Digital manufacturing: history, perspectives, and outlook

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Abstract: Digital manufacturing has been considered, over the last decade, as a highly promising set of technologies for reducing product development times and cost as well as for addressing the need for customization, increased product quality, and faster response to the market. This paper describes the evolution of information technology systems in manufacturing, outlining their characteristics and the challenges to be addressed in the future. Together with the digital manufacturing and factory concepts, the technologies considered in this paper include computer-aided design, engineering, process planning and manufacturing, product data and life-cycle management, simulation and virtual reality, automation, process control, shopfloor scheduling, decision support, decision making, manufacturing resource planning, enterprise resource planning, logistics, supply chain management, and e-commerce systems. These technologies are discussed in the context of the digital factory and manufacturing concepts.

Keywords: information technology, computer-integrated manufacturing, computer-aided design, computer-aided engineering, computer-aided manufacturing

1 INTRODUCTION

The need for reduced development time together with the growing demand for more customer-oriented product variants have led to the next generation of information technology (IT) systems in manufacturing. Manufacturing organizations strive to integrate their business functions and departments with new systems in an enterprise database, following a unified enterprise view [1]. These systems are based on the digital factory/manufacturing concept, according to which production data management systems and simulation technologies are jointly used for optimizing manufacturing before starting the production and supporting the ramp-up phases [2]. Digital manufacturing would allow for, first, the shortening of development time and cost, second, the integration of knowledge coming from different manufacturing processes and departments, third, the decentralized manufacturing of the increasing variety of parts and products in numerous production sites, and, fourth, the focusing of manufacturing organizations on their core competences, working efficiently with other companies and suppliers, on the basis of effective IT-based cooperative engineering.

The evolution of IT in manufacturing is described in the next section. Recent developments and the digital manufacturing concept are then discussed, followed by the conclusions regarding the perspectives and the outlook of digital manufacturing in the future.

2 IT IN MANUFACTURING

Over the past few decades, the extensive use of IT in manufacturing has allowed these technologies to reach the stage of maturity. The benefits of the new tools have been thoroughly examined and their efficiency in many applications has been proven. Their application ranges from simple machining applications, to manufacturing planning and control support. From the early years of the introduction of numerical control and all the way to machining centres, manufacturing cells, and flexible systems, costs and increased power have been the main advantages of IT [3]. An example of the introduction of IT, in the manufacturing world, is the concept of
computer-integrated manufacturing (CIM). This concept was introduced in the late 1980s, favouring the enhancement of performance, efficiency, operational flexibility, product quality, responsive behaviour to market differentiations, and time to market. However, the full strategic advantage of information technologies was poorly understood at that time and could not be exploited to its full extent [3].

The inventory control and material requirements planning (MRP) systems were introduced in the 1960s and 1970s respectively. Such systems were further enhanced with the integration of tools capable of providing capacity and sales planning functionalities together with scheduling capabilities and forecasting tools. The result was the introduction of the closed-loop MRP [4]. Nevertheless, the advances in microprocessor technology, the advent of the internet era, the standardization of software interfaces, the wide acceptance of formal techniques for software design and development, and the maturity of certain software products (relational database management systems and computer-aided design (CAD) systems, for instance) paved the way for facilitating the integration among diverse software applications [1]. The evolution of information systems over the last decade has played a crucial role in the adoption of new information technologies in the environment of manufacturing systems [5].

2.1 Computer-aided technologies

CAD is considered among the technologies that have boosted productivity, allowing faster time to market for the product and dramatically reducing the time required for product development. Although the first CAD applications were inherently difficult to use owing to the text-based input systems and the extremely slow computational equipment, their successors have become more than necessary in today’s manufacturing companies, regardless of their size. Affordable solutions, offering a modern photorealistic graphical user interface, are nowadays available in the market. Functionalities of such systems integrate finite element analysis (FEA), kinematics analysis, dynamic analysis and full simulation of geometrical properties including texture and mechanical properties of materials. The CAD systems have become indispensable to today’s manufacturing firms, because of their strong integration with advanced manufacturing techniques. CAD models are often considered sufficient for the production of the parts, since they can be used for generating the code required to drive the machines for the production of the part. Rapid prototyping is an example of such a technology.

