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Introduction to Digital Manufacturing System

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Abstract
Manufacturing digitization is now again a top research priority for industry application, and digital manufacturing is essential to this process. Regarding the goal of digital manufacturing, there is, nevertheless, a dearth of consensus in the literature. This study aims to explore the idea and field of applications of digital manufacturing (DM) utilizing the acquiring traction of Industry 4.0 paradigm. The concepts are formulated, and new technological features are found based on a content analysis. The conceptual positioning of digital manufacturing and the delimitation of its application contribute the better perception of the future issues that organizations will confront.

***Keywords*:** Digital manufacturing, smart manufacturing, Industry 4.0, digital factory, manufacturing life cycle

1.1 Introduction

Manufacturing has transitioned from single technology to integrated systems because of the digital revolution. The term “Industry 4.0” concerns the fourth industrial revolution, which brings about intellectual, linked, and decentralized production. It represents a new degree of structure and control over the whole value chain of a product during its life cycle. As a matter of fact, the content and nature of manufacturing itself are changing due to innovations being unleashed by advancements in data storage,

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human–machine interaction robotics, new computing capacities, and additive manufacturing [1, 2].

Emerging technologies have recently a revolutionary effect on manufacturing concepts, techniques, models, and even enterprises. The phrase "Industry 4.0" concerns the new technological developments that are being incorporated into the industry to address various global concerns. These developments are focused on virtual and digital technologies and are fueled by real-time data interchange and flexible manufacturing, which allows for customized production [3–5]. Industry leaders concur that digital manufacturing techniques will revolutionize every facet of value chains' manufacturing systems, as digital manufacturing falls under the purview of Industry 4.0 technologies. Computer integrated manufacturing (CIM), which was created in the 1980s when computing costs dropped and computers could be widely utilized for planning, scheduling, and machine and automation control, is the forerunner of digital manufacturing technology. Manufacturing science and other relevant topics are integrated into the manufacturing business through the work of CIM [6]. The interdisciplinary nature of manufacturing is perhaps unavoidable. The perception of digital manufacturing, which emphasized the prerequisite for process design and more collaborative product, emerged from the combination of engineering science of CIM and organizational sciences like total quality management, concurrent engineering, and lean manufacturing. The literature on digital manufacturing mentions two aspects, even though they are not new. First, it is still unclear what digital manufacturing is and what makes it special. The main concept of digital manufacturing, which is production improvement through technological integration, is shared by all its definitions. There is a distinction between the application domain and this convergence, though. Another widespread misconception is that "digital factory" and "digital manufacturing" are interchangeable terms. It is troublesome when terms connected to digital manufacturing lack a clear meaning since it hinders researcher-to-researcher communication and makes it more challenging for managers to design, plan, and carry out digital manufacturing efforts. It is yet unknown how Industry 4.0 factors affect digital production and whether advancements in technology have an impact on its use. Therefore, the idea of this study is to explore what digital manufacturing means in relation to Industry 4.0. A thorough assessment of the literature was done to provide answers to these queries. Different concepts related to digital manufacturing were evaluated by means of content analysis of technical and scientific journals. The paper discusses the better understanding of the future challenges that companies face by positioning digital manufacturing theoretically and delimiting its application domain.

1.2 Manufacturing as Craft and Technique

Manufacturing has always been a skill in the lengthy historical process. To stay warm, early humans hand-processed raw fur, developed crude tools for hunting, and created the first cooking implements. Mankind advanced because of these basic tools and abilities. Early skills and handcrafts established European production methods; for instance, the ancient paraffin casting process was frequently utilized in advanced rapid prototyping manufacturing. Manufacturing evolved into a skill that allowed human history to progress from the Stone Age into the Bronze Age. Ancient manufacturing technologies made enormous contributions to human civilization in addition to bringing great glory to feudal rulers. Manufacturing began as a skill and progressively evolved into a technology in the seventeenth century. The social division of labor saw significant changes with the introduction of the steam engine and the metal cutting machine. Eventually, hand workers were no longer employed in manufacturing.

1.3 Manufacturing Becoming a Science

The West invented the advanced manufacturing processes. In the nineteenth century, it progressively moved toward mechanization and electrification, leading to the development of mechanical production. The production saw significant growth beginning in the 1980s, when several innovative production concepts and techniques were introduced. These novel ideas—such as agile manufacturing, automated manufacturing, intelligent manufacturing, concurrent engineering (CE), etc.—help us to analyze and project the future of manufacturing. These ideas also support and advance one another's growth in terms of analysis and forward-looking thinking. As a result, the manufacturing is now a science, encompassing engineering, organization, information, and other sciences rather than a single technology or talent.

