaviour, material and physical properties (Fenves 2001). The core model is influenced by the 'entity-relationship' data model that consists of two main classes, objects and relationships, corresponding to the Unified Modelling Language's (UML's) terms of class and association class respectively. The core model can support design for tolerancing and integration with process planning by expanding its 'assembly relationship'. The aggregate product model (Yao *et al.* 1998b, Bradley and Maropoulos 1998, Yao *et al.* 2000a) is closely linked to the core model classes and has been specifically structured to support design and process planning activities from the early stages of product design. The drive for standards to support interoperability has led to the definition and continuous development of STEP that is updated to support assembly and fabrication representation.

New CAD systems are rapidly adopting features of 3D virtual reality environments for product definition and viewing, with associated geometric, dimensioning and tolerancing (GD&T) capabilities. The analysis and management of tolerances in complex assemblies and the rapid verification of dimensional conformance using flexible computer-aided metrology have been identified as core research activities in relation to designing complex products with a view to improving their ease of manufacture and assembly. Of great significance is also the development of a systematic design workflow process for exploiting the capabilities of emerging virtual design environments together with proprietary web-enabled product data management systems to assist in the specification of high quality products in a distributed and collaborative manner.

4.2. *Process modelling and process planning*

Process modelling and process planning research has substantially enriched the interface with the design environment with feature-based and object-oriented methods for manufacturing and assembly, enhancing interoperability with product modelling (Yao *et al.* 2000b). For the initial stages of product development, aggregate process models are defined to allow the early application of production considerations during product definition (Maropoulos 1995b). The formal definitions, 'semantics', of aggregate process models are formalized using UML, whilst XML methods are used for their syntax in order to ensure interoperability and communication within an internet-based environment. The essential principles for the definition of aggregate process models are as follows (Maropoulos 1995a).

- (i) Controlled simplification of detailed process models.
- (ii) Limited input data requirements.
- (iii) Utilize company-specific product and process knowledge.
- (iv) Perform core technological checks concerning processes.
- (v) Incorporate only the basic, overall geometry of parts and features.
- (vi) Function-driven operation.
- (vii) Conformance with standards.
- (viii) Conformance with the team-based approach to concurrent engineering.

The Process Specification Language (PSL) is at an advanced stage of development at NIST (Cutting-Decelle *et al.* 2000, Schlenoff 2000). The PSL project's goal is to create a standard language for process specification in order to integrate multiple process-related applications throughout their life cycle. PSL has recently been proposed as an international standard (ISO 18629). The PSL project is developing formal, common definitions, 'ontology' that are semantics to support interoperability by 'preserving the links' between process modelling, process planning and scheduling. Because of these explicit and unambiguous definitions, information exchange can be achieved without relying on hidden assumptions or subjective mappings. It must be stressed that PSL is not the only source of process semantics. Two other possible sources for semantics are UML and the Workflow Management Coalition's Workflow Reference Model. PSL semantics are represented using the Knowledge Interchange Format (KIF). KIF is a formal, declarative language developed for the exchange of knowledge among disparate computer programs (Genesereth and Fikes 1993). KIF can express arbitrary logical assertions and rules, and it allows for the representation of knowledge about knowledge (meta knowledge). Thus, KIF provides the level of rigour necessary to unambiguously define concepts, a necessary characteristic to exchange process information using the PSL ontology. Although PSL does not mandate a single syntax for exchanging process descriptions, the project proposes to standardize on an XML framework, as XML defines a well tested, widely used and extensible standard syntax for representing structured data.

Process models are the essential repositories of data and methods for performing process planning and the calculation of quality, cost and delivery (QCD) performance data. CAPP research resulted in a limited number of commercial applications for machining, sheet metal and assembly work. The development of CAPP lags considerably behind that of CAD, the main reasons being:

- (i) the complexity of the planning interactions within the factory and the extended enterprise,
- (ii) the difficulties created by the asynchronous planning and scheduling of production within a supply network,
- (iii) the large search spaces available for the implementation of most processes, resulting in sub-optimal routings, and
- (iv) the lack of consistent methods for incorporating measurement and simulation knowledge data and feedback into the process modelling and planning procedures.

In the domain of process modelling there is a rapid convergence of four major technologies;

(i) computer technologies for 3D solid modelling and graphic representation,
(ii) computational analysis mathematical models for stress, thermal and vibration analysis,
(iii) process modelling models for the analysis of the part and machine interaction and the derivation of process parameters, time and cost,
(iv) materials science for the fundamental study of processes at the atomic level.

These technologies will ensure that the process modelling research will remain at the interface of several scientific disciplines from materials science and metallurgy to nanotechnology and numerical, computational optimization methods.