Process planning activities determine the necessary manufacturing processes and their sequence in order to produce a given part economically and competitively [1]. Towards this direction, the computer-aided process planning (CAPP) systems have been used for the generation of consistent process plans and are considered as being essential components of the CIM environments [6]. Denkena et al. [7] proposed a holistic component manufacturing process planning model, based on an integrated approach combining technological and business considerations in order to form the basis for developing improved decision support and knowledge management capabilities to enhance available CAPP solutions. Kim and Duffie [8] introduced a discrete dynamic model design and have analysed the control algorithms for closed-loop process planning control that improve response to disturbances, such as rush orders and periodic fluctuations in capacity. In their work, Azab and ElMaraghy [9] presented a novel semigenerative mathematical model for reconfiguring macrolevel process plans. In the same work, it is claimed that reconfigurable process planning is an important enabler of changeability for evolving products and systems. Finally, Ueda et al. [10] introduced a new simultaneous process planning and scheduling method of solving dilemmas posed by situations where a process plan and a production schedule conflict, using evolutionary artificial neural networks, based on emergent synthesis.

Computer-aided engineering (CAE) systems are used to reduce the level of hardware prototyping during product development and to improve the understanding of the system [11]. The CAE systems support a large number of engineering research fields, including fluid mechanics (computational fluid mechanics), dynamics (simulation of machines and mechanisms), mechanics of materials (FEA), thermodynamics, and robotics. For instance, Brinksmeier et al. [12] conducted an extensive survey on the advances in the simulation of grinding processes together with a series of models that can be implemented in simulation systems.

Following the development of the CAD systems, the concept of computer-aided manufacturing (CAM) was born. The great step towards the implementation of CAM systems was the introduction of computer numerical control (CNC). Apart from the fact that this new technology has brought about a revolution in manufacturing systems by enabling mass production and greater flexibility [13], it has also enabled the direct link between the three-dimensional (3D) CAD model and its production. Newman and Nasseri [14] proposed a universal manufacturing platform for CNC machining, where the applications of various computer-aided systems (CAx) applications can seamlessly exchange information. The proposed platform is based on the standard STEP-NC. In addition, standardization of programming languages for these
machines (G&M code and APT) leads solution developers to integrate an automatic code generation in their applications. From that point on, CAD and CAM systems have been developed allowing for part design and production simulation. Engineers have the ability to visualize both the part and the production process, to verify the quality of the part and then physically to perform the manufacturing process with minimum error probability.

Other systems, such as computer-aided quality [15] systems, have also started to emerge and to become part of the engineering workflow. Product data management (PDM) and product life-cycle management (PLM) systems, on the other hand, allow for performing a variety of data management tasks, including vaulting workflow, life-cycle, product structure, and view and change management. PDM systems are claimed to be able to integrate and manage all applications, information, and processes that define a product, from design to manufacture to end-user support. PDM systems are frequently used for controlling information, files, documents, and work processes and are required to design, build, support, distribute, and maintain products. Typical product-related information includes geometry, engineering drawings, project plans, part files, assembly diagrams, product specifications, numerical control machine-tool programs, analysis results, correspondence, bill of material, and engineering change orders.

PLM is an integrated information-driven approach to all aspects of a product’s life cycle from its design inception, through its manufacture, deployment, and maintenance to, finally, its removal from service and, its final disposal. Some of the benefits reported by the use of PLM involve the reduced time to market, improved product quality, reduced prototyping costs, savings through the reuse of original data, features for product optimization, and reduced waste and savings through the complete integration of engineering workflows. These systems are theoretically supposed to tie everything together, allowing engineering, manufacturing, marketing, and outside suppliers and channel partners to coordinate activities.