1.3.1 Engineering Science in Manufacturing

Computers were employed in manufacturing from the beginning by Harrington, Merchant, and Bjorke, who suggested automating, optimizing, and integrating all manufacturing system functions with the CIM concept. CIM grew organically into the robotics and artificial intelligence (AI) domains in the 1980s. The manufacturing industry is integrating the formation of CIM, which has served as a link between manufacturing, systematic science, and other significant topics. The CIM age, which uses Harrington, Bjorke, and Merchant as examples, covers the scheduling of Flexible Manufacturing Systems (FMS) as well as the controlled problems associated with various production machines, such as servocontrol on robots. It also covers the substantial processes of each manufacturing technology, such as semiconductor manufacturing, welding, and machining. By linking the original CIM idea with relevant scientific problems, its structural scheduling advances in manufacturing from engineering to manufacturing science.

First, the original scientific principles and methodologies for the study of manufacturing techniques can be applied to the physical process of manufacturing. Physical theory, such as how plastic deformation is interpreted from atomic dislocation theory and how transistors are interpreted from lattice physics, can be used to describe the physical processes involved in materials processing and semiconductor manufacturing.

Furthermore, there exists an extensive body of scientific information pertaining to solid mechanics, materials science, and optics. To explain the precision, steady time, and stability of manufacturing machines, there are several well-developed control theories. Furthermore, by fusing tribology and dynamic analysis regarding cam, linkage, and propelling equipment, a theory has been developed regarding mechanical control in a different settings.

The analysis techniques including statistical modelling, optimization, queuing theory, and discrete event simulation are used in FMS planning. These are only the department of industrial and operational research's primary techniques. The scientific method of constraint-based reasoning has been added to the field of artificial intelligence in recent years. In conclusion, dispatching activities are now well supported by a developed mathematical theory, which is crucial to the production scheduling process. Even though the manufacturing industry uses a lot of the engineering scientific procedures mentioned above, they truly cannot function properly without merging with the organizational approaches.

1.3.2 Organizational Science in Manufacturing

CIM is a representation of the fusion of engineering science and organizational sciences such as lean production (LP), concurrent engineering (CE), and total quality management (TQM). In contrast to traditional machining, which involves packing unneeded parts into a packed production line, the "Toyota production system," as promoted by Toyota Motor

Corporation, employs FMS to increase production with reducing work in process. This method of working is commonly referred to as JIT manufacturing. Another pertinent phrase that emphasizes cutting down on work in process and inventory is lean manufacturing (LM). Toyota also promotes a novel approach to quality control (QC) at the same time. According to the conventional concept of quality control, the finished items are examined to make sure they fall within the intended size range. These parts will be rejected if they do not fit the required measurements. On the other hand, Toyota's new techniques concentrate on measurement during production processes. As a result, the emphasis shifts to testing throughout the entire process rather than inspecting and discarding unqualified items after manufacturing. Furthermore, it is important to pre-adjust machines to prevent the appearance of defective goods. It is known as in-process quality control or TQM. Furthermore, it assigns accountability to the specific employee and/or equipment rather than disclosing issues to the inspector.

As a result, TQM is included in the CIM cycle, which also comprises consumer demand, enterprise integration, and CE. In the new cycle, synchronous design, a subject intimately associated with TQM, is occasionally used to refer to CE. Since most American businesses had grown accustomed to over-the-wall manufacturing in the previous decades, organizational science characterized by CE, LM, JIT, and TQM, and combined with engineering science, characterized by CIM, took a leading role in the progression of American manufacturing in the late 1980s, laying the groundwork for the country's economic boom in the following decades. To put it briefly, manufacturing integration became a new idea and concept when CIM merged with organizational science. Throughout the 1990s, agile manufacturing and open structural manufacturing are two emerging ideas. Businesses with quick reconfiguration capabilities should respond to new customers that have demands on "due date, quality, and product variety." The CIM circle, sometimes referred to as CIM++, consists of the following exterior concept circles: enterprise integration (virtual companies), consumer wants, and completely excellent management (CE). CE is directly related to TQM in the recently added rings. In the late 1980s, excessive over-the-wall production by American companies led to the importance of CE growing. By the late 1980s, the engineering sciences of CIM along with the organizational sciences of CE, JIT, LM, and TQM, had significantly improved U.S. production techniques. This prepared the groundwork for the 1990s' financial boom. In conclusion, CIM will embrace the organizational science concerns based on the aforesaid evolution process. The aforementioned new trends were extended into Internet-based manufacturing in the mid-1990s, with a focus on shared manufacturing services and design. The development of the Internet, video conferencing and easy access to aviation made it possible to expand international trade. Globally dispersed large corporations, for instance, leverage the superior design team of one nation to shift production to another, where labor costs are lower, and manufacturing productivity is higher. A product created in a cutting-edge design office may now be swiftly and affordably built in another location using inexpensive labor to the development of the audio-visual network conferences and World Wide Web in the twentieth century.