4.3. *Advanced factory equipment and layout design and modelling*

Factory and equipment modelling and optimization technology have two main elements:

(i) 3D technology for production equipment modelling and representation and,
(ii) methods for factory modelling and optimization.

The rapid advances in 3D graphics modelling methods combined with the rapid development of fast computer processors have allowed the accurate modelling and visualization of complex production machines using detailed, 3D solid models, with associated kinematic and dynamic properties. These can be used for modelling and analysing the processes required for the manufacture of discrete parts modelled in the design phase, such as machining, casting and deformation processes. Specially defined computational models are used for analysing key interactions between the material being processed and the machine elements including chatter analysis for vibration prevention in machining, finite element analysis (FEA) models for stress calculation in dies during material deformation, and thermal models for the prevention of thermally induced deflections during welding.

In terms of assembly processes, kinematic and dynamic models are used to analyse robotic manipulation and assembly of parts together with DFM/DFA systems that simplify design to improve producibility. The new technology for modelling, visualization and design of advanced factory equipment will find extensive applications in machine tool design and modelling, particularly in the challenging new field of parallel kinematic machine tools (Weck and Staimer 2002). In conclusion, the convergence of computational analysis, materials modelling and 3D manufacturing equipment modelling tools will enhance the theoretical understanding of processes as well as improve machine design and process control.

Methods for factory design and optimization have traditionally focused on the design of cells for modular or cellular manufacture. The contribution of cluster analysis and operations research work for optimizing the factory elements and the flow of products has been very significant (Baker and Maropoulos 2000). Many clustering algorithms have been defined for the identification of similarities between processing requirements of parts and the subsequent creation of production cells. A recent effort relates to cell design and positioning within the factory, an activity that can be carried out without the requirement for the involvement of cluster analysis experts (Baker and Maropoulos 1997). These methods allowed the limited interlinking with 2D discrete event simulation systems via the exchange of spreadsheet files that contained key routing and machine positioning and availability data. The advent of 3D equipment and factory modelling tools necessitates the development of a new generation of factory design and visualization tools that will combine the traditional optimization techniques with new methods for factory modelling based on the rapid re-engineering of physical resources, and the definition of re-configurable facilities that deliver the required business responsiveness.

4.4. *Physical-to-digital environment integrators*

The physical-to-digital environment integrators represent a wide range of technologies that can be used for the bi-directional transfer and communication of data, models, measurements as well as process status and expert feedback between the digital and the physical domains. These technologies fall into three large sub-categories.

(i) Predictive manufacturing system performance analysis and feedback by evaluating simulated performance of a scheduling/planning scenario, over a given time period. Discrete event simulation systems are deployed to achieve this task, mitigating risk for bottleneck processes and identifying constraints and performance opportunities regarding material flow and the reduction of inventory and lead times.

(ii) Measurement technologies and digitization technologies

- Measurement technologies for the identification of the real 3D location, orientation and shape of key product features in order to compare with the digitally held representation. This is critical for complex and large product assembly and fabrication, particularly when the modular design and manufacture practice is deployed, aiming at the integration of various modules on one site. Recent advances in optical methods for dimensional metrology (Schwenke *et al.* 2002) and fast, low-cost computation have led to the widespread deployment of laser trackers and digital photogrammetry for general purpose coordinate metrology (Estler *et al.* 2002). It should be noted, however, that in all cases the management of uncertainty (errors) requires considerable expertise and infrastructure (Estler *et al.* 2002).
- Measurement technologies for the identification of the location and orientation of work-holding and processing elements. This is used for robotic and assembly line calibration and machine tool calibration. Again laser trackers can be used here.
- Digitization and laser scanning technologies for the capturing of physical factory data regarding the shape and size of production facilities and production machines. This is important in order to enrich the 3D digital model of processes with an enhanced representation of the production system including additional processing stations as well as work-holding equipment and transportation equipment. This is critically important for the early detection of collisions and the identification of safety and ergonomic considerations.
- Advanced sensing, communication and control techniques for autonomous and intelligent manufacturing. This sub-category includes a very wide range of sensors and factory equipment used for data capture and feedback to the digital control environment, starting from the elementary barcode readers and progressing to integrated visualization and control systems for flexible manufacturing system control from remote locations. Of key importance for the realization of modular and re-configurable manufacturing systems is the development of the 'Open Controller Architecture' that will underpin the functionality of future CNC products (Pritschow *et al.* 2001).

