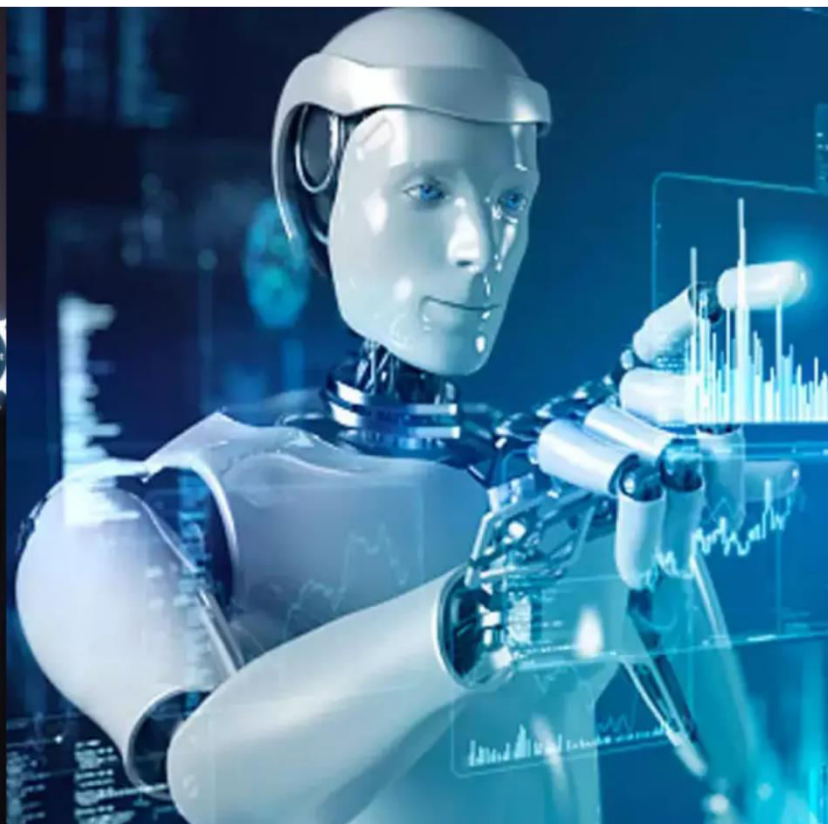




International Journal of Innovative Research in Science Engineering and Technology (IJIRSET)

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)



Impact Factor: 8.699

Volume 14, Issue 8, August 2025

A Critical Review on the Journey of Digital Manufacturing from Origins to Innovations Ahead

¹Dr. Pravin Dharmraj Patil, ²Dr.D.S. Deshmukh, ³Dr. Pawan D. Meshram, ⁴Dr. Dinesh D. Puri, ⁵Dr. Dipak C. Talele

¹Assistant Professor, Department of Mechanical Engineering, S.S.B.Ts, College of Engineering & Technology, Bambhori, Jalgaon, Maharashtra, India

²Principal & Professor of Mechanical Engineering at Madhukarrao Pandav College of Engineering, Bhandara, MS, India

³Associate Professor and Head, Department of Oil Technology, UICT, KBCNMU, Jalgaon, Maharashtra, India

⁴Associate Professor, S.S.B.Ts College of Engineering & Technology, Bambhori, Jalgaon, Maharashtra, India

⁵Assistant Professor, Department of Mechanical Engineering, S.S.B.Ts College of Engineering & Technology, Bambhori, Jalgaon, Maharashtra, India

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, shop floor 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.

Digital manufacturing technology is a broad category, in many ways much broader than the CAD technology marketplace. In the CAD world the output is basically a 3D geometric model, 2D drawing, and possibly some non-graphic or textural attributes that describe non-geometric properties like colour, weight, and part number. Digital manufacturing technology needs to simulate a much broader variety, as it is the link from the virtual world where products and their associated manufacturing processes are defined, to the physical world where products are physically produced. Components can be produced using many different technologies including subtractive machining processes like milling and turning; formed by stamping and forging; moulded via compression, injection, or transfer process; built up using additive techniques like composite layups; and even by rapid prototyping.