1.3.3 Multi-Crossed Disciplines in Manufacturing

The rapid advancement of contemporary science and technology, particularly in the areas of microelectronics, computers, networks, and information technology, has resulted in a profound and revolutionary shift in the nature and application of manufacturing industry, manufacturing theory, and manufacturing technology.

The advancement of relevant computer science and mathematics theory also helps manufacturing. Communication networks and multimedia computer systems provide remote operation, distribution, virtual collaboration, parallelism, and monitoring. Computer networks and electronic commerce make remote management, production, maintenance, and sales possible. It is required to create a mathematical model using intelligent techniques from computer science and mathematics to represent, compute, and infer the physical parameters as well as management and scheduling in the manufacturing progression. Manufacturing science will arise from manufacturing intelligence science and computational manufacturing science.

The field of manufacturing has also benefited from the advancement of information theory. Broadly speaking, human factors are involved in every aspect of manufacturing, including information processing, transmission, expression, and so forth. Information theory has to do with how industrial resources are configured optimally and run efficiently. Information technology–based manufacturing informatics will answer these linked research problems.

The comparison between the biological and manufacturing processes illuminates novel approaches to addressing issues in manufacturing, such as flexibility, autonomy, and intelligibility. As a matter of fact, the field of bionic manufacturing is spearheading this developing study.

Excellent management and operation are essential for manufacturing. There are non-technical issues with human factors, collaboration and competitiveness among businesses, and the integration of production resources. Fundamental to all those production problems is technology management. It seems that manufacturing will inevitably follow the trend of becoming more interdisciplinary. Future manufacturing disciplines will require an increasing amount of topic knowledge, which will create the new foundation of manufacturing science, as manufacturing science and technology continue to expand and advance. Manufacturing concepts such as open-architecture, agile, networked, and virtual corporations seem fascinating. Innovative technologies in engineering science offer fresh approaches to producing goods and services, like the Web. But with manufacturing operations becoming more and more digitalized, manufacturing process, manufacturing management, and manufacturing information require a bigger and more modern perspective than in the past. Digital manufacturing (DM) has crept into our daily existence.

1.4 Concepts and Research and Development Status of Digital Manufacturing

Digital manufacturing is a collection of information management systems that facilitate decision-making across the industrial life cycle. Utilizing collaboration tools, information sharing models, computer integrated systems, and simulation, the product, the manufacturing process, and the factory are all designed, redesigned, and analyzed in an integrated manner. It frequently uses legacy systems like supply chain management (SCM), manufacturing execution systems (MES), and enterprise resource planning (ERP), as well as product life cycle management (PLM) systems and interfaces. Microelectronics, automation, computers, telecommunications, networks, and informatics are just a few examples of the science and technologies that have developed quickly since the middle of the twentieth century, and information technology is at the center of this tidal wave. The "network" and "informatization" of the twenty-first century will transform how people access, process, exchange, and use knowledge. It will also lead to an unparalleled improvement in people's social structures, lifestyles, and patterns of production. New ideas, theories, technologies, concepts, and approaches can be generated endlessly on this foundation. The terms digital valleys, digital libraries, digital enterprises, digital homes, digital economies, and even digital earths, which are commonly used to describe the spatial distribution and temporal sequence of various information on the earth, are synonymous with research projects that are regularly being presented and have started to enter our lives [7]. As the backbone of the country's economy, the manufacturing sector is responsible for carrying out critical tasks that include producing wealth and living resources for people's material needs, as well as providing technical equipment to the country's economic sectors and defense industries. After over fifty years of tremendous advancements in science and technology, together with a new technological revolution, the manufacturing sector is currently confronted with three significant unresolved issues: networks, expert services, and the resulting difficulty. Therefore, it is difficult to handle the time variability, nonlinearity, and disparity of organizational structure and functions in industrial systems utilizing conventional operating modes and control processes. Furthermore, the manufacturing sector is undergoing a profound revolution because of the quick changes in consumer demand, intense global competition in the economy, and the quick development of high-tech products. The breadth and depth of manufacturing activities have also significantly increased, and the sector is moving toward automation, intelligence, network integration, and globalization [8]. As a result, significant modifications are made to the machining of manufacturing information, storage, transmission, and processing, causing the manufacturing sector to progressively transition from its historically energy-driven condition to one that is information-driven. Digitalization has emerged as a crucial driving force in the manufacturing industry's product life cycle. As a result, digital manufacturing (DM) is emerging as a new mode of production to meet the demands of a diversified, increasingly personalized consumer base, a large manufacturing network, and an increasingly complex product structure. As such, DM is expected to play a substantial role in the manufacturing industry's future growth.