Technically speaking, today’s PDM and PLM systems mainly focus on the administration of computer files, without, however, having much access to the actual content of these files. Instead, the CAD systems are used for developing product models, since geometry data constitute the major part of the product-defining characteristics [16]. On the other hand, PLM systems often include a mature collaborative product design domain and aim at encompassing design and management of the manufacturing processes and digital manufacturing, the latter representing a strategic and important milestone in the advancement of PLM. Digital manufacturing has arrived as a technology and discipline within PLM that provides a comprehensive approach for the development, implementation, and validation of all elements of the manufacturing process, which is foreseen by researchers and engineers to be one of the primary competitive differentiators for manufacturers.

In today’s state of the art, the PDM and PLM solutions in one of the most complex industrial domains, the automotive industry, use concepts such as the generative template: a solution aiming to reduce design cycle time in several development processes by employing computer models to incorporate component and knowledge rules that reflect design practice and past experience. In the templates, various elements included in product design are combined. The templates are then reused either by the same team, project, or company, or through the extended enterprise by way of exchanges between original equipment manufacturers (OEM) and suppliers. This components-based approach accelerates and simplifies the design.

During the design of a new product or process, it is essential that all the knowledge and experience available (either on the product or process design) gained through time can be accessed easily and rapidly. This can be achieved with the use of archetypes and templates. A process archetype is a way of classifying standard solutions that do not need any further development so that they can be available whenever necessary, within a very short time. Archetypes can also include information on newly developed innovative processes that have been assessed for their efficiency in order for any implementation risks to be minimized in case the application of this process is under consideration.

2.2 Manufacturing control

Manufacturers will base their future controller selection on factors such as adherence to open industry standards, multi-control discipline functionality, technical feasibility, cost-effectiveness, ease of integration, and maintainability. More importantly, embedded systems and small-footprint industrial-strength operating systems will gradually change the prevailing architecture, by merging robust hardware with open control. Integration of control systems with CAD and CAM and scheduling systems as well as real-time control, based on the distributed networking between sensors and control devices [17] currently constitute key research topics. For instance, ElMaraghy et al. [18] developed a methodology of compensating for machining errors aimed at maximizing conformance to tolerance specifications before the final cuts are made.

New developments in the use of wireless technologies on the shopfloor, such as radiofrequency
identification (RFID), as a part of automated identification systems, involve retrieving the identity of objects and monitoring items moving through the manufacturing supply chain, which enable accurate and timely identification information [19]. More recently, the installation of wireless technologies on the shopfloor such as RFID, global system for mobile communications (GSM), and 802.11 has been a new IT application area on the industrial shopfloor [20]. However, the integration of wireless IT technologies at an automotive shopfloor level is often prevented because of the demanding industrial requirements, namely immunity to interference, security, and high degree of availability.

On the other hand, in the automotive assembly, IT is applicable to a series of processes such as production order control, production monitoring, sequence planning, vehicle identification, quality management, maintenance management, and material control [21].

2.3 Simulation

Computer simulation has become one of the most widely used techniques in manufacturing systems design, enabling decision makers and engineers to investigate the complexity of their systems and the way that changes in the system’s configuration or in the operational policies may affect the performance of the system or organization [22].

Simulation models are categorized into static, dynamic, continuous, discrete, deterministic, and stochastic. Since the late 1980s, simulation software packages have been providing visualization capabilities, including animation and graphical user interaction features. Computer simulation offers the great advantage of studying and statistically analysing what-if scenarios, thus reducing overall time and cost required for taking decisions, based on the system behaviour. Simulation systems are often integrated with other IT systems, such as CAx, FEA, production planning, and optimization systems.

While factory digital mock-up (DMU) software allows manufacturing engineers to visualize the production process via a computer, which allows for an overview of the factory operations for a particular manufacturing job, the discrete event simulation (DES) helps engineers to focus closely on each individual operation. DES may help decision making in the early phases (conceptual design and prestudy) on evaluating and improving several aspects of the assembly process such as location and size of the inventory buffers, the evaluation of a change in product volume or mix, and throughput analysis [23].