KEYWORDS: Digital Manufacturing, CAD/CAM, CAE, CAPP, CIM, Simulation.

I.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. 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. 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.

Companies of all sizes are realizing that digital manufacturing solutions can be used to define, simulate, validate, and improve manufacturing processes without the cost and time often associated with physical trial and error. Flexible manufacturing concepts enable companies to design a cell, production line, and even an entire factory, to produce a variety of products by reconfiguring existing equipment. Lean is a system or methodology developed in Japan that seeks to reduce waste in manufacturing processes. Just as product engineering uses CAE technology to simulate product performance in many scenarios or use cases, digital manufacturing enabling technologies can be used to design and simulate the production facility—including its layout, tools, equipment, fixtures, and processes—with lean concepts fully integrated. This paper discusses these issues and illustrates through two case studies how manufacturing companies can benefit from various digital manufacturing enabling solutions today.

II. LITERATURE SURVEY

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, 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. 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. 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. 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.

III. DIGITAL MANUFACTURING COMPONENTS

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. 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 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 introduced a discrete Digital Manufacturing 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 presented a novel semi generative 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. 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. 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), thermo- dynamics, and robotics. For instance, Brinksmeier 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, it has also enabled the direct link between the three-dimensional (3D) CAD model and its production. Newman and Nassehi 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 product and then physically to perform the manufacturing process with minimum error probability. Other systems, such as computer- aided quality 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. Digital Manufacturing 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. 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.

- *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.

- *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.

Simulation models are categorized into static, dynamic, continuous, discrete, deterministic, and stochastic. 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’.

- *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 hard-ware 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. 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.

- *Process Definition & Optimization*

“Process definition, simulation, and optimization,” from a digital manufacturing perspective, is generally referred to as manufacturing process management (MPM). In general, MPM is a collection of technologies and methods used to define how best to manufacture a given product.

MPM is a holistic approach to defining optimized manufacturing processes by using a set of integrated tools often governed by a central information repository (e.g., a PDM system).

IV.RECENT DEVELOPMENTS

- *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.

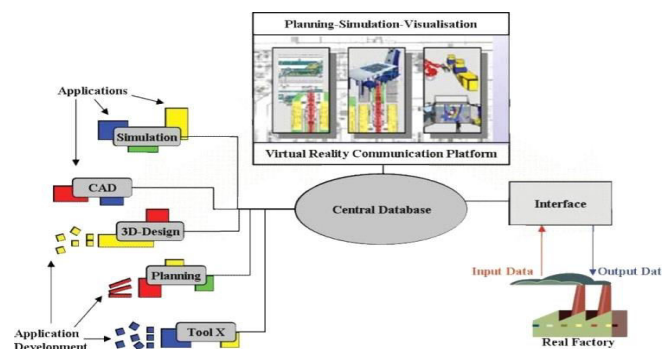


Fig. 1 The vision of the digital factory

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. 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. 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. Human motion simulation for integrating human aspects in simulation environments has been another key field of interest (Fig. 3). 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.

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. Research activities have been

|DOI: 10.15680/IJIRSET.2025.1408036|

also launched for the definition and implementation of VR- and augmented-reality-based collaborative manufacturing environments, which are applicable to human-oriented production systems.

- *Industrial Activity & Practices*

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.

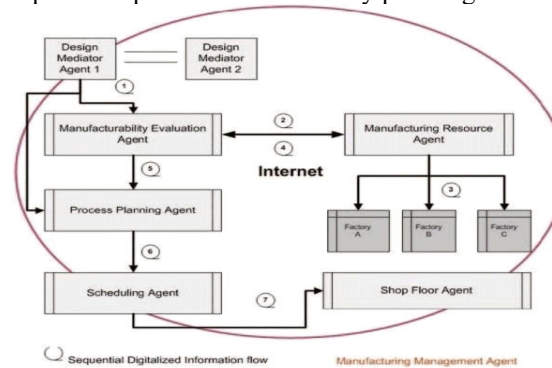


Fig. 2 A web-based multi-agent system framework



Fig. 3 Human simulation in digital manufacturing environments

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. 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. Similarly, General Motors has utilized a three-dimensional work cell 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. 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. BMW and DaimlerChrysler are also among the users of similar applications. General Motors has used DES in several case studies and has demonstrated the ability of using simulation for optimizing resources and identifying constraints. 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. The method of digital planning validation (DPV) has recently gained some interest (Fig. 5). 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.