The goal of this study was to describe digital manufacturing considering the new Industry 4.0 paradigm. "Technology advancements are making digital manufacturing real to many, and many companies are using pieces of digital manufacturing without realizing it," according to Dalton-Taggart [9] in 2005. It seems that this is still the case. Furthermore, as noted by Coffey [10], a group of manufacturing employees are likely to highlight different aspects of digital manufacturing depending on their expertise and particular job responsibilities when asked to define the term and explain its operation. The goal is to create a digital representation of the factory's resources and procedures, facilitating material flow and layout studies as well as enhancing the production process' tangible elements. While "digital manufacturing" expands on this idea by leveraging digital representations of the product and process, its primary focus is still on integrating business domains and technologies to enhance the full product life cycle. The true function of digital manufacturing is to link various stages of the

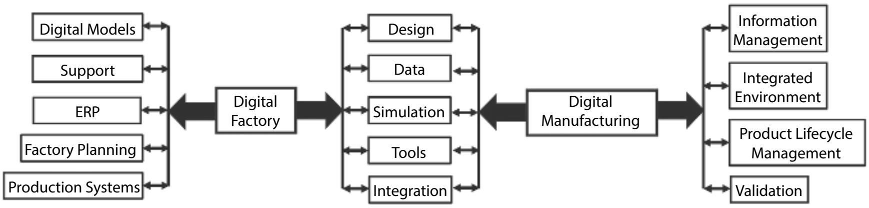

Figure 1.1 Relationship between digital factory and digital manufacturing.

product life cycle with digital data that contain management and design intent and use those data to make intelligent automation and more astute, effective business decisions. DM includes a wide variety of developing tools that were mostly created in isolation. Manufacturers have just come to understand the advantages of integrating and connecting the many DM parts. Digital manufacturing is supported by several widely used and well-established technologies. However, the ability to use in real time and in combination with other uses a wide range of new options for industrial application. Despite several similarities between DM and DF, the former is not an extension or progression of the latter. Both serve distinct functions and can even be utilized advantageously in tandem. Figure 1.1 displays the relationship between digital factory and digital manufacturing.

1.5 Definition of Digital Manufacturing

Digital manufacturing, which makes the use of technologies, i.e., virtual reality, databases, computer networks, and rapid prototyping, is a manufacturing process that adapts to customer demands by analyzing, organizing, and recombining information about products, processes, and resources, putting function simulation and product design into practice; and producing goods quickly to meet quality standards and customer demands. The dominating development path of advanced manufacturing technology as a new subject of manufacturing science is reflected in the production of many manufacturing disciplines [11]. The idea of DM initially appeared in numerical control technology, commonly referred to as computer numerical control (CNC) machine tool. Digital design and management have evolved together with computer-aided design (CAD) and material requirements planning (MRP). Over the past ten years, rapid prototyping, computer networks, virtual reality, and other tools have made it possible to quickly realize product functions and simulate design changes. This has allowed for the rapid analysis, planning, and repurposing of various types of information, including control, process, product, and resource information, as well as the coordination and sharing of information to quickly manufacture products that meet customer demands.

Every procedure involved in the digital activities has a connection to DM. In this method, control flow and control parameters are transmitted to production equipment *via* digital signals. Through the digital network, manufacturing enterprises can exchange various types of signals, such as design, process, manufacturing, manufacturing knowledge, and skill in the form of digital signals. In terms of global manufacturing, businesses can create and produce the corresponding product in accordance with their own supremacy through dynamic partnerships, as all users submit their requests through digital networks. The combination of network information technology, manufacturing technology, and digital technology led to the concept of digital manufacturing (DM). It also follows naturally from the digitization of manufacturing systems, production systems, and enterprises [12]. Digital signals are used as control variables in manufacturing devices, for instance. All types of information, including knowledge, techniques, graphics, and data, are digitally stored and transmitted within manufacturing companies over digital networks. Global manufacturing