An extension to simulation technology (the virtual reality (VR) technology) has enabled engineers to become immersed in virtual models and to interact with them. Activities supported by VR involve factory layout, planning, operation training, testing, and process control and validation [24, 25].

Other applications include the verification of human-related factors in assembly processes by employing desktop three-dimensional simulation techniques, replacing the human operator with an anthropometrical articulated representation of a human being, called a ‘mannequin’ [26].

2.4 Enterprise resource planning and optimization

Enterprise resource planning (ERP) systems attempt to integrate all data and processes of an organization into a unified system. A typical ERP system will use multiple components of computer software and hardware to achieve the integration. A key ingredient of most ERP systems is the use of a unified database to store data for the various system modules. ERP has been associated with quite a broad spectrum of definitions and applications over the last decades [27].

The manufacturing resources planning (MRP II) systems apart from incorporating the financial accounting and management systems have been further expanded to incorporate all resource planning and business processes of the entire enterprise, including areas such as human resources, project management, product design, materials, and capacity planning [4].

The elimination of incorrect information and data redundancy, the standardization of business unit interfaces, the confrontation of global access and security issues [4], and the exact modelling of business processes, have all become part of the list of objectives to be fulfilled by an ERP system. Large implementation costs, high failure risks, tremendous demands on corporate time and resources [4], and complex and often painful business process adjustments are the main concerns pertaining to an ERP implementation. Considering the current trend in the manufacturing world for maximizing their communication and collaboration, the ERP system functionality has also been extended with supply chain management solutions [28].

The ERP systems often incorporate optimization capabilities for cost and time savings virtually from every manufacturing process. Indicative examples involve cases from simple optimization problems, shopfloor scheduling, and production planning to today’s complex decision-making problems [29, 30]. Monostori et al. [31] have proposed a scheduling system capable of real-time production control. This system receives feedback from the daily production through the integration of information coming from the process, quality, and production monitoring subsystems. The system is able to monitor deviations
and problems of the manufacturing system and to suggest possible alternatives for handling them.

A new generation of factory control algorithms has recently appeared in literature, known as ‘agent based’. In Sauers’ [32] work a software agent technology is discussed and proposed as the middleware between the different software application components on a shopfloor. Agents are a promising technology for industrial application because they are based upon distributed architecture; however, issues such as synchronization, interfacing agents, and data consistency among agents impose difficulties on their practical application [23].

3 RECENT DEVELOPMENTS

3.1 Academic research

Recent developments in digital manufacturing may be categorized into two major groups. The developments of the first group have followed a bottom-up approach considering digital manufacturing, and extending its concepts, within a wider framework, e.g. the digital factory or enterprise. The developments of the second group have followed a top-down approach considering the technologies in support of individual aspects of digital manufacturing, e.g. e-collaboration and simulation.

According to the Verein Deutscher Ingenieure, the digital factory includes models, methods, and tools for the sustainable support of factory planning and factory operations. It includes processes based on linked digital models connected with the product model [33]. At a theoretical level, several researchers have contributed to the definition of the digital factory vision and suggested how this vision could be implemented in reality (Fig. 1) [34]. Data and models integration has been a core research activity to support implementation. The introduction of consistent data structures for improving the integration of digital product design and assembly planning and consequently supporting a continuous data exchange has been investigated in the literature [35]. Similar activities have focused on the definition of semantic correlations between the models distributed as well as the associated databases and the introduction of appropriate modelling conventions [33]. On top of these developments, a number of methodologies for computer-supported co-operative development engineering, within a digital factory framework, have been published. Some researchers further suggested software architectures for relationship management and the secure exchange of data [36].