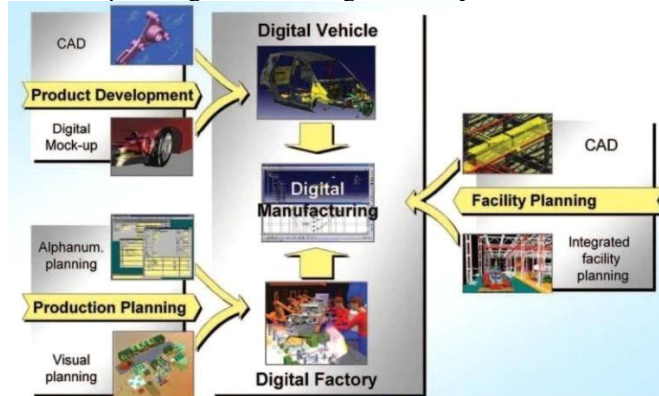


Fig. 4 Digital manufacturing links product development, production planning, and facility planning

The so-called virtual process week is another relevant method applied to BMW working practices. 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. 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.

V.DIGITAL MANUFACTURING

The Missing Link

While product-engineering groups have been leveraging computer-aided (i.e., digital) technologies for many years, their manufacturing-engineering colleagues have, for the most part, only been using digital manufacturing simulation and other related tools for a rather short period of time— and when used, they have been relegated to a small niche where failure in manufacturing production was not an option. The latest implementations of digital manufacturing tools enable closed loop simulation and change impact analysis from product concept through production. In general, CIMdata defines digital manufacturing as systems that support the definition of processes used to produce a product, including supporting simulation and analysis of those processes, and the manufacturing environments used to produce the product, including production equipment and lines.

• 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. 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. 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.

By exploiting digital manufacturing, manufacturing enterprises expect to achieve the following:

- (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.

VI. APPLICATIONS

- Data synchronization from design through manufacturing in an enterprise information management environment, including linkage and data integration among CAD, CAM, tool design, ERP, MES, and other software applications.
- A systematic, structured, visual, and analytical approach to part and assembly computer-aided process planning to obtain an optimal process solution. Establishing and cataloguing manufacturing constraints, costs, throughputs, and best practices is also performed.
- Detailed line, cell, station, and task design for part manufacturing and assembly process management, including plant design and creation of mechanical assembly-line layouts.
- Discrete event simulation of manufacturing operations and material flows to visualize, validate, and optimize processes, including production line balancing, measurement, and verification of line performance. Simulation and assessment of worker movement, ergonomics, safety, and performance is provided to assure compliance with government and industry standards.
- Maintaining and managing information on manufacturing resources, including software to support communization and re-use of parts, assemblies, equipment, and processes. The software also provides manufacturing documentation, shop floor instruction, improved visualization, effective communication, and collaboration among workers.
- Programming of robots, welding, painting, coordinate measuring machines, and other factory equipment, as well as creation, testing, optimizing, and managing printed circuit boards and product assemblies. Quality planning, product inspection, control of dimensional variation, and continual assessment of production quality is also provided.
- To effectively define, simulate, and optimize manufacturing processes, a range of manufacturing-oriented software tools need to be organized and integrated. PDM applications that provide extensive data and business process management capabilities provide this backbone. The key technology components are described in the following sections.

VII.CONCLUSION

- 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 model- ling 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.
- According to CIMdata's research and experience, digital manufacturing is developing rapidly in a technological sense, but the market has grown more slowly than expected.