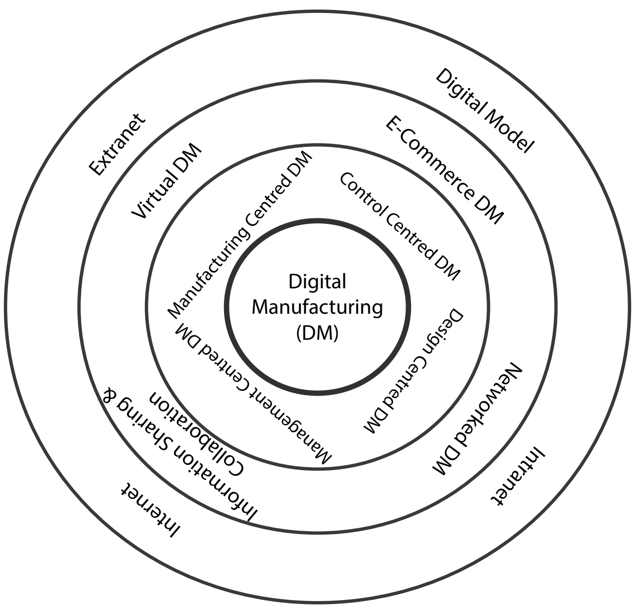

Figure 1.2 Digital manufacturing concept.

companies employ digital networks to disseminate information, and small, medium, and large companies work together to swiftly and efficiently make goods. Individuals, businesses, shop floors, gadgets, sales representatives, and markets make up the nodes using Internet network in the DM environment. Conversely, the design-centered DM, manufacturing-centered DM, control-centered DM, and management-centered DM are all included in DM. Now, virtual manufacturing serves as the digital factory's entity, networked manufacturing is the application of DM's globalization, and digital products and e-commerce represent the dynamic federation of DM. Figure 1.2 illustrates the idea of DM. Various DM concepts with DM at their center illustrate how DM affects various application levels in Figure 1.2.

1.5.1 Digital Manufacturing Concept Used as Control

First, numerical control technology (also known as CNC) and NC machine tools are responsible for the notion of DM. With NC technology, machines are controlled by numerical and character-based instructions. It regulates pressure, temperature, flow, angle, speed, and mechanical factors. These parameters are measurable and controlled in addition to being able to be stated numerically. The device is referred as NC equipment if it performs its automatic function *via* numerical commands. Though obviously far from DM, it serves as a crucial foundation for DM.

The multiple-machine approach, sometimes known as "direct digital control," is a way to accomplish fundamental controlling using one or more computer numerical control devices. It evolved with the advancement of numerical control technology. The term "flexible manufacturing cell" (FMC) refers to the cooperative operation between several CNC machine tools and industrial robots. Large-scale machining automation will be achieved with the help of a logistic automation system by joining several FMCs or workstations to form an FMS.

Digital control can automate production processes, detect and regulate process parameters, alert users to errors, and even recommend maintenance and offer decision suggestions. A local area network (LAN) made up of networking many NC machine tools could automate the manufacturing processes of several workshops because of advancements in computer and network technology. Moreover, every piece of equipment's controller or control system will turn into an Internet node, which causes the production process to evolve toward automation on a bigger and more sophisticated scale. The central notion that assumes control is the so-called DM idea.

1.5.2 Digital Manufacturing Concept Used as Design

Computer-aided design (CAD) has evolved since the advent of computers, the fusion of mechanical design technologies and computer graphics. Its foundation is engineering analysis and computation, with databases serving as its means and an interactive graphics system serving as its means. Accurate two- and three-dimensional item descriptions are possible with the CAD system, which also enhances product descriptions and production process productivity. As with NC machine tools and NC technology, the rise and development of CAD establishes the groundwork for the digitization and automation of the product design process in the production sector.

The CAD product design data will first be converted into data regarding the manufacturing and processing guidelines for a product. The processing equipment will be grouped and arranged in accordance with the work phases and planned method. The next steps involve choosing cutters, fixtures, and measurement equipment, determining the cutting parameters, and calculating the auxiliary and maneuvering times for each procedure. This is known as CAPP or computer-aided process planning. All plans are converted, such as those for assembling, detecting, manufacturing, etc., and all data related to management, product-oriented design, cost accounting, manufacturing, processing, etc., into computer-understandable data that can be shared throughout the entire manufacturing process, elevating CAD to a new level. This makes CAD/CAPP/CAM integrative. Computer networks have made it possible for CAD technology to collaborate and coordinate to enable online design in recent years. The concept of digital manufacturing is centered on design and is the result of extensive research into several areas including distributed cooperative design, multimedia visual environment technology, group collaboration and intelligence design between multiple businesses, product data management systems, sharing, multiple teams, multiple individuals, and multiple applications. Network and information technologies are developing quickly.