The new concept of digital enterprise technology (DET) has also been recently introduced 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 [37]. As such, it embodies the technological means of applying digital manufacturing to the distributed manufacturing enterprise. DET is implemented by a synthesis of technologies and the systems of five main technical areas, the DET 'cornerstones', corresponding to the design of product, process, factory, technologies for ensuring the conformance of the digital environment with the real one, and the design of the enterprise. On the basis of the DET framework, a new methodology has been suggested that focuses on developing novel methods and tools for aggregate modelling, knowledge management, and test on validation planning to 'bridge' the gap that exists between conceptual product design and the organization of the corresponding manufacturing and business operations (Fig. 2) [38].

From a technological point of view, new frameworks for distributed digital manufacturing have appeared on the scene. Recent developments focus on a new generation of decentralized factory control algorithms known as 'agent based'. A software agent, first, is a self-directed object, second, has its own value systems and a means of communicating with other such objects, and, third, continuously acts on its own initiative [39]. A system of such agents, called a multi-agent system, consists of a group of identical or complementary agents that act together. Agent-based systems encompassing real-time and decentralized manufacturing decision-making capabilities have been reported [40]. In such a system, each agent, as a software application instance, is responsible for monitoring a specific set of resources, namely machines, buffers, or labour that belong to a production system, and for generating local alternatives upon the occurrence of an event, such as a machine breakdown. Web-based multi-agent system frameworks have also been proposed to facilitate collaborative product development and production among geographically distributed functional agents using digitalized information (Fig. 3) [41]. The proposed system covers product design, manufacturability evaluation, process planning, scheduling, and real-time production monitoring.

The advances in DMU simulation technologies during the 1990s were the key stone for the emergence of VR and human simulation in digital manufacturing. These advances have led to new frameworks that integrate product, process, resource, knowledge, and simulation models within the DMU environment [42].

The VR technology has recently gained major interest and has been applied to several fields related to digital manufacturing research and development. Virtual manufacturing is one of the first fields that attracted researchers' interest. A number of VR-based environments have been demonstrated, providing desktop and/or immersive functionality for process analysis and training in such processes as machining, assembly, and welding [25, 43]. Virtual assembly simulation systems focusing on digital shipbuilding and marine industries, incorporating advanced simulation functionalities (crane operability, block erection simulation in virtual dock, etc.) have also been introduced by Kim et al. [44]. Human motion simulation for integrating human aspects in simulation environments has been another key field of interest (Fig. 4). Several methodologies for modelling the motion of digital mannequins, on the basis of real human data, have been presented. Furthermore, analysing the motion with respect to several ergonomic aspects, such as discomfort, have been reported [28, 30, 45].

Collaborative design in digital environments is another emerging research and development field. The development of shared virtual environments has enabled dispersed actors to share and visualize data, to interact realistically, as well as to make decisions in the context of product and process design activities over the web [46]. Research activities have been also launched for the definition and implementation of VR- and augmented-reality-based collaborative manufacturing environments, which are applicable to human-oriented production systems [47, 48].

3.2 Industrial practices and activities

In industrial practice, digital manufacturing aims at a consistent and comprehensive use of digital methods
of planning and validation, from product development to production and facility planning.

The Accessible Information Technology (AIT) Initiative and its offspring projects launched during the 1990s by the automotive and aerospace industry in Europe have been pioneering in driving digital manufacturing advances, aiming at increasing the competitiveness of industry through the use of advanced information technology in design and manufacturing [49]. On that basis, the automotive industry still drives today a number of relevant developments in digital manufacturing.

In BMW, the three series at Leipzig has been BMW's best launch ever, as they achieved 50 per cent fewer faults per vehicle and have recorded far better process capability measures than in the past because of the use of the simulation of production processes at a very early stage of design [50]. Similarly, General Motors has utilized a three-dimensional workcell simulation (iGRIP) provided by digital enterprise lean manufacturing interactive application (DELMIA), allowing the engineers to generate three-dimensional simulations and to translate models created in other commercially available packages. During 2002, Opel utilized DELMIA for the simulation of the production process of its Vectra model allowing for a very fast production launch [51]. Finally, computer-aided three-dimensional interactive application (CATIA) machining simulation tools have given manufacturing experts at Daimler a chance to test virtually the 'choreography' for the production of parts, ensuring that the finished product will meet precise design expectations.

