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Digital Manufacturing- Applications Past, Current, and Future Trends

Phani Kumari Paritala[a], Shalini Manchikatla[b], Prasad KDV Yarlagadda[a*]

[a] School of chemistry, Physics and Mechanical Engineering, Queensland University of Technology, Brisbane, QLD 4001, Australia.
[b]Department of Mechanical Engineering, GITAM University, Hyderabad, Telangana 502329, India.

Abstract

Increasingly the convergence of natural environment (land, water, air and life), built environment (housing, buildings, transportation and infrastructure) and digital environment (computing power, the internet, big data, and technology) is shaping the economies and societies. Smart living is taking root. Mass customization of products and services is preferred over mass production. Businesses wish to serve an individual customer at a competitive cost comparable to the mass production cost, with shortest possible development time and production time. This requires manufacturing to change from a more labour intensive processes to information technology enabled mechanical processes. Digital manufacturing is a broader concept of manufacturing innovation in which the digital and material advancements enable the company to conceive products in a desired style and quantity in time scales shorter than the conventional methods while efficiently managing the entire product lifecycle. It is about defining manufacturing processes and managing manufacturing process information via full digital product definition. It encompasses visualization, manufacturing simulation, ergonomic and human factor analyses, holistic view of product and process design, and product design sensitive to the process constraints and capabilities. This article emphasizes the need and driving forces for adopting digital manufacturing, transformation of manufacturing to smart manufacturing, present applications and future scope of digital manufacturing.

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Keywords: Digital manufacturing, Additive manufacturing, Digital transformation, 3D Printing

* Corresponding Prasad KDV Yarlagadda. Tel.: +6-173-138-5167; Fax: +6-173-138-3381.
E-mail address: y.prasad@qut.edu.au.

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1. Introduction

The increase in global competitiveness, diversification of customer requirements, dynamic and unpredictable market trends; challenges the manufacturing market to integrate design, manufacturing, and product support processes in order to shorten the product development time and deal with constantly increasing complexity in products and manufacturing enterprises without compromise in quality. Information technology has also dramatically influenced the traditional industry (Lan, Ding, Hong, Huang, & Lu, 2004). In this era, quick response to the business opportunity is considered as one of the most important factors for withstanding competitiveness. Intelligent manufacturing systems such as e-manufacturing, Digital manufacturing, and Virtual manufacturing serve as a new paradigm in the manufacturing environment to refine the manufacturing business, as technology capabilities expand and business conditions change (Kim, Lee, Park, Park, & Jang, 2002). Traditional manufacturing processes designed for mass production of identical products is labor intensive and increases the development time and cost. On this backdrop, the advanced manufacturing or digital manufacturing is becoming apparent.

Digital manufacturing is an emerging area within PLM that supports collaboration across several phases of the product lifecycle which has been evolved from manufacturing initiatives such as design for manufacturability, computer integrated manufacturing, flexible manufacturing, lean manufacturing etc. (Jovanovic & Hartman, 2013). The digital technology is breaching the walls of manufacturing due to the recent developments in areas such as artificial intelligence, 3D printing, human-machine interaction, automation and robotics along with an explosion in data and new computing capabilities. The disruptive and productive impacts of digital on the operations of organizations such as IT, telecommunications, manufacturing, entertainment, media, and publishing etc. are materialized (Hartmann, King, & Narayanan, 2015).

Additive manufacturing (AM) a 3D printing technology that creates parts through the addition of materials have transformed the engineering and manufacturing industries from mass production of identical products to low-volume production of innovative, customized, and sustainable products. The unique capabilities of AM processes to produce intricate shapes with multi-material properties and complex architectures has found its applications in various areas like automotive aerospace, defense, medical, consumer products, architecture, food etc. The purpose of this article is to discuss the driving forces for transformation to digital and the development of manufacturing to smart manufacturing. Applications of AM processes, conclusions regarding the present perspectives and future of digital manufacturing are further discussed.

2. Conventional and Digital Manufacturing

The conventional method is an in-line process in which the product is designed and the drawings are forwarded to shop floor for manufacturing the prototype. While digital technology is a cyclic process in which the product is designed conceptually and innovated in computer-aided design software. These designs and the processes are simulated for checking the feasibility of manufacturing the product. The product is inspected at every stage of the manufacturing process by the inspection techniques and tested by computer aided quality control methods. The supply chain management is also digitized for effective inventory and producing customized products. Marketing of the product is done by using the social media for improving the profitability. Figure 1 shows the conventional and digital manufacturing processes.

3. Driving forces

The manufacturers are burdened with outdated production facilities to meet the market demands which reduce the adaptability to market conditions. In this ever-changing economy, companies realized the importance of accepting new technologies for overcoming the barriers. The driving forces for adapting digital technologies are time to market (short product development time), improved productivity (in terms of quality and reduced wastage), managing cost and customized product requirements. In the recent years, the digital tools such as cloud computing, rapid manufacturing, data analytics, virtualization, knowledge library and social networks are vastly used by the companies for each stage of the product lifecycle.