1.5.3 Digital Manufacturing Concept Used as Management

The highest level of the industrial and management information systems is formed by the creation and implementation of internal MRP, which is based on constantly shifting market information, user forecasts, and orders, targeted at the decision-making model, and long-term interests. Through these processes, they assess an enterprise's production and management, develop an investment strategy, project its future and operating conditions, and set up the assignment of production. A comprehensive products data management (PDM) system aims to assist manufacturing companies' management and production processes in rapidly reconstructing and integrating in line with market demands. This involves product design, research and development, market demand for products, service, engineering manufacture, maintenance, sale in the product lifetime, and ultimately, the achievement of process integration centering on supply chain and product. Enterprise requirement planning (ERP) is currently the most widely used advanced information technology–based management platform. ERP combines advanced management concepts with information technology to facilitate the easy integration and synthesis of working, capital, and logistical flow in enterprise management activities. As a result, the management-centered DM concept is developed, with ERP serving as the focal point and integrating several PDM/MRP/MIS/ERP systems.

1.5.4 Digital Manufacturing Concept Used as Manufacturing

Based on the theory and technology of virtual reality and manufacturing, and rapid manufacturing, it can rapidly analyze, plan, coordinate, process, share, and control information about products, resources, and manufacturing. It can also realize simulation and prototyping of manufacturing to produce design and function of products that satisfy user needs. Through the digital network, all data pertaining to digital manufacturing processes are transmitted digitally at every stage of the production life cycle. Users use the network to post demand data, and different international businesses use it to their advantage to gain complementary benefits and build strong partnerships to jointly develop and produce related products *via* the digital network. These data are gathered in data warehouses and databases and are derived from intelligence theory and intelligent sensing technology. Furthermore, many manufacturing techniques and production process data still exist. To achieve the high reliability of product quality, high performance of manufacturing equipment, and customer satisfaction—all of which constitute the perspective of taking manufacturing as the center of DM—an intelligence model must be established. This model will optimize, analyze, process, and regulate all the data and information in the manufacturing process and system. To put it concisely, in the context of digital marketing, a vast network of data and statistics is created, and every entity—including people, businesses, workshops, gear, merchandise, dealers, and markets—becomes a mark, node, or digital code. The product's designated DM information and technology will emerge as the primary motivators that control the manufacturing sector during the design, production, sale, and maintenance phases. In the twenty-first century, DM science, DM theory, DM technology, and the concepts and innovations of other scientific domains will form the basis of manufacturing science.

1.6 Features and Developments of Digital Manufacturing

Digital manufacturing (DM) has emerged as the dominant approach to advancing the growth of the manufacturing sector in the twenty-first century, both as a unique manufacturing technology and a production approach. Its salient characteristics are as follows: in terms of description and expression, its digital manifestation possesses unique significance and can be reused; in terms of manufacturability analysis and product performance evaluation, it exhibits predictability in terms of product development and performance; and in the context of a network environment, manufacturing activities are independent with respect to time, place, and distance. DM modernizes the scientific foundation of conventional manufacturing by converting product design manufacturing from partial experience, partial quantification, and qualitative mode into comprehensive digital quantification. As a result, several fundamental ideas and important technological concerns are generated including manufacturer process modeling and simulation, digital product information expression, numerical control technology, and digital prototyping technology.

Currently, geometric reasoning, computational geometry, manufacturing computing, manufacturing informatics, and other topics are the main topics of DM-based theoretical study. The engineering application oriented research of geometry has been given great importance by the geometric centers of the American Polytechnic University and Navy Research Institute [13]. These centers have also made significant advances in the application of digital prototyping technology. The research of complexity and uncertainty at the forefront of DM in the network environment is done by Monostori *et al.* [14]. Lee conducts efficient research on surface design and processing techniques using the five-axis processed complex surface as his study object [15]. With the backing of large National Natural Science Fund projects, the School of Mechanical Science & Technology at Huazhong University of Science and Technology carries out extensive research on computer manufacturing and digitalization of the product model with notable successes [16]. Constrained analysis and constraint problem solving, or how to realize multi-objective global optimization of product development, are the important theoretical issues in DM. The workpiece fixturing, mold typing, interference checking, fixture designing, and grasp planning are all included in the constraint analysis. The notions of C-space and spinor space, as well as reachable and accessible analyzing techniques, have emerged as key concepts in the study and are essential tools for solving constraint analysis in the manufacturing process [17]. Comprehensive research has been carried out by Wuhan University of Technology on intelligence reconfigurable ERP system, information security, embedded intelligence numerical control, and so on [18–21].