At Volvo, DES has been used as a tool for continuous process verification in industrial system development [52]. BMW and DaimlerChrysler are also among the users of similar applications [53]. General Motors has used DES in several case studies and has demonstrated the ability of using simulation for optimizing resources and identifying constraints [54]. Ford has also been using computer simulation, in some form or other, for designing and operating its engine manufacturing facilities since the mid-1980s. Case studies in advanced manufacturing engineering for a powertrain at DaimlerChrysler, have identified virtual modelling as an emerging technology for automotive process planners [55].

Fig. 3 A web-based multi-agent system framework [41]

Fig. 4 Human simulation in digital manufacturing environments [29]
The method of digital planning validation (DPV) has recently gained some interest (Fig. 5) [56]. Based on a validation process running in parallel to that of digital planning, the DPV method developed by DaimlerChrysler consists of both the continuous checking of digital planning results as well as the process reviews at certain points in time, the so-called process days. During the process days, the current planning states are validated through geometrical checks of the assemblies, the simulation of processes, or detailed examinations of layouts. The DPV method is based on the DMU techniques and simulation. In analogy to the product, DMU for the product development, can be regarded as a kind of process DMU of production planning within the digital factory.

The so-called virtual process week is another relevant method applied to BMW working practices [57]. This method addresses the assessment of the assembly planning by a group of people responsible for the process. Based on the product structure, visualization scenes are created. By using the group function of visualization the system parts are shown subsequently according to the assembly plan. The participants use eight criteria to assess the operation. All results are documented in a database online. In the end, statistical evaluations of the database show where operations have to be clarified in more detail, or where the geometry of parts will have to be changed because of bottlenecks during the online operation.

New methods and technologies for virtual assembly in the digital factory have been investigated by Volvo, DaimlerChrysler, Fiat, and Ford in the context of the Eu Integrated Project ‘MyCar’, driven by Volvo and Laboratory for Manufacturing Systems and Automation, University of Patras [58]. The OEMs are seeking novel approaches to achieving an improvement in the data communication and to providing a foundational IT CAx architecture that enables the various tools to interoperate seamlessly and the processes to be managed efficiently. Digital validation of production of body-in-white and assembly as well as simulation for virtual ramp-up of production cells and lines, including virtual commissioning, are investigated. The human simulation of manual, automated, and mixed processes for improving the consideration of human factors is another topic of major research.

4 DIGITAL MANUFACTURING: OUTLOOK

The speed-up of a manufacturing process consists of two aspects: one is the speed-up of product development to reduce development lead time and the other is that of production to reduce production lead time [59].

In parallel, the quality and manufacturing cost of the final product are determined again in both the design and production phases. This demonstrates that there is a significant need for a bridge to be built between the production of development and the real production; digital manufacturing aims to play this part.

Years ago, both FEA and computer-aided machining were the true ‘black arts’ of manufacturing. With products that devolved out of high-end academic research, these software products often needed highly trained, highly scientific minds, and a deep
and healthy bank account. In the 1990s, both FEA and computer-aided machining suddenly became affordable and usable, even on the shopfloor. FEA integrated with mainstream design products has meant that most testing and analysis can be conducted quickly and with reliable results. Now, an engineer can find out much earlier in the process if a design has any flaws and then can eradicate them quickly. The recent technology improvements are making digital manufacturing real to many, and many companies are using pieces of digital manufacturing without realizing it [60].

Nevertheless, digital manufacturing needs to be further exploited in order to close the gap between the product definition (configuration of components and required manufacturing processes) and the actual manufacturing production activities within the enterprise [61]. Simulation and VR can now be used in order to significantly reduce costs and time to market. Manufacturing is only 30 per cent of the product development cost but the remaining 70 per cent is locked during the design phase of new product development [62].

