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Simulation in Manufacturing: Review and Challenges

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Abstract

Simulation comprises an indispensable set of technological tools and methods for the successful implementation of digital manufacturing, since it allows for the experimentation and validation of product, process and system design and configuration. Especially in todays' turbulent manufacturing environment, which is affected by megatrends such as globalisation and ever-increasing requirements for higher degree of product customisation and personalisation, the value of simulation is evident. This keynote paper investigates the major milestones in the evolution of simulation technologies and examines recent industrial and research applications and findings. Based on this review, the identification of gaps in current practices is presented, and future trends and challenges to be met on the field are outlined. The considered simulation methods and tools include CAx, Factory layout design, Material and Information flow design, Manufacturing Networks Design, Manufacturing Systems Planning and Control, Manufacturing Networks Planning and Control, Augmented and Virtual Reality in product and process design, planning and verification (ergonomics, robotics, etc.). The evolution, advances, current practices and future trends of these technologies, industrial applications and research results are discussed in the context of the contemporary manufacturing industry.

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Keywords: Manufacturing; Simulation; Information and Communication Technologies

1. Introduction

Manufacturing is defined as the transformation of materials and information into goods for the satisfaction of human needs [1]. In the current highly competitive business environment, the manufacturing industry is facing constant challenges of producing innovative products at shortened time-to-market. The increasing trend towards globalisation and decentralisation of manufacturing [2] requires real-time information exchanges between the various nodes in a product development life cycle, e.g., design, setup planning, production scheduling, machining, assembly, etc., as well as seamless collaboration among these nodes. Product development processes are becoming increasingly more complex as products become more versatile, intricate and inherently complicated, and as product variations multiply to address to the needs of mass customisation [3]. Simulation modelling and analysis is conducted in order to gain insight into this kind of complex systems, to achieve the development and testing of new operating or resource policies and new concepts or systems, which live up to the expectation of modern manufacturing, before implementing them and, last but not least, to gather information and knowledge without disturbing the actual system [4]. It becomes evident from the total number of directly related papers (15,954) from the early 70s till today, that simulation is a continuously evolving field of research with undoubted contribution to the progress of manufacturing systems. This paper investigates the evolution, advances, current practices and future trends of simulation methods and tools. More specifically, CAx, factory layout design, material and information flow design, manufacturing networks design, manufacturing systems and networks planning and control, augmented and virtual reality in product and process design, planning and verification (ergonomics, robotics, etc.) are examined (Figure 1).

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1.1. Review Methodology

This review is based on academic peer-reviewed publications that use simulation not only in manufacturing applications but also simulation in general, over a period of 54 years, from 1960 to 2014. The review focuses mainly on simulation methods and tools as described in the abstract and was carried out in three stages: (a) search in scientific databases (Scopus, Science Direct and Google Scholar) with relevant keywords, (b) identification of relevant papers by abstract reading and (c) full-text reading and grouping into research topics. The relevant keywords utilised were: simulation and manufacturing in combination with CAx, layout design, material flow design, manufacturing networks and systems planning and control, augmented reality, virtual reality, ergonomics, digital mock up, lifecycle assessment, product data management, enterprise resource planning, knowledge management, manufacturing execution systems, process simulation, supervisory control and data acquisition and supply chain. As a result, the literature was organised based on keywords enabling the distinction between the relevant and irrelevant topics of academic papers (Figure 2).

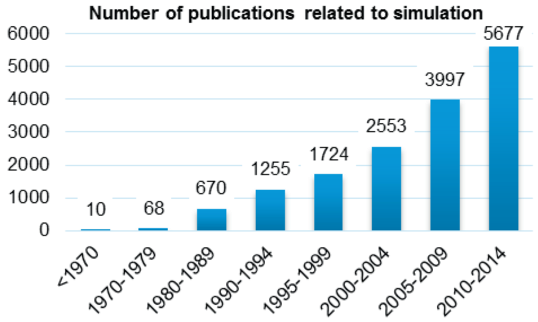

Figure 1: Number of publications related to simulation technology

1.2. Definitions

Hereby, two of the most prominent definitions of simulation in the manufacturing context are presented and are adopted for the scope of the present research work. “Simulation modelling and analysis is the process of creating and experimenting with a computerised mathematical model of a physical system” [5]. “Simulation is the imitation of the operation of a real-world process or system over time. Simulation involves the generation of an artificial history of the system, and the observation of that artificial history to draw inferences concerning the operating characteristics of the real system that is represented” [6].

1.3. The Historical Trends of the Evolution of Simulation

It is generally considered that the contemporary meaning of simulation originated by the work of Comte de Buffon who proposed a Monte Carlo-like method in order to determine the outcome of an experiment consisting of repeatedly tossing a needle onto a ruled sheet of paper. He aimed at calculating the probability of the needle crossing one of the lines. So, it is obvious that although the term “Monte Carlo method” was invented in 1947, at the start of the computer era, stochastic sampling methods were used long before the evolution of computers [7]. About a century later, Gosset used a primitive form of manual simulation to verify his assumption about the exact form of the probability density function for Students t-distribution [8]. Thirty years later, Link constructs the first “blue box” flight trainer and a few years later, the army adopts it in order to facilitate training [9]. In the mid-1940s, simulation makes a significant leap with the contribution of Tochter and Owen develop the General Simulation Program in 1960, which is the first general purpose simulator to simulate an industrial plant that consists of a set of machines, each cycling through states as busy, idle , unavailable and tailed [10].