The foundation for achieving digital manufacturing is building a digital representation of a product and giving a computer-understandable digital definition of the full product life cycle. The geometric, physical, knowledge, and prototype models are the most researched product models. Most static descriptive models, such as the geometric and knowledge models, are employed in product design and manufacture. For product-oriented performance analysis, dynamic simulation models such as the physical model and prototype model are employed [22, 23]. Positive design, reverse engineering, and combined topics are the main ways to obtain digital product models; nevertheless, these techniques are limited to digitalizing the product's geometric information [24]. One of the main characteristics of DM is that, in addition to handling a significant volume of traditional engineering data and visual information, it also needs to handle a significant volume of empirical knowledge and other non-geometric information. The prevailing body of knowledge in the subject must be digitalized to elevate DM technology to the status of technological innovation. There is a lot of work to be done to digitalize physical parameters in the extreme manufacturing process and convert these data into a format that the computer can manage [25].

The ability of the manufacturing equipment to handle digital information in a network environment is a crucial feature of DM systems. Coordinate measurement machines (CMMs), welding machines, industrial robots, and other digital manufacturing equipment (referred to as "digital equipment") have evolved from basic executive manufacturing entities into integrated information processing devices. To meet the demands of the market and develop products quickly, these devices must be able to perform autonomous control, state detection, motion planning, self-preservation, self-reorganization, and self-modeling in a network environment. In the context of product innovation and market competition, they must also be able to adjust. Digital equipment like adaptive control for shifting working conditions, motion planning under various constraints, parameter identification based on sensor data, and digital modeling of the driving process are examples of how movement is becoming digitized [26, 27]. The intricate trajectory of machining generates interference checking, high-accuracy machining, automatically under high-speed conditions, and error compensation [28]. Dynamics modeling, the effects of stress, temperature, and other physical factors on extreme working conditions [29], high-speed tracking control in a numerical control with visual guidance [30], the adaptability and capability of autonomous control for variations in working conditions [31] are all covered in the illustrative study. These studies are primarily limited to a certain piece of machinery or set of operations. For example, the CMM probe's path planning, an industrial robot's motion planning, and the CNC machine's cutter interpolation operation are all controlled by a different programming system (heterogeneous equipment). These systems, which solve the problem of relative motion between objects under geometric constraints, are very similar to each other.

A thorough programming system has not yet been developed for this digital equipment due to its various application areas; integration and cooperation are required, as well as further study. It is challenging to guarantee that control theories and procedures are founded on the previous model due to the complexity of the manufacturing process. The theories and techniques of digital modeling in dynamics, system identification based on sensor data, intelligence planning, and autonomous control have severely limited the ability to resolve these problems [32]. The sharing of manufacturing resources, the communication of DM information, and the improvement of manufacturing system performance have all been made possible by the computer network. DM places more of an emphasis on autonomous adaptation to the manufacturing environment and coordination and collaboration among the component units in a network environment [33]. Most of the current research on manufacturing process planning, coordination, and collaboration [34, 35] focuses on the system level; however, there is a dearth of in-depth analysis on how to address equipment heterogeneity, complex interactions, and collaborations between different types of equipment. Now the concentration is more focused on network communications, remote operation, and data exchange when studying how DM equipment adapts to the network environment [36]. Less attention is concentrated to problems like basic DM equipment's autonomous adaptation and automatic perception of the complex and dynamic manufacturing environment. These now constitute the primary issues that must be resolved to free up the system's integral performance.

It is evident from the research progress and analysis above that DM is still a new field of study, but one that is expanding quickly. The fundamental theoretical literature on diabetes mellitus lacks systematicity and is not close to a scientific theoretical framework. To support its healthy development, DM is the foundation of many innovative manufacturing technologies. It must be focused on the methodical investigation and have its own unique scientific theoretical framework established. DM science, a new disciplinary system, is created to satisfy the demands of modern growth.

1.7 Digital Manufacturing Science: Significance and Research Approach

1.7.1 Fundamental Idea and Significance

Digital manufacturing includes all-digital analysis, design, operation, and administration of fundamental scientific questions as well as a digital operating environment that supports the entire product life cycle. Beginning with basic production and progressing to digitalization, DM has progressively expanded its scope beyond the digital concept, development, and evolution to encompass a product's entire life cycle and operational environment. The entire product life cycle is supported by a digital operating environment, and digital manufacturing encompasses all-digital analysis, design, operation, and administration of basic scientific concerns. As a result, DM research has developed into a systematic field that incorporates fundamental theories and technologies from technical studies as well as modern manufacturing technology to create DM science. The goal of DM science, an interdisciplinary field, is to organize the discipline theory system around DM, including the architecture model, modeling theory, and modeling techniques, as well as the fundamental disciplinary theory of DM. Consequently, this is how DM science is defined:

DM is a science that focuses on the optimal operation of the DM system. Its primary research contents include fundamental ideas and important technologies. Its primary research methodology is informatics and system engineering.