Based on responses from industry, Dalton-Taggart [60] defined digital manufacturing as ‘the ability to describe every aspect of the design-to-manufacture process digitally – using tools that include digital design, CAD, office documents, PLM systems, analysis software, simulation, CAM software, and so on’. The concept is that the passage of data from one department or discipline to another should be seamless so that the data created are immediately reusable in a different discipline. Several benefits can then be derived. By exploiting digital manufacturing, manufacturing enterprises expect to achieve the following [61]:

(a) shortened product development;
(b) early validation of manufacturing processes;
(c) faster production ramp-up;
(d) faster time to market;
(e) reduced manufacturing costs;
(f) improved product quality;
(g) enhanced product knowledge dissemination;
(h) reduction in errors;
(i) increase in flexibility.

The industries that benefit the most from utilizing these methodologies are those with capital-intensive manufacturing and those with very complex products but very low production, even single-unit production. For the capital intensive manufacturers, the return on investment is calculated on the basis of the decrease in the time to market by 30–50 per cent, due to efficient concurrent engineering, reducing the product cost by 10–25 per cent through multiple iterations of design for manufacturing and design for assembly, and reducing the costly engineering changes to product design and production tooling, during launch, by 80–90 per cent [63]. Organizational issues including technical teams and efficient product change management constitute an important challenge, which has already started to be investigated [64].

Enterprises already exploiting these benefits are showing great potential for future growth. Daimler-Chrysler, General Motors, Boeing, and Lockheed Martin have publicly declared that digital technologies have saved them millions of dollars in just a few years. Similar savings have been realized in the semiconductor industry [63]. Further research effort is, however, required to be able to simulate the assembly process fully and to avoid costly installations and lengthy start-up periods. This is because digital simulation and planning of assembly processes are based on various enabling technologies such as immersive VR, collaborative virtual design and digital human simulation for manual assembly system, and ergonomic assessments [23].

In digital manufacturing, the ambiguity of tacit knowledge in manufacturing should be eliminated thoroughly, and the tacit knowledge should be transformed into tangible knowledge, namely numerical values and/or equations and finally into digital values [59]. This is expected to minimize the production performance diversities frequently observed between globally distributed production sites of extended enterprises.

Since up to 60 per cent of the value of automobiles and fighter aircraft are sourced from suppliers, the digital manufacturing environment must be accessible across the supply chain to support today’s business-to-business method [63]. The spreading of the internet and the software technologies that arise from it provide the means for the globalization of the services offered [65]. Modern information technology can support the communication among the various nodes of the extended production network, but then systematic data management becomes critical. Optimized data management is required through all the stages of digital manufacturing for its efficient exercise. Three-dimensional design data can result in huge data files. Gigabytes of information in one or two files mean massive wait times, the inability actually to send them anywhere, and a huge barrier to digital manufacturing. However, the acceptance of XML as a communication format and the development of additional formats (such as XVL, JT, and U3D) provide very high compression without a loss of information [60].

In the new manufacturing paradigm suggested by Manufuture for the year 2020, digital manufacturing is defined as a key research area for the implementation of the knowledge-based factory of the future. It will be a key element in product and process knowledge acquisition, helping to translate from implicit
to explicit knowledge. Additionally, it is driven by the application and standardization of the information and communication technologies and the increasing demand for the efficiency of operations in global networks [66]. The tools of future engineering and management of manufacturing are digital and distributed. The identified research priorities include the development of integrated tools for industrial engineering and adaptation of manufacturing, taking into account the configurability or partial autonomy of systems, the development of a standard data model of factories and the management of factory data, including open networks of engineering and real-time management of manufacturing data [67].

5 CONCLUSIONS

Digital manufacturing incorporates technologies for the virtual representation of factories, buildings, resources, machine systems equipment, labour staff and their skills, as well as for the closer integration of product and process development through modelling and simulation.

Closing the gap between the product definition and the actual manufacturing production activities within the enterprise, fully transforming tacit manufacturing knowledge into tangible, and, finally, digital knowledge, optimizing data management, and developing standard models are some key priorities.

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