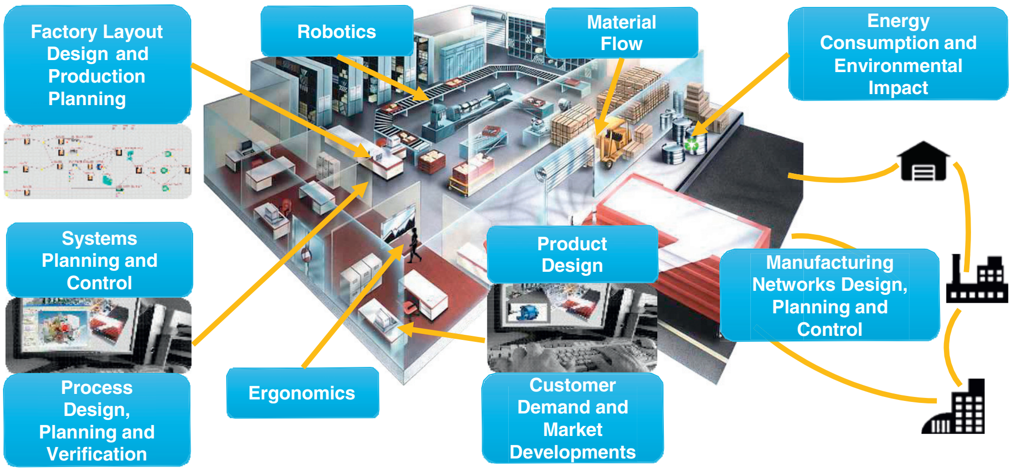

Figure 2: The investigated domains of contemporary manufacturing

They also introduce the three-phase method for timing executives, publishes the first textbook in simulation “The Art of Simulation” (1963) and developed the wheel chart or activity-cycle diagram (ACD) (1964). During the period 1960-1961, Gordon introduces the General Purpose Simulation System (GPSS) [8]. With use of light, sound motion and even smell to immerse the user in a motorcycle ride, Heilig designed the Sensorama ride, which is considered as a predecessor of Virtual Reality (VR) [11]. Simultaneously, Nygaard and Dahl initiate work on SIMULA and they finally release it in 1963 and Kiviat develops the General Activity Simulation Program (GASP). In 1963, the first version of SIMSCRIPT is presented for non-experts and OPS-3 is developed by MIT [10]. Sutherlend presents manipulation of objects on a computer screen with a pointing device [11]. Although, a significant evolution of simulation is noticed, there are still problems concerning model construction and model analysis which are mentioned and addressed by Conway et al. [8]. General Precision Equipment Corporation and NASA uses analogue and digital computers to develop Gemini simulators [9]. Lackner proposes the system theory as a basis for simulation modelling. In 1968, Kiviat introduces the entity/attribute/set concept in SIMSCRIPT II [12]. In the same time, Sutherland constructs head-mounted computer graphics display that also track the position of the users head movements and the Grope project explores real-time force feedback [11]. Two years later, power plant simulators are introduced [9]. In 1972, an explanatory theory of simulation based on systems-theoretic concepts is presented by Zeigler [12]. In 1973, Pritsker and Hurst introduce the capability for combined simulation in GASP IV and Fishman composes the state-of-the-art on random number generation, random variate generation and output analysis with his two classical texts [13]. Clementson extended ECSL (Extended Control and Simulation Language) with the Computer Aided programming System using ACD representation and Mathewson develops several versions of DRAFT to produce different programming language executable representations in 1975. In 1976, Delfosse introduces the capability for combined simulation in SIMSCRIPT II.5 as C-SIMSCRIPT and a year later, user interface is added to it [8]. Moreover, Bryant initiates parallel simulation [12]. In 1978, computer imaging with the introduction of digital image generation is a significant contribution to the advancement of simulation. In the beginning of the 1980s, major breakthroughs take place, military flight simulators, naval and submarine simulators are produced and NASA develops relatively low-cost VR equipment [9]. Nance introduces an object-oriented representational approach in order to join theoretical modelling issues with program-generation techniques and with software engineering concepts. Balci and Sargent contribute to formal verification and validation. Law and Kelton contribute with their first edition which includes advanced methodologies concerning random number generation, random variate generation and output analysis. Furthermore, Schruben develops event graphs in 1983 [8]. While, Visual Interactive Simulation is initiated in 1976 by Hurrion and becomes commercially available in 1979 through SEE-WHY, it is properly described in methodological terms, contrasting the active and passive forms in model development and experimentation, by Bell and O’Keefe in 1994 [14]. In early 1990s, real-time simulations and interactive graphics become possible due to the increased computer power and commercial VR applications become feasible [11]. In 1990, as well, Cota and Sargent develop a graphical model representation for the process world view,

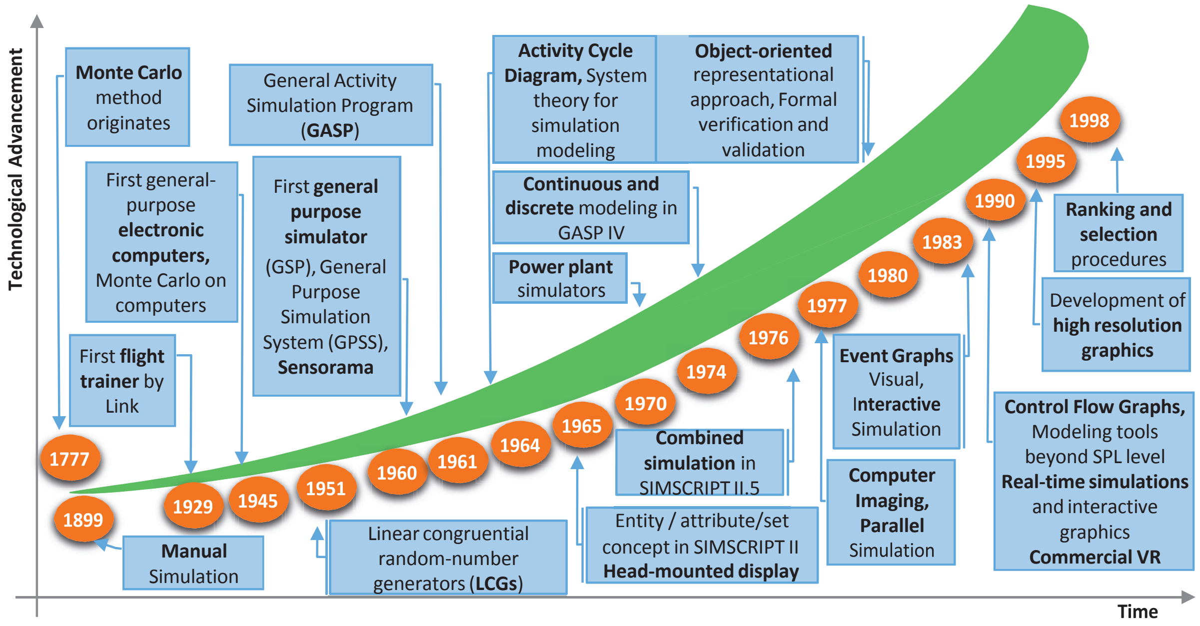

Figure 3. Historical Evolution of Simulation.

named Control Flow Graphs which are subsequently extended to Hierarchical Control Flow Graphs in order to help the control of representational complexity by Fritz and Sargent in 1995 [12]. In addition, the development of high-resolution graphics focuses on gaming industry surpassing in that way the military industry [9]. In 1997, Knuth describes comprehensively the random number generation techniques and tests for randomness [8]. The historic evolution of simulation is also depicted in (Figure 3).

1.4. Types of Simulation Models

Simulation models are categorised based on three basic dimensions: 1) timing of change, 2) randomness and 3) data organisation. Based on whether the simulation depends on the time factor or not, it can be classified into static and dynamic. A static simulation is independent of time while dynamic simulation evolves over time. Dynamic simulation can be further categorised to continuous and discrete. In discrete simulation, changes occur at discrete points in time while in continuous, the variable of time is continuous.

In addition, discrete simulation is divided to time-stepped and event driven. Time-stepped consists of regular time intervals and alterations take place after the passing of a specific amount of time. On the other hand, in event-driven simulation, updates are linked to scheduled events and time intervals are irregular. As far as the dimension randomness is concerned simulation can be deterministic or stochastic. Deterministic means that the repetition of the same simulation will result to the same output, whereas, stochastic simulation means that the repetition of the same simulation will not always produce the same output. Last but not least, simulation is classified to grid-based and mesh-free according to data organisation. Grid-based means that data are associated with discrete cells at specific locations in a grid and updates take place to each cell according to its previous state and those of its neighbours. On the other hand, mesh free relates with data of individual particles and updates look at each pair of particles [15], [16].

2. Simulation in product and production lifecycles

The following two sections present a mapping between the simulation methods and tools to product and production lifecycles (Figure 4).