4.5. *Enterprise integration technologies*

This technical category includes methods for Product Data Management (PDM), together with technologies for real-time management, planning and scheduling of production such as production planning and control (PPC) and enterprise resource planning (ERP) systems as well as methods for the formation and management of supply networks. The rapid introduction and development of the internet has provided a decisive advancement in the communications infrastructure, which when combined with the definition of interoperability standards and methods, such as STEP and XML, allows the drastic redefinition of efforts to achieve the integration and coordination of distributed functions and development groups within the enterprise.

Product data management (PDM) systems bridge the five technical cornerstones of DET, as they are deployed for the management of legacy product information and the communication and management of product specification and design activities, from the very early stages. Current systems offer good capabilities in data management and workflow coordination, whilst they offer very little support in the critical area of knowledge management and representation. The rapid advances in vendor offerings in terms of digital design and manufacturing modelling systems can be seen in the convergence of CAD with process modelling and process planning within 3D virtual environments. It becomes feasible to combine the 3D physics-based modelling of discrete manufacturing processes and assembly (manual and robotic) with 3D discrete event simulation. Such systems when interfaced with e-enabled design and PDM software can be used for the visualization and analysis of processing options within the distributed enterprise and are deployed in a wide range of industrial sectors from automotive to aerospace, defence and consumer electronics. Several vendors offer such systems with continuously updated functionality that reflect user's needs and input from research organizations and universities.

The development of e-business and supply chain logistics using the internet has progressed well in relation to the procurement and logistics of services as well as commodities and simple manufactured products with considerable modularization in design, such as bearings, fasteners and electronic components. E-business, however, has not progressed as expected in relation to complex manufactured products, with a high level of customization in the design and functionality and high levels of 'knowledge intensive' aspects in production and service (Vogt and Maropoulos 2002). The main barriers relate to:

(a) providing a technical solution to the vast communication, information exchange and project/data coordination and management problem within the distributed network, and
(b) aligning the business processes and logistics/procurement workflow of supply network companies to utilize collaborative and distributed e-procurement.

Technology advances in web-centric PDM, ERP and e-procurement systems will allow the migration of flexible and, in due course, affordable, internet-based enterprise integration technologies to Small and Medium Enterprises (SMEs) of the supply network (Serve *et al.* 2002, Pant and Ravichandran 2001, Chapman *et al.* 2000). This will allow the development of production networks (Wiendahl and Lutz 2002) that offer inherent business responsiveness. A new generation of PPC/ERP systems would need to be developed for network production as detailed planning would need to be done by individual network members and the general planning would be performed at network level (Wiendahl and Lutz 2002). PPC systems in networks will have to deal with small and highly variable order volumes, requiring the application of load-oriented control methods (Wiendahl 1998) that split network orders into sub-orders that are individually scheduled at the required resources and released according to network partners. The application of 'agents' is offering promising advantages within a production network as they can be deployed for network design (Huang and Nof 2000) and network coordination (Villa 2001).

5. Some new challenges for the research community

In order to satisfy the industrial requirements for early design evaluation, new DET functions must be developed. The following is a selection of new or enhanced functions required.

5.1. *Distributed and collaborative operation and knowledge management*

This should include;

(a) cooperative and distributed design and planning,
(b) capturing and making use of distributed design and process knowledge,
(c) synchronization of web-centric design and process planning systems.

Computer-supported collaborative product design is a key activity, fundamental to the specification and realization of complex artefacts on a global basis. A recent Travel Study (Maropoulos 2002c) revealed that to support collaborative design, NIST has developed:

(a) an information modelling framework to support the creation of 'design repositories',
(b) knowledge-based system interoperability using a generic core representation for product development knowledge, and
(c) extensions to current ISO 10303 (STEP) based data formats that improve existing data transfer capabilities from traditional computer-aided design (CAD) systems to immersive CAD systems.

To date, the power of the internet has not been fully utilized on an enterprise-wide basis for the technical planning of manufacturing operations. In terms of industrial applications, this is a fundamental reason for the relative failure of business-to-business interactions for custom or complex products. For complex products, there is a huge number of alternative opportunities to employ various processes for components manufacture and assembly. Furthermore, these processes can be implemented by employing many different resources and this makes the potential process planning search space extremely large. The lack of DET functionality to assist distributed teams by the rapid analysis of processing options that are available within an enterprise is a key constraint, severely limiting the efficiency of design and sourcing decisions taken during the early stages of product development.

Closely related to the management of processing options is the management of process knowledge within distributed product and process development teams. The progression from the traditional knowledge-based systems, such as expert and rule-based systems, must be based on robust methods for knowledge data mining, codification and management (Maropoulos 2002a, 2002c). The knowledge management functions require technology development that is much wider than the manufacturing applications and will be the subject of substantial R&D efforts over the next ten years.