- According to CIMdata estimates for calendar year 2010, industrial spend associated with digital manufacturing grew to slightly less than a half-billion dollars, and yet technology leaders are adopting it across multiple manufacturing industries.
- The main reason for the adoption of digital manufacturing technology is the same as for the adoption of simulation for product design—it is faster, cheaper, and more accurate to design and simulate in software versus physical trial and error.
- Digital manufacturing provides a set of tools that support and complement lean manufacturing concepts and practices.
- Changes to manual and automated cells and factory material flow can be simulated without having to physically implement them.
- Digital manufacturing also enables manufacturing flexibility by allowing cells to support more product variations by changing cell control programs or by making minor equipment changes rather than major retooling.
- While manual methods have been used in kaizens for many years, digital simulations can significantly streamline the process and allow a cell or a full production line to be improved in the context of the entire factory rather than in isolation.
- The integration of PLCs allows bidirectional communication with the virtual world.
- PLCs can be driven directly by the software model so controller feedback, physical latencies, and events are incorporated. This capability is a potential game changer.
- By allowing the capture of physical plant operations within the virtual environment, a new process can be progressively validated, which is especially important in high-risk situations.
- Taken to the extreme, a complete factory can be designed and simulated to optimize operations virtually before the foundation is even poured— from raw material in on one side to the finish groups out on the other.
- At Zollner Electronics just-in-time and just-in-sequence manufacturing is coordinated using Tecnomatix software to manage inbound material in support of their kanban process.
- Zollner Electronics also uses process simulations to improve the sales and customer support processes.
- Customers find the graphical simulations easier to understand and they can use the information to make better decisions about how their product is manufactured.
- Leading manufacturers and consulting firms like Zollner Electronics and Applied Manufacturing Technologies are leveraging technology from Tecnomatix to improve customer communication, optimize production, and even to do digital commissioning of entire factories.
- All of which enables faster, lower cost, predictable launches that lead to profitable production and customer satisfaction.

REFERENCES

- [1] Chrysosolouris, G. "Manufacturing systems –theory and practice, 2nd edition, 2006 (Springer-Verlag, New York)".
- [2] Westkaemper, E. "Strategic development of factories under the influence of emergent technologies".
- [3] Cagliano, R. and Spina, G. "Advanced manufacturing technologies and strategically flexible production".
- [4] Umble, E. J., Haft, R. R., and Umble, M. M. "Enterprise resource planning: Implementation procedures and critical success factors".
- [5] Birchfield, G. "Advanced process control, optimization and information technology in the hydrocarbon processing industries – the past, present and future".
- [6] Cay, F. and Chassapis, C. "An IT view on perspectives of computer aided process planning research".
- [7] Denkena, B., Shpitalni, M., Kowalski, P., Molcho, Z., and Zipori, Y. "Knowledge management in process planning".
- [8] Kim, J.-H. and Duffie, N. A. "Backlog control design for a closed loop PPC system". Azab, A. and ElMaraghy, H. A. "Mathematical modelling for reconfigurable process planning".
- [8] Ueda, K., Fujii, N., and Inoue, R. "An emergent synthesis approach to simultaneous process planning and scheduling".
- [9] King, G. S., Jones, R. P., and Simner, D. "A good practice model for implementation of computer-aided engineering analysis in product development".
- [10] Brinksmeier, E., Aurich, J. C., Govekar, E., Heinzel, C., Hoffmeister, H. W., Klocke, F., Peters, J., Rentsch, R., Stephenson, D. J., Uhlmann, E., Weinert, K., and Wittmann, M. "Advances in modelling and simulation of grinding processes".
- [11] Yeung, M. K. "Intelligent process-planning system for optimal CNC programming – a step towards complete automation of CNC programming. Integrated Mfg Systems".



INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA



INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

IN SCIENCE | ENGINEERING | TECHNOLOGY

 9940 572 462  6381 907 438  ijirset@gmail.com



www.ijirset.com

Scan to save the contact details