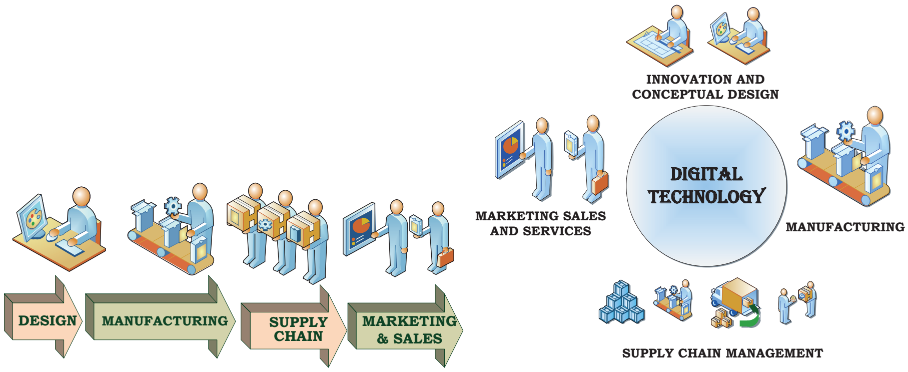

Figure 1: Conventional and Digital manufacturing processes.

4. Manufacturing to Smart Manufacturing

Computer Aided Design (CAD), the use of computer technology to design the components based on various criteria is developed gradually along with the demand for Computer-Aided Manufacturing (CAM), a channel for converting the virtual models to physical products with the use of NC machines. Later the development of Computer Integrated Manufacturing (CIM) to control the production process by data communication and automation with the help of robots found its application in automotive and aerospace industries. Further, the integration of Total quality management (TQM), Just in Time (JIT) manufacturing, Concurrent Engineering (CE), Lean Manufacturing (LM) and engineering science with CIM created a revolution in the manufacturing sector. Moreover, the rapid developments in science and technology, market trends and demand for customized products transformed computer integrated manufacturing to digital manufacturing (Zhou, Xie, & Chen, 2011). Digital manufacturing a network driven, technology-based approach to manufacturing, integrates modeling, simulation, visualization, data analytics, manufacturing, supply chain and various other processes by a digital link to define, manage and collaborate the overall product life cycle. DM technologies reduce time to market, cost and increase the efficiency of products and processes by analyzing the data for an optimal design even before it is built.

Cloud-based design and manufacturing (CBDM), a customized service oriented networked product development model is also considered as a new emerging technology that will revolutionize digital manufacturing and design innovation with the aid of cyber-physical systems (CPS), internet of things (IoT) and big data. CPS is crucial in design and development of future CBDM systems which include system integrity, data security, intellectual property and privacy. IoT enables technology to improve manufacturing automation, supply chain management, remote maintenance and diagnostics in future CBDM systems. Big data help designers to derive decisive customer needs from the existing data to improve and develop designs (Wu, Rosen, Wang, & Schaefer, 2015). The classification and clustering of product and process data result in comprehensive digital documentation of the product emergence process by identifying correlations and recurrent patterns with the aid of data mining techniques where tacit planning knowledge can be revealed and reintegrated into new process planning workflows in order to enhance planning efficiency and facilitate decision-making (Wallis, Stjepandić, Rulhoff, Stromberger, & Deuse, 2014).

Digital manufacturing enables the simulation of the entire manufacturing processes by the concept of the virtual factory which is a fusion technology that combines procurement, production, product logistics, service and diverse IT technologies related to manufacturing based on digital manufacturing technology for predicting, solving and controlling problems in the virtual environment (Choi, Jun, Zhao, & Noh, 2015).

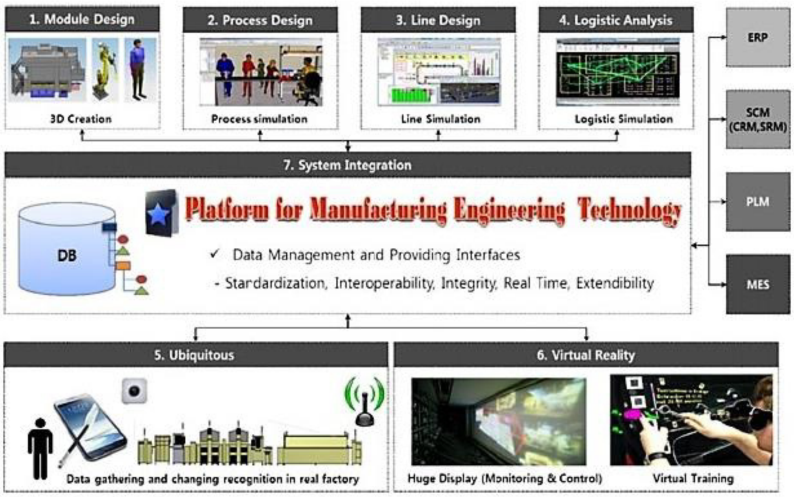

Figure 2: Architecture of the virtual factory (Choi, Kim, & Noh, 2015).