2.1. Product and Production Lifecycle

Initially, the basic concept or idea for a product is conceived considering the initial request from a customer and, subsequently, it is transformed into a working prototype. Satisfaction of the initial customer request is followed by marketing appraisal of the product in relation to its potential demand from additional customers. If no further demand if foreseeable, then the product is retained in the design- and-build facility in order to relate the customers' voice to product design requirements, and translate these into characteristics

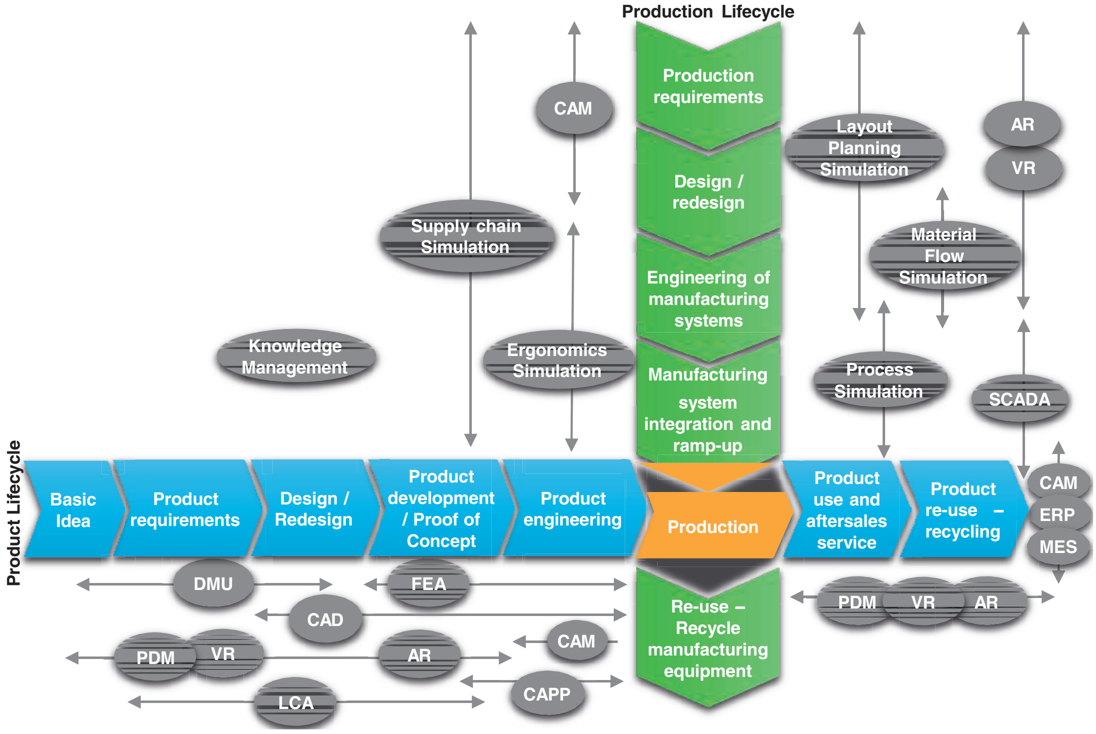

Figure 4. Mapping of Key-Enabling Technologies on Product and Production lifecycle [lifecycle phases adapted from EFFRA FoF 2020 Consultation Document]

of parts, manufacturing operations, and production requirements [17].

The aim of the product development process is to ensure that the product and its components meet the required specifications [18]. Thereinafter, innovative engineering allows collaborating teams to streamline the engineering of the product and of the production process engineering. The digital factory concept enables the integration of CAD designs and CAE information and the synchronisation of the engineering processes that require the participation of the entire value chain accessing all product information needed. Moreover, it provides the opportunity to all product-related teams to work together effectively without regard to physical location [19].

Following the production of the product, maintenance ensures that a system continually performs its intended functions at its designed level of reliability and safety [20]. At the end of product lifecycle, the product is recycled which means that the product retains its geometrical form and it is reused either for the same purpose as during its original life-cycle or for secondary purposes [21]. Instead of recycling, remanufacturing is used. Used or broken-down products or components are restored to useful life [22].

As far as production lifecycle is concerned, at first, the design stage starts with a stakeholder analysis to identify the constraints and degrees of freedom for the design. It should be mentioned that stakeholders have different interests in and requirements to the system [23].

After the specification of the requirements the design and redesign of manufacturing systems follows which is summarised as manufacturing system engineering (MSE). It is a complex, multi-disciplinary process that involves not only people located at different production sites, but also a variety of tools that support special subtasks of the process.

During the process development phase, the rough solutions from the design phase are refined to a level that allows investigation with analysis tools. If system dimensions are fixed, first contact with suppliers is established to integrate them in the further system definition [24]. In the final system definition phase, one solution is refined to a detail that allows to start system implementation. This phase is characterised by system integration, where previously identified subsystems are composed to a complete system. Fine tuning of subsystem cooperation and fixing of last details lead to the final system definition and emission of orders to suppliers [25].

As soon as the integration is completed the production ramp-up begins. It is defined as the period between the end of product development and full capacity production. Two conflicting factors are characteristic of this period: low production capacity, and high demand [26].

Finally, to face environmental problems, manufacturers undertake efforts on recycling namely, recovering materials or components of used equipment in order to make them available for new products or processes [27].

2.2. Product and Production Lifecycle Tools

Augmented Reality (AR)

Augmented Reality (AR) is defined as a real-time direct or indirect view of a physical real-world environment that has been enhanced/augmented by adding virtual computer-generated information to it. AR systems aim at enhancing the way the user perceives and interacts with the real world [28]. In the modern, highly competitive manufacturing environment, the application of augmented reality consists an innovative and effective solution to simulate, assist and improve the manufacturing processes. The challenge is to design and implement integrated AR-assisted manufacturing systems that could enhance the manufacturing processes, as well as product and process development, leading to shorter lead-times, reduced costs and improved quality [3]. In the field of automobile development, rudimentary car prototypes are completed by virtual components with the use of AR and design decisions [29]. In addition, the exploitation of AR environment in the rapid creation and modification of freeform surfaces is introduced and methods for enabling increased flexibility during exploratory, conceptual industrial product design through three-dimensional (3D) sketch-based user input are explored [30]. The facilitation of robot programming and trajectory planning is succeeded with the use of an AR-based system. The system takes into consideration the dynamic constraints of the robots but it is still limited as far as the achieved accuracy is concerned [31]. In order to enhance the perception of the user towards a product design, a fiducial marker is sent to the customer which can be used for AR visualisation via handheld devices. Each AR marker is mapped to specific 3D models and functionalities [32]. AR was applied through integrating a hybrid rendering of volume data, vision-based calibration, accurate real-time tracking methods, tangible interfaces, multimedia annotations, and distributed computation and communications at DaimlerChrysler [33].

Computer Aided Design (CAD)

Computer-Aided Design (CAD) is the technology related to the use of computer systems to assist in the creation, modification, analysis and optimisation of a design [34]. Nowadays, the strong competition in market increases significantly the level of requirement in terms of functionality and quality of products. At the same time, the complexity of the design process is increasing, whereas product development time is decreasing. Such constraints on design activities require efficient CAD systems and adapted CAD methodologies [18]. A Life Cycle-CAD (LC-CAD) provides an integrated design of a product and its life-cycle, manages the consistency between them and evaluates their performance concerning the environment and the economy with the use of simulation [35]. In addition, an effort is made in order to partially retrieve 3D CAD models for design reuse using a semantic-based approach [36]. A framework of collaborative intelligent CAD, which consists of the collaborative design protocol and the design history structure is proposed. It reasons redundant design, reduces design conflicts and is the basis for the implementation of more intelligent collaborative CAD systems [37]. Attention is paid to the fundamental activity of engineering using CAD systems with emphasis on CAD graphical user interfaces (GUIs) and how they can be potentially enhanced using game mechanics to provide more engaging and intuitive environments [38]. Innovative CAD methods for complex parts modelling in parametric CAD system are applied in the industry and presented by [18].