5.2. *Conceptual and embodiment design evaluation*

The key development priorities herein should be:

(a) 'Data resistant' algorithms for continuous design evaluation, from the early stages.
(b) Early feedback evaluation from the planning and manufacturing cycles.
(c) 'Design by function' support from DET process modelling and planning functions (integration of process and assembly constraints and capabilities).

The major problem faced during the early evaluation of designs is the over-reliance on traditional, feature-based CAPP/CAM methods that are most effectively employed during re-design and detailed design. The density of information available during the very early stages of design may not allow feature-based planning methods to function in a reliable manner. At present, most CAPP/CAM algorithms are hard-coded in terms of product model data requirements and, as such, they cannot deal with a varying degree of data for product specification. 'Data-resistant' process models and planning algorithms need to be developed to allow for seamless design evaluation, from the very early stages. Methods are also needed to allow the integrated progression of the process planning activity from the early design stages to the traditional feature-based methods. This should include the ability to enrich the process models used for early design assessment by receiving and evaluating design and planning feedback from the more detailed product development stages (Maropoulos 2002a).

A key industrial need is to support 'design by function' applications for complex products by the integrated consideration of discrete parts' manufacture and assembly planning. The traditional process modelling and planning functionality is fragmented as it usually considers discrete parts manufacture separately from assembly. This frequently creates additional planning iterations, as assembly constraints are not identified early on. More importantly, this approach does not allow the optimization of designs for the intended product function, as design specifications are influenced by the sequential assessment of component tolerances. The availability of 3D tolerance management systems that are integrated with CAD offers the potential to optimize sub-assemblies by the combined consideration of assembly and process constraints.

5.3. *New generation enterprise resource modelling for technology evaluation*

Research should seek to develop the following functions.

(a) 'Resource-aware' planning for multi-site, enterprise resource modelling.
(b) Manufacturing technology evaluation and synthesis for the extended enterprise.
(c) Widening of the optimization domain (the beyond the machine tool/process issues).
(d) Identification of 'critical path' in terms of technology and logistics.

A vital aspect of early design evaluation is the allocation of components and sub-assemblies to supply network companies and the early assessment of the overall product manufacturability in terms of quality, cost and delivery (QCD) considerations. The vast array of options and the complexity of the physical resources available for product realization within a dynamic e-network, make present planning and resource modelling methods rather inadequate. New, 'resource-aware' planning methods are needed for the creation of a much closer and dynamic interrelationship between the main entities of the process planning environment and the resources, both humans and machines, available within a rapidly formed distributed enterprise (Maropoulos 2002b). This functionality will require integration of CAPP with PDM functions.

New, commercial systems for product modelling, digital manufacture and PDM are making use of clearly defined data structures for product, process and resource modelling, hence forming an essential information management infrastructure. The continuous development of STEP, together with object oriented methods (XML, Java, C++) for internet applications and SQL database connectivity allow the increasingly reliable communication of information within the extended enterprise. This information management infrastructure can now be used to support the development of new, process optimization functionality for the early design stages that can reach beyond the 'machine tool' level. For instance, it is now feasible to seek the early optimization of production routes within multiple sites as part of the make-or-buy decision making and also to optimize manufacturing technology resources within the supply network for delivering a new product within certain cost, quality and delivery performance criteria. In terms of optimization methods, the large search space available makes the application of evolutionary computing methods, such as Genetic Algorithms and Simulated Annealing, particularly appealing.

6. Concluding comments

The rapid technology advances in computer graphics, processing capability and distributed information management, together with the definition of new data and knowledge exchange standards open new opportunities and horizons for the distributed and flexible coordination of data and knowledge flow between web-centric systems. These technologies will allow the development of new business processes to take advantage of the rapid formation of production networks and effectively manage workflow during all phases of a product's life cycle. Digital Enterprise Technology (DET) represents this emerging, new synthesis of technologies and systems for product and process development and life-cycle management on a global basis.

In terms of commercial developments, there is a notable convergence of product and process modelling and analysis technologies and systems in major vendor offerings. This is manifested by the gradual offering of process and equipment visualization/modelling functionality within product design systems. New underpinning technologies in terms of distributed and virtual CAD, 3D tolerance management, advanced 3D process and equipment modelling tools, large scale metrology using laser trackers and web-centric PDM systems, are now becoming mature enough to support new DET functionality. The main industrial benefits from the development of such DET functionality will include:

(a) the global management and mitigation of the realization risk for complex products,
(b) the rapid evaluation of manufacturing technology options for process-intensive environments via the combined optimization of product structure, processing requirements and production network configuration, and
(c) the effective management of the life cycle of complex products.

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