DM is a manufacturing methodology that incorporates information technology and mathematics. From the standpoints of development and production, they delineate the essential features of DM. It creates DM equipment, DM technology, digital products, and other research fields. It is employed in the processes of product design and manufacture. The intrinsic characteristics of DM, which change the definition of the production mode, are revealed by their research. DM is closely related to concepts such as intelligent manufacturing, network manufacturing, and virtual manufacturing. DM summarizes some of the characteristics of the technologies from various perspectives and serves as the primary path for their advancement. Though they represent various manufacturing concepts and demonstrate the effectiveness of altering manufacturing processes, increasing manufacturing efficiency, and lowering manufacturing costs from various angles, DM ought to be the foundation of the advanced manufacturing theories and technologies. Since DM is an open concept, numerous application systems can be created by applying its theory and technology to different advanced production systems in manufacturing engineering. We can identify the shared theoretical and technical foundation of all modern manufacturing systems by abstracting the manufacturing ideas and technologies that underpin them. As a result, the system built using shared theory and technology can serve as a basis for the application of different advanced manufacturing methods.

1.7.2 Research Aspects

The DM system is the research object of DM science, and as such, informatics and system engineering methodology are the research methods used. First and foremost, informatics technique must be applied in DM science. DM is based on quantitative description and uses information and expertise to build and operate the manufacturing system as efficiently as possible. The foundation and center of the system's informatization is digitalization. Informatics focuses on objects that are dominated by information phenomena. These objects share many characteristics with manufacturing processes and systems, and they typically fall into the category of complex systems and advanced motion forms, such as human–machine intelligence, advanced machine manufacturing systems, and manufacturing conditions. On the one hand, these things frequently have a very intricate structure of materials, making it challenging to describe and analyze them using conventional methods. Since the objects are the things that are subject to the information phenomenon, the problem should be resolved using information-related perspectives and methodologies, such as the integrated approach and the evolutionary approach. These techniques are the foundation of the overall methodology, and the two criteria are the rules for correctly applying the complete methodology. Taken together, these techniques create the informatics methodology, which is used in DM science research. Second, the system engineering methodology needs to be applied in DM science. According to ideas of systems engineering, a "system" is an organic whole with distinct functions that is assembled from several interdependent and interacting components. As a result, the DM system can naturally combine all its fundamental theories with all technologies and demonstrate all the functions. As a result, the services are provided to all kinds of advanced manufacturing techniques. This method's characteristics can be stated as follows:

- ***The ability to understand thought***
  Studies the entire hardware and software stack, including all manufacturing techniques in DM systems, and approaches issues in the manufacturing process by examining them from both a global and process-wide perspective. To avoid focusing on one issue at the expense of another, it is imperative that the manufacturing system, different applications of environmental factors, and the dynamic process are synthesized when addressing and resolving pertinent manufacturing process problems.
- ***Combining Knowledge***
  To improve production processes, the quickly developing field of digital manufacturing integrates cutting-edge technology including automation, artificial intelligence, and the Internet of Things. Smart factories, additive manufacturing, digital twin technology, supply chain integration, cybersecurity in manufacturing, data analytics and artificial intelligence, sustainability, and human–machine cooperation are important study topics in digital manufacturing. These domains foster innovation in product design and customization in addition to increasing productivity and efficiency. The effective and sustainable implementation of these technologies is the main focus of researchers and practitioners.
- ***The target's optimality***
  Refers to all facets of the DM system, including planning, designing, building, managing, and operating it. Its constant goal is state and effect optimization, with a focus on process optimization and global area optimization.

Since DM systems are the subject of DM science research, the best possible operation of DM systems is the research objective of DM science. The use of several contemporary sophisticated manufacturing technologies is supported by this system, which serves as its fundamental foundation.

1.8 Conclusion

Digital manufacturing is a revolutionary method that incorporates cutting-edge technology into the production process, including additive manufacturing, IoT, and AI. In addition to cutting expenses and lead times, it improves quality, flexibility, and efficiency. Utilizing automation and real-time data, businesses may enhance decision-making, streamline processes, and react quickly to market demands. Industry use of digital manufacturing raises the possibility of innovation and competitiveness. But there are obstacles to overcome, like worker adaptation, cybersecurity, and technological integration. All things considered, digital manufacturing not only increases production efficiency but also strengthens the manufacturing ecosystem's resilience and sustainability.

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