Computer Aided Process Planning (CAPP)

Process planning deals with the selection of necessary manufacturing processes and determination of their sequences to 'transform' the ideas of designers into a physical component economically and competitively [39]. Currently, manufacturing is moving towards a more advanced, intelligent, flexible and environmentally-friendly policy so it demands advanced and intelligent CAPP systems [40]. A holistic component manufacturing process planning model based on an integrated approach which combines technological and business considerations is developed in order to ameliorate decision support and knowledge management capabilities and advance the existing CAPP [41]. CAD/CAPP/CAM systems are integrated in order to evaluate alternative process plans in different levels, through which, the exploitation of the available resources and their optimal setup can contribute in the overall sustainability of the production facilities [42]. The authors in [43] introduce a highly specialised CAPP/CAM integrated system, called Generative Pattern Machining (GPM), for automatic tool paths generation to cut die pattern from the CAD model of the stamping die. GPM is being used by DaimlerChrysler pattern shop very successfully.

Digital Mock Up (DMU)

A digital mock-up (DMU) consists of 3D models which integrate the mechanical structure of a system [44]. A virtual prototype is created to identify problems in the initial design and it often leads to design changes and multiple iterations of the prototype as a means to optimize the design without the need for a physical model. This eliminates time and money and perhaps more importantly, the initial design and virtual prototype can be created with simultaneous input from every engineer involved in the project [45]. Digital mock-up is a rapidly evolving technology and a lot of advances are presented in this field. A heterogeneous CAD assembly method constructs a Digital Mock-Up system which facilitates the avoidance of mismatches and interferences during precision design processes [46]. Furthermore, a digital mock-up visualisation system can import giga-scale CAD models into the memory of a computer simultaneously based on a compression representation with triangular patches [47]. Also, DMU is applied for the verification and validation of the ITER remote handling system design utilizing a system engineering framework. The DMUs represent virtual remote handling tasks and provide accuracy and facilitation to the integration into the control system [44]. Moreover, AIRBUS Military researches the implementation of industrial Digital Mock-Up (iDMU) concept to support the industrialisation process of a medium size aero-structure [48]. Finally, coloring the DMU enables highlighting the required attributes from the customers. This method was tested and implemented in collaboration with Airbus [49].

Life Cycle Assessment (LCA)

Life cycle assessment is a data intensive analysis conceived to track, store and assess data over the entire product life cycle [50]. For a product to perform its function it must be developed, manufactured, distributed to its users and maintained during use. All these phases include supportive activities that consume resources and cause environmental impacts. In order to get an impression of this total impact, the analysis must focus on the product system or the life cycle of the product [21]. As a result of the environmental awareness, developments in the field are significantly increasing. The current and foreseen roles of sustainable bioprocess system engineering and life cycle inventory and assessment in the design, development and improvement are explored [51]. The dependence between the manufactured precision of a product and its environmental impact during its entire lifecycle is estimated with the use of an extended LCA methodology to evaluate the impact of manufacturing process precision on the functional performance of a product during its use phase [52]. Also, a computational approach for the simultaneous minimisation of the total cost and environmental impact of thermodynamic cycles is attempted with the exploitation of a combination of process simulation, multi-objective optimisation and LCA within a unified framework [53]. A methodology for the development of a reliable gate-to-gate LCA is integrated in a simulation tool for discrete event modelling of manufacturing processes and enables the characterisation of single machine behaviour and the evaluation of environmental implications of industrial operation management before the real configuration of the manufacturing line [50]. A methodology, implemented through a software tool, is used for the investigation of the environmental impact caused by centralised and decentralised manufacturing networks, under heavy product customisation [54]. Lastly, a wide variety of industrial applications in the field is presented by [21].

Product Data Management (PDM)

Product data management integrates and manages all the information that defines a product, from design to manufacture and to end-user support [55]. Current manufacturing industry is facing an increasing challenge to satisfy customers and compete in market. To stay competitive, manufacturing companies are adopting IT solutions to facilitate collaborations and improve their product development/production. Among these IT solutions, product data management (PDM) systems play an essential role by managing product data electronically [56]. A new concurrency control model for PDM succeeds in improving the concurrency ability of PDM systems by adapting the accessibility of entities according to the action that the users will perform and the product architecture of the entity [57]. A new concept of product as a pivotal element is proposed. The product incorporates all the information about itself which refers to a so-called ONTO-PDM "Product Ontology" and as a result, the information exchange between the systems related to it is succeeded by the minimisation of semantic uncertainty [58]. Concerning industrial applications, Unified Modelling Language-based approaches are used for modelling and implementing PDM systems especially concerning product structure and workflow [59].

Virtual Reality

Virtual Reality (VR) is defined as the use of real-time digital computers and other special hardware and software to generate the simulation of an alternate world or environment, believable as real or true by the users. VR is a rapidly developing computer interface that strives to immerse the user completely within an experimental simulation, thereby enhancing the overall impact and providing a much more intuitive link between the computer and the human participants [11]. VR has found application from the design to the process simulation phase [60]. Currently, new semantic-based techniques are introduced in order to facilitate the design and review of prototypes by providing usability and flexibility to the engineer / designer [61]. In the field of collaborative management and verification of design knowledge, a new platform, called DiCoDEv (Distributed Collaborative Design Evaluation), eases the cooperation among distributed design experts with the use of a shared virtual environment. The VR environment provides the multiple users with the capability of visualizing, immersing and interacting with the virtual prototype; managing efficiently the knowledge during the product design phase; collaborating in real-time on the same virtual object and reviewing it and making an ergonomic evaluation with the use of digital human simulation [62]. Furthermore, an intelligent virtual assembly system using an optimal assembly algorithm provide haptic interactions during the process of virtual assembly [63]. Another haptic VR platform, named as HAMMS, is introduced in order to facilitate the performance, the planning and the evaluation of virtual assembly of components [64]. Finally, VR tools are applied to fusion in ITER project facilitating maintenance and integration aspects during the early phase design [65].

Computer Aided Manufacturing (CAM)

Computer Aided Manufacturing (CAM) can be defined as the use of computer systems to plan, manage and control the operations of a manufacturing plant through either direct or indirect computer interface with the production resources of the plant. In other words, the use of computer system in non-design activities but in manufacturing process is called CAM [66]. The application of CAM in the production offers advantages to a company to develop capabilities by combining traditional economies of scale with economies of scope resulting in the desired flexibility and efficiency [67]. An effort is made in order to optimize the machining of complex shaped parts with flat-end tools with the use of a novel five-axis tool path generation algorithms [68]. A methodology facilitates the determination of global optimum tool paths for free form surfaces with the incorporation of an algorithm which aims at finding the optimal tool path and succeeding minimisation of the average cutting forces without exceeding a pre-set maximum force magnitude [69]. An integrated system of part modelling, nesting, process planning, NC programming and simulation and reporting for sheet metal combination processing functions has been applied in several sheet-metal manufacturing plants [70].

Enterprise Resource Planning (ERP)

An Enterprise Resource Planning (ERP) system is a suite of integrated software applications used to manage transactions through company-wide business processes, by using a common database, standard procedures and data sharing between and within functional areas [71]. ERP systems are becoming more and more prevalent throughout the international business world. Nowadays, in most production distribution companies, ERP systems are used to support their production and distribution activities and they are designed to integrate and partially automate financial, resource management, commercial, after-sale, manufacturing and other business functions in to one system around a database [72]. A literature-based and theory-driven model was developed in order to test the relationship between ERP system implementation status and operational performance [73]. Moreover, a general risks taxonomy for ERP maintenance is investigated with the use of analytic hierarchy process [74]. An objectives-oriented approach with one evaluation model and three optimisation models addresses key management issues in the implementation of critical success strategies (CSSs) to ensure the success of an ERP project [75]. In order to deal with the problem of independence in risk assessment, an approach using Coloured Petri Nets is developed and applied to model risk factors in ERP systems [76].

Ergonomics Simulation

Ergonomics are defined as the theoretical and fundamental understanding of human behaviour and performance in purposeful interacting socio-technical systems, and the application of that understanding to design of interactions in the context of real settings [77]. In the past, workplace ergonomic considerations have often been reactive, time-consuming, incomplete, sporadic, and difficult. Ergonomic experts who were consulted after problems occurred in the workplace examined data from injuries that had been observed and reported. There are now emerging technologies supporting simulation-based engineering to address this in a proactive manner. These allow the workplaces and the tasks to be simulated even before the facilities are physically in place [78]. The comparison between ergonomic measurements in virtual and real environments during some specific task is analysed in [79]. Also, with the use of USAs

VR Lab, named "HEMAP", training simulations were explored and ergonomic risks were estimated and spacecraft flight systems were evaluated as part of the design process [80]. ErgoToolkit implements ergonomic analysis methods, already available in literature or company practice, into digital tools for ergonomics, namely, Posture Definition and Recognition and Stress Screening, integrated into state-of-the-art virtual manufacturing software. [81]. An approach to human motion analysis and modelling which respects the anthropometric parameters is tested and the real motion data are collected and processed with the use of statistical methods and the models that are produced can predict human motion and direct digital humans in the virtual environment [82].

Knowledge Management

Knowledge Management (KM) is defined as the process of continuously creating new knowledge, disseminating it widely through the organisation, and embodying it quickly in new products/services, technologies and systems [83]. KM is about facilitating an environment where work critical information can be created, structured, shared, distributed and used. To be effective such environments must provide users with relevant knowledge, that is, knowledge that enables users to better perform their tasks, at the right time and in the right form. KM has been a predominant trend in business in the recent years [84]. Firstly, an explorative study on the Personal Knowledge Management is conducted and an active knowledge recommender system model, which is built on distributed members personal knowledge repositories in the collaborative team environments, is proposed [85]. Moreover, the implementation process of Lean Production and forms to classify knowledge are introduced in [86]. A pattern-based approach to knowledge flow design starts from basic concepts, uses a knowledge spiral to model knowledge flow patterns and operations, and lays down principles for knowledge flow network composition and evolution [87]. As far as the industrial applications of knowledge management is concerned, a framework for marketing decision making with the use of agent technology, fuzzy AHP (Analytical Hierarchy Process) and fuzzy logic is implemented in a car factory [88].

Layout Planning Simulation

Facility layout planning (FLP) refers to the design of the allocation plans of the machines/equipment in a manufacturing shop-floor [89]. Factory layout design is a multidisciplinary, knowledge-intensive task that is of vital importance to the survival of manufacturers in modern globally competitive environment. The need to design and construct a new factory layout or reconfigure the current one has increased largely because of the fast changes in customer demand both from product quantity and product variety aspects. This requires companies to be more agile to plan, design and reconfigure the factory layout to be able to introduce new products to market and keep their competitive strength [90]. Using predefined objects, a layout model can be implemented in 3D avoiding the drawing stage of the equipment and virtual reality factory models created provide the user with the ability to move through factory mock-ups, walk through, inspect, and animate motion in a rendered 3D-factory model [91]. Moreover, a method implemented in a web-based tool is able to generate job rotation schedules for human based assembly systems [92]. A method of deriving assembly line design alternatives and evaluating them against multiple user-defined criteria is applied in an automotive case [93]. An AR-based application is developed which aims at meeting the need and demands of an AR-supported factory and manufacturing planning, usability, analysis functionalities and accuracy demands. It provides the user with the necessary tools for production planning and measuring tasks [94].

Manufacturing Execution Systems (MES)

A manufacturing execution system (MES) is a system that helps manufacturers attain constant product quality, comply with regulatory requirements, reduce time to market, and lower production costs. As manufacturers strive to become more competitive and provide world-class service to their customers, emphasis has been placed on total quality management (TQM) programs. The need for a quality manufacturing system solution is a driving factor creating the demand for MES. The functions of MES are consistent with the goals of TQM applied to industrial manufacturing companies [95]. A holonic MES that utilizes a given schedule as a guideline for selecting among task execution alternatives, which are independent from the original schedule, is proposed [96]. An innovative design and verification methodology for an autonomic MES is presented. Its basis consists of well-defined interactions between autonomic agents which perform the monitor-analyse-plan-execution loop and simultaneously they manage orders and resources [97]. This system was extended to allow selfish behaviour and adaptive decision-making in distributed execution control and emergent scheduling [98]. A Radio Frequency Identification (RFID)-enabled real-time manufacturing execution system is proposed and tested in a collaborating company which manufactures large-scale and heavy-duty machineries. On the shop-floor, RFID devices are used in order to track and trace manufacturing objects and acquire real-time production data and identification and control of disturbances [99].

Material Flow Simulation

Materials flow within manufacturing is the movement of materials through a defined process or a value stream within a factory or an industrial unit for the purpose of producing an end product [100]. In today's changing manufacturing world with new paradigms such as mass customisation and global manufacturing operations and competition, companies need greater capabilities to respond quicker to market dynamics and varying demands. The adoption of suitable production and materials flow control (PMFC) mechanisms, combined with the implementation of emergent technologies, can be of great value for improving performance and quality of manufacturing and of service to customers [101]. An automated motion planning framework, integrated into the scene modelling workflow from a material flow simulation framework generates automatically motion paths for moving objects. It depends on an actual model layout and it avoids collision with other objects [102]. An integrated planning approach for the evaluation and the improvement of the changeability of interlinked production processes before the event actually takes place is proposed. The key element of the approach is the use of material flow simulation of variant scenarios [103]. An approach is designed to support the management of a ship repair yard by integrating in an open and flexible system a number of critical business functions with production planning, scheduling and control. This approach is implemented in a software system fully developed in Java and designed by using UML [104]. An assignment logic of the workload to the resources of a dairy factory has been implemented in a software system. The system simulates the operation of the factory and creates both a schedule for its resources and a set of performance measures, which enable the user to evaluate the proposed schedule [105]. A P3R-driven modelling and simulation system in Product Lifecycle Management (PLM) is introduced and implemented in automotive press shops. It consists of a P3R data structure for simulation-model generation, an application based on the P3R object-oriented model and a concurrent material flow analysis system [106].

Process Simulation

A manufacturing process is defined as the use of one or more physical mechanisms to transform the shape of a material's shape and/or form and/or properties [1]. Newly emerging composite manufacturing processes, where there exist only limited industrial experience, demonstrate a definite need for process simulations to reduce the time and cost associated with the product and process developments [107]. The FEDES software (Finite Element Data Exchange System) included case studies for simulation of manufacturing process chains including aero-engine components [108]. A simulation-based approach for modelling and dimensioning process parameters in a process chain as well as the corresponding technological interfaces are introduced [109]. Procedure models for an efficient and target figure dependent analysis including identification, categorisation, prioritisation and interdependencies of a big variety of process parameter constellations by means of the developed simulation models are presented in [110]. A methodology of sequentially simulating each step in the manufacturing process of a sheet metal assembly is proposed [111].

Supervisory Control and Data Acquisition (SCADA)

SCADA is the technology that enables a user to collect data from one or more distant facilities and to send limited control instructions to those facilities [112]. Certain services in our society are essential to our way of life, including clean water, electricity, transportation, and others. These services are often manufactured or delivered using Supervisory Control and Data Acquisition (SCADA) systems. An integrated framework for control system simulation and near-real-time regulatory compliance monitoring with respect to cybersecurity named SCADASim is presented [113]. The vulnerabilities caused by interdependencies between SCADA and System Under Control are examined and analysed with the use of a five-step methodical framework. A significant step of this framework is a hybrid modelling and simulation approach which is used to realize identification and assessment of hidden vulnerabilities [114]. The interdependencies between industrial control systems, underlying critical infrastructures and SCADA are investigated in order to address the vulnerabilities related to the coupling of these systems. The modelling alternatives for system-of-systems, integrated versus coupled models, are also under discussion [115]. SCADA systems are applied worldwide in critical infrastructures, ranging from power generation, over public transport to industrial manufacturing systems [116].

Supply Chain Simulation

A supply chain is the value-adding chain of processes from the initial raw materials to the ultimate consumption of the finished product spanning across multiple supplier-customer links [117]. Modern manufacturing enterprises must collaborate with their business partners through their business process operations such as design, manufacture, distribution, and after-sales service. Robust and flexible system mechanisms are required to realize such inter-enterprises collaboration environments. A generic hybrid-modelling framework for supply chain simulation is presented in [119]. A method to model, simulate and optimize supply chain operations by taking into consideration their end-of-life operations is used to evaluate the capability of OEMs to achieve quantitative performance targets defined by environmental impacts and costs of lifecycle [120]. A method of examining multi objective re-configurability of an Original Equipment Manufacturer supply chain is presented in order to adapt with flexibility dynamically changing environmental restrictions and market situations [121]. A discrete-event simulation model of a capacitated supply chain is developed and a procedure to dynamically adjust the replenishment parameters based on re-optimisation during different parts of the seasonal demand cycle is explained [122]. A model is implemented in the form of Internet enabled software framework, offering a set of characteristics, including virtual organisation, scheduling and monitoring, in order to support cooperation and flexible planning and monitoring across extended manufacturing enterprise [118]. Finally, the application of the mesoscopic simulation approach to a real-world supply chain example is illustrated utilizing the software MesoSim [119][123].

Manufacturing Systems and Networks Planning and Control

A modern manufacturing network is composed of cooperating OEM plants, suppliers and dealers that produce and deliver final products to the market [124]. Original Equipment Manufacturers (OEMs) operate in highly competitive, volatile markets, with fluctuating demand, increasing labour costs in developing countries, and new environmental regulation [125]. Driven by the ever increasing need to reduce cost and delivery times, OEMs are called to efficiently overcome these issues by designing and operating sustainable and efficient manufacturing networks. The complexity and the stability of manufacturing systems is investigated by introducing concepts based on discrete event simulation and nonlinear dynamics theory. [126]. Furthermore, the evaluation of the performance of automotive manufacturing networks under highly diversified product demand is succeeded through discrete-event simulation models with the use of multiple conflicting user-defined criteria such as lead time, final product cost, flexibility, annual production volume and environmental impact due to product transportation [127]. Alternative network designs are proposed and evaluated through a set of multiple conflicting criteria including dynamic complexity, reliability, cost, time, quality and environmental footprint [124]. A method implemented in a software tool comprises of a mechanism for the generation and evaluation of manufacturing network alternative configurations [128]. A continuous modelling approach for supply chain simulation was applied in the automotive industry and depicted that initial inventory levels and demand fluctuation can create delivery shortages and increased lead times [129].

3. Comparison of material flow and layout design simulation tools

Focusing on the areas of material flow simulation and layout design, a review is hereafter attempted for some of the market leading tools [130] in these types of simulation. The tools are Anylogic by Anylogic [131], Arena by Rockwell Automation [132], FlexSim by FlexSim Software Products [133], Plant simulation by Siemens [134] and Witness by Lanner [135].

Criteria for comparing the simulation tools

The review of the above software tools was based on criteria derived by Gupta et al., (2010) [136] and Carrie A., (1988) [137] and adjusted to the purposes of this paper. Four main groups of criteria are developed and they are classified.

Firstly, hardware and software considerations are examined such as coding aspects, software compatibility and user support. The capability of additional coding provides the user with flexibility and robustness, facilitating the modelling of complex systems. Software compatibility refers to the interaction of the tool with others in order to exchange data which is vital for the efficient modelling of manufacturing systems. User support including documentation, demos, tutorials and services provided by the software supplier are also examined. Criteria for modelling capabilities are investigated and more particularly general features and modelling assistance. General features include the purpose of the software, the experience required for developing a model and the ease of use. In addition, modelling assistance refers to the comprehensiveness of prompting, namely if the software succeeds in providing helpful and understandable prompting to facilitate the model development, on-line help if it is provided and whether the package provides satisfactory libraries and templates. Moreover, emphasis is given on simulation capabilities. Visual aspects are related to the type and quality of graphical facilities provided by the software. Another significant criterion is, of course, the efficiency of the package expressed by its capability to model a complex system, to improve the quality and to save time needed for the complete model. Furthermore, testability, which is the facilities for the verification of the model, is examined. Experimentation facilities include the improvement of the quality of the simulation results and the speed of the experimentation process. The provision of statistical data and the way they are collected by the user are also taken into consideration. Last but not least, input/output issues are considered. The way the results are presented and the type and the quality of output reports are of high significance. Also, the analysis that the specific package provides is evaluated as well as its manufacturing capabilities. The developed scale from 1 to 5 star is as follows (Table 1):

Table 1. Rating scale for the characteristics of simulation tools.

Number of stars	Significance
*	Inadequate
**	Adequate
***	Satisfactory
****	Very satisfactory
*****	Outstanding

A model of a flexible manufacturing system (FMS) was adapted from the literature and specifically, from Chryssolouris et al. (1992) [138].

It consists of:

- five five-axis machining centres, each machine has 90 tools and a tool exchange station
- three automated guided vehicles (AGVs) that follow a wire guided path and are used for the delivery of tools and workpieces to the machine
- an automatically control washing station
- a Coordinate Measuring Machine (CMM)
- two material review stands for on-demand part inspection
- one tool pre-set and load area
- two ten-pallet carousels for setting up work-pieces, tombstones, or any other appropriate fixture, with each carousel containing two load/unload stations

The types of parts loaded in the example are assumed to be independent of the FMS operation as they are determined from factors outside the system. Each part has different operations to be performed and arrives at the FMS accompanied by a process plan (namely, a set of instructions that determine the sequence of the different operations as well as their technological constrains).

Firstly, the parts arrive at the loading station of the FMS. As they arrive and as a pallet is available, they are fixtured on the 2 ten-pallet carousels. The parts are held on the carousel until they are picked up by an AVG and brought to any of the different work centres. Once a part leaves the loading station, it remains within the system till is finished. Upon completion of a part, an AVG will bring the part back to the loading station where it will be unloaded, removed from the station, and further processed through the rest of the manufacturing system. The FIFO (First In First Out) rule is utilised for the assignment of each part to the proper AVG and work-centre.

In order to facilitate the modelling, the following assumptions are made based on the real system. At first, tools are available to perform any operation on any part. The processing times for transportation are considered to be equal, irrespective of where the AVGs are and what part they carry. The parts arriving at the FMS consist of a number of operations. These parts are accompanied by a process plan which determines the operational characteristics of the different operations as well as the sequence of these operations. Finally, resources within one work centre are assumed to have the same technological characteristics, although they may have different operating costs and operations assigned to one resource or another may have different processing times. Nevertheless, all resources within a work centre are capable of performing any operation assigned to the work centre. In parallel processing terminology, the resources within a work centre are assumed to be unrelated (Table 2). The results from the comparison are depicted in Table 3.

Table 2. Input data to the simulation model.

Operation	Processing time (minutes)		Operating costs($)	
	min.	max.	min.	max.
Machining	20	100	30	45
Inspection	10	20	60	75
Review	5	10	60	75
Washing	5	10	6	
Transportation	2 (average)		6	

Operation sequencing information

	JT-1	JT-2	JT-3	JT-4	JT-5	JT-6	JT-7	JT-8	JT-9	JT-10
Task 1	M	M	M	M	M	M	M	M	M	M
Task 2	R	W		W	W	W	W	R	R	W
Task 3	M	M		I		I	I		W	I
Task 4	I	I		M		R	M		M	
Task 5	W			R			W			

Arrivals	10 x 8-hours shifts	
Arrival rates (mean Poisson distribution)	JT-1,2,4,7.9 0.00275	JT-3,5,6,8,10 0.0055
Different part types	10	

Table 3. Comparative matrix of commercial simulation tools.

Criteria Groups	Comparison Criteria	Simulation Software Tools				
		AnyLogic	Arena	Flexsim	Plant Simulation	Witness
Hardware and Software	Coding aspects	****	***	**	****	**
	Software compatibility	***	**	***	****	***
	User support	****	**	****	****	***
General features	Purpose	General	General	General	General	General
	Experience required	***	****	**	***	**
	Ease of use	***	**	**	***	****
Modelling assistance	On-line help	****	**	****	***	**
	Library and templates	***	**	****	****	***
	Comprehensiveness of prompting	***	**	***	***	***
Simulation capabilities	Visual aspects	****	**	*****	****	***
	Efficiency	****	**	****	****	***
	Testability	****	***	****	****	***
	Experimentation facilities	***	***	****	****	***
	Statistical data	****	***	****	****	****
Input / Output	Input/output capabilities	****	***	****	*****	****
	Manufacturing capabilities	****	**	****	****	*****
	Analysis capabilities	***	***	****	****	***

4. Conclusions and future trends

Digital manufacturing technologies have been considered an essential part of the continuous effort towards the reduction in the development time and cost of a product as well as towards the expansion in customisation options. The simulation-based technologies constitute a focal point of digital manufacturing solutions, since they allow for the experimentation and validation of different product, process and manufacturing system configurations. The simulation tools reviewed in this research are constantly evolving and they certainly lead towards more efficient manufacturing systems. But, in the current highly competitive business environment, which is constantly facing new challenges, there is always need for even more efficient and adaptive technologies. Hereafter, the identification of the major gaps of each simulation related key enabling technology are discussed and future trends are outlined.

Augmented Reality

AR applications in manufacturing and design requires a high level of accuracy in tracking and superimposition of augmented information. Very accurate position and orientation tracking will be needed in operations such as CNC simulation and robot path planning. Computer-vision-based tracking will not be able to handle high frequency motion as well as rapid camera movements. Hybrid systems using laser, RFID and other types of sensing devices will be required. Another basic issue in AR is the placing of virtual objects with the correct pose in an augmented space. This is also referred to as Registration. As different tracking methodologies possess their own inherent deficiencies and error sources, it is necessary to study the best tracking method for a particular application which could be subject to poor lighting condition, moving objects, etc. AR displays require an extremely low latency to maintain the virtual objects in a stable position. An important source of alignment errors come from the difference in time between the moment an observer moves and the time the corresponding image is displayed. This time difference is called the end-to-end latency, which is important as head rotations can be very fast and this would cause significant changes to the scene being observed. Further research should focus on the setup of an AR environment which consists of four essential elements: target places, AR content, tracking module and display system [139].

Computer Aided Design

Current deficiencies and limitations of current CAD tools are the complexity of menu items or commands, the limitation of active and interactive assistance while designing in CAD and the integration of informal conceptual design tools in CAD. Moreover, current tools include inadequate human–computer interface design; focused on functionality but not on usability and fixation on design routines [139].

Computer Aided Process Planning

To fulfil the needs of modern manufacturing processes, computer-aided process planning should be responsive and adaptive to the alterations in the production capacity and functionality. Nowadays, conventional CAPP systems are incapable of adjusting to dynamic operations and a process plan, created in advance, is found improper or unusable to specific resources. This phenomenon results in spending a significant amount of time and effort unnecessarily [140].

Digital Mock Up

According to the reviewed literature, DMU scope has to be extended to the services function. Services engineers are also stakeholders of the product development and should be able to exploit the DMU to design services [48].

Virtual Reality

Moreover, VR tools should be integrated not only in the central planning phases, but in every phase of the factory planning process. VR should not only be used for visualisation means, but also for collaborative and communicative means [141]. VR is now used in many industrial applications and cuts costs during the implementation of a PLM. The main challenges are a result of the following drawbacks. Implementation of a CAE simulation is a time-consuming process and VR systems used in industry focus on one or a few particular steps of a development cycle (e.g. design review), and may be used in the framework of the corresponding product development project review. There is no VR tool in the current state of the art which enables us to deal globally with the different steps of the PLM and the corresponding projects reviews [142].

Lifecycle Assessment

A few challenges concerning LCA that should be highlighted are LCA modularisation and standardisation of environmental profiles for machine tools. Also, "hidden flows'' modelling should be addressed and data accuracy should be ameliorated. Last but not least, value stream mapping is of high importance [50].

Product Data Management

As far as the future trends in the field of PDM are concerned, the efficiency of these systems can be further enhanced by studying factors that affect the accessibility of product data, for example, the nature of data in different timeframe of a development, the relationship between the maturity of the data and the probability of them being modified [57].

Computer Aided Manufacturing

As a result of the dynamically changing and evolving manufacturing environment, the need is presented for effective coordination, collaboration and communication amongst all the aspects of production, from humans to machines. The future CAM systems need to focus on collaborative technics, effective communication and efficient data exchange [67].

Enterprise Resource Planning

Future trends of ERP systems, on technological level, include software as a service, mobile technology and tightly integrated business intelligence. The tendency of being able to obtain ERP functionality as a service has to be mentioned. Especially in the mid-market, the ERP suites will no longer be hosted internally but instead will be obtained as a service offered by the ERP provider. New ways of providing software are to be investigated, mainly linked with the development of cloud computing [143]. In addition, access to information with the use of mobile devices has become a reality even for end consumers over the last years. The ERP system providers should face these challenges by offering mobile-capable ERP solutions [144], [145]. Another important issue is the reporting and data analysis which grows with the information needs of users. Business Intelligence (BI) is becoming not only easier to use over time but also tighter integrated into ERP suites [72].

Ergonomics Simulation

Many advances have been made during the last decades, and the amount of possible applications is growing in the field of ergonomics. Yet much research has still to be conducted for many open issues. Systems' complexity and number of features are only increasing and ways of effectively implementing them should be explored. The interaction between models is required, as well, for an integrated approach of common daily design problems which is directly related to an integration of models into an encompassing DHM. Moreover, techniques for measuring human quantities, which has not become easier despite the evolution of the technical means, should be evolved. Another issue is the harmonisation of the data representation in different disciplines. Without such agreement it will remain extremely difficult to develop integrated models [146].

Knowledge Management

Agent-oriented approaches to knowledge management and collaborative systems need further development. Methodologies are needed that support the analysis of knowledge management needs of organisations and its specification using software agents and agent societies. Also, reusable agent-oriented knowledge management frameworks, including the description of agent roles, interaction forms and knowledge description should be developed. The existence of agent-based tools for organisational modelling and simulation that help determine the knowledge processes of the organisation is crucial. Finally, research should focus on the role of learning in agent-based KM systems, namely, how to use agent learning to support and extend knowledge sharing [84].

Layout Design Simulation

Today, in the field of layout design simulation, some commercial software can represent decoupling data from 3D model and export them in XML or HTML format. While this is an export of properties, this cannot fully solve the interoperability and extensibility issues since the interoperability depends on how the different software and users define contents of data models [90].

Manufacturing Execution Systems

In the turbulent manufacturing environment, a key issue of modern Manufacturing Execution Systems is that they cannot plan ahead of time. This phenomenon is named decision myopia and causes undoubtedly significant malfunctions in manufacturing [96].

Process Simulation

The planning, the data transfer and the optimisation of manufacturing process chains must be integrated into a common model. Moreover, the macro-scale manufacturing process chains are optimised with simulation tools using numerical techniques such as the FEM while the micro-scale manufacturing process chains are mainly optimised by experimental approaches. This shows that the macro-scale manufacturing process chains are more mature than the micro-scale manufacturing process chains in terms of modelling and simulation which indicates that modelling and simulation of micro-scale manufacturing process chains is still a challenge. Also, the macro-scale manufacturing processes chains are not fully understood and there are still challenges for improving the manufacturing process chains related to different industries and development of new manufacturing process chains for new emerging applications [108].

Material Flow Simulation

Moreover, while the steady decline in computational cost renders the use of simulation very cost-efficient in terms of hardware requirements, commercial simulation software has not kept up with hardware improvements. Concerning material flow simulation, it can be very time-consuming to build and verify large models with standard commercial-off-the-shelf (COTS) software. Efficient simulation-model generation will allow the user to simplify and accelerate the process of producing correct and credible simulation models [106].

Supervisory Control and Data Acquisition

Whilst SCADA systems are generally designed to be dependable and fail-safe, the number of security breaches over the last decade shows that their original design and subsequent evolution failed to adequately consider the risks of a deliberate attack. Although best practices and emerging standards are now addressing issues which could have avoided security breaches, the key problems seem to be the increased connectivity and the loss of separation between SCADA and other parts of IT infrastructures of organisations [116].

Supply Chain Simulation

Identifying the benefits of collaboration is still a big challenge for many supply chains. Confusion around the optimum number of partners, investment in collaboration and duration of partnership are some of the barriers of healthy collaborative arrangements that should be surpassed [147].

Manufacturing Systems and Networks Planning and Control

Existing platforms do not tackle the numerous issues of manufacturing network management in a holistic integrated manner. The results of individual modules often contradict each other because they refer to not directly related manufacturing information and context (e.g. long term strategic scheduling vs. short term operational scheduling). The harmonisation, both on an input / output level and to the actual contents of information is often a mistreated issue that hinders the applicability of tools to real life manufacturing systems.

General Challenges

Apart from the gaps for each technological method / tool, general future challenges and trends are discussed in the following section.

Firstly, developers of simulation tools are gradually introducing cloud-based technologies in order to facilitate the mobility of the applications and the interoperability between different partners. Currently, only few commercial tools have integrated this function. Moreover, the even more complex processes and products demand high performance simulations which require powerful and expensive CPUs. In addition, efforts are being made towards the creation of application that run in multiple and mobile devices. The extended use of open and cloud-based tools can address these problems and result in high performance computing at a minimum cost.

Nowadays, simulation software tools usually offer only dedicated application object libraries for developing fast and efficient models of common scenarios and they can be characterised as limited concerning the broad field of manufacturing. Another issue is that while there is a great variety of functions and resources, the vast majority of tools are focused only to a small percentage of them. There is also a lack of proper data exchange among different domains and few or no common standards or integrated frameworks, which cause difficulties in the interoperability and collaboration between systems and partners. The use of incremental model building, on the one hand allows in-process debugging and on the other hand increases the complexity of the model. All the issues could be address with the development and utilisation of multi-disciplinary and multi-domain integrated simulation tools.

As far as the lifecycle simulation is concerned, the poverty of adequate modelling tools should be noted. Only few applications take into serious consideration product life-cycle costs and environmental issues. In addition, tools usually aim at the re-manufacturing of specific product types and they are still insufficient for de-manufacturing of products. So, the researchers should focus on the development of tools for the field of lifecycle management.

Currently, object-oriented, hierarchical model of plants, encompassing business, logistic and production processes exist but the direct integration of modelling tools with CAD, DBMS (ORACLE, SQL Server, Access, etc.), direct spreadsheet link in/out, XML save format, HTML reports is still limited. As a result, simulation tools that will assure the multi-level integration among them should be developed.

Gradually, enterprises are starting to adopt the concept and the models of the virtual factory. But, still the technologies related to virtual factory and especially these concerning data acquisition, control and monitoring are still in their infancy, expensive, complicated and hard to apply. So, the research should move towards the direction of real-time factory controlling and monitoring and applicable and affordable tools should be developed.

Effort is made in order to create smart, intelligent and self-learning tools. The current practice involves integrated neural networks and experiment handling, inbuilt algorithms for automated optimisation of system parameters and custom model. Moreover, there are applications that base on empirical or past data and some knowledge-based advisory systems. Although, satisfactory, analytical simulation capabilities in continuous processing units can be noticed, research is required in order to develop more intelligent tools that will lead to autonomous and-self adapting systems.

The use of simulation for human-centred learning and trainings should be evolved and spread. Currently, it is used restrictedly in the fields of aviation and automotive due to the fact that it is costly and time-consuming but if affordable tools are developed, the trainings will become more effective in the long run.

Last but not least, the complexity of existing frameworks used in the design phases is increased and requires high skill and long processing time which, as a result, do not facilitate the use of crowdsourcing.

In conclusion, there is a significant evolution of simulation tools but they are still undoubtedly a fertile field of research.

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