Figure 2 shows the architecture of the virtual factory. For successful implementation of a virtual factory, SangSu Choi et al suggested that the implementation of top-down approach from managerial viewpoint simultaneously with a bottom-up approach to the gradual development of detailed technologies. The concept of the virtual factory in a top-down approach can be applied to non- financial performance indicators like site monitoring measurement, enterprise control monitoring, automation, unmanned operation, demand/supply prediction and quality improvement. Bottom-up approach develops relevant element technologies such as factory design which includes the development of factory requirement, basic design, detailed design and testing for determining the manufacturing method, machine equipment, cell, process and output (Choi, Kim, et al., 2015).

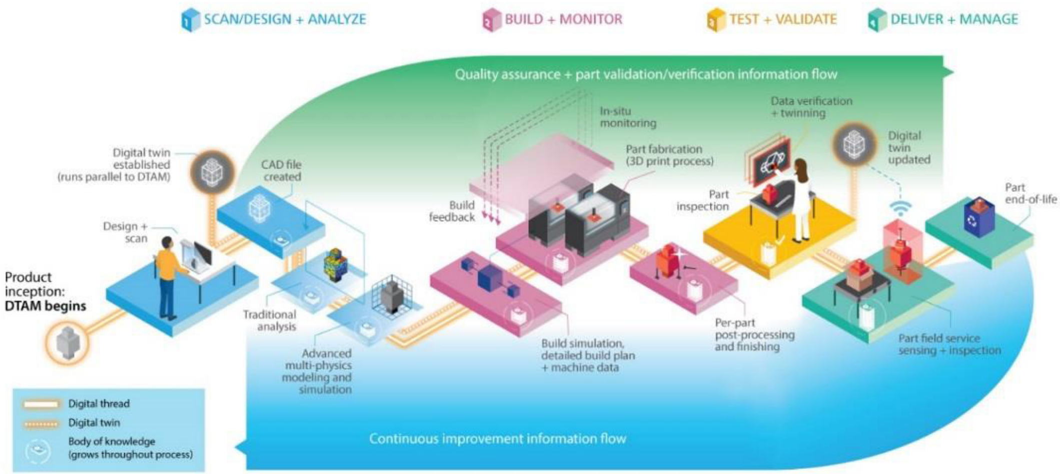

Figure 3: Digital thread for the additive manufacturing process (Mark Cotteleer, et al., 2016)

5. Additive Manufacturing

Additive manufacturing, also known as layered manufacturing (3D printing, Direct digital manufacturing) is an advanced manufacturing technique that replaces process-based job shop operations with product model driven operations based on a 3D CAD model (Holmström, Holweg, Khajavi, & Partanen, 2016). The 3D geometry is converted into a series of motion commands for an additive manufacturing machine by a class of geometric algorithms known as slicers. Digital thread for additive manufacturing (DTAM) , a single, seamless strand of data (Mark Cotteleer, Stuart Trouton, & Dobner, 2016) originating from a CAD model in the design environment and moving towards a pre-processing environment to produce the distinct tool paths making up each layer; followed by a manufacturing environment to fabricate complex shapes (Steuben, Iliopoulos, & Michopoulos, 2016) is well aligned with AM for managing data across the lifecycle maintaining complex relationships between the part geometry, material and individual processes used to create the final part and is collectively know as AM Informatics (Mies, Marsden, & Warde, 2016). Figure 3 explains the digital thread for the additive manufacturing process.

6. Applications of Digital manufacturing

6.1 Automotive Industry

The automotive industry, being the early adopters of rapid prototyping has seen remarkable advancements in manufacturing and technology which resulted in customized designs, cleaner, lighter and safer products at lower cost and reduced time to market. Applications of 3D printing in the automotive industry range from building prototypes, jigs, and fixtures, tooling, low volume end user products and concept models and reproducing parts. Various 3D printed innovations like variable 3D printed turbo technology for Koenigsegg One:1, safe smart and sustainable LM3D 3D printed car series from local motors, on demand 3D printing of Audi spare parts, new chassis construction for Blade a 3D printed supercar by Divergent Microfactories, race ready parts for WilliamsF1, thumb tool for BMW, etc. are now available (Hall, 2016). The advantages of AM in the automotive industry include increased –speed in the product design phase of new product development by enhancing quality, customized fabrication of tooling with reduced cost, complex designs with reduced weight, reduced assembly and production costs. However, the application of AM in the automobile industry is facing few challenges like low production speed of AM, limitations of AM in producing large parts and shortage of skilled personnel. Despite the challenges, the freeform capabilities of AM and reduced time to market of the final product is playing an important role in shaping the automotive industry (Giffi, Gangula, & Illinda, 2014). Figure 4 illustrates the applications of AM in Automotive industry.

6. 2 Aerospace and defense Industry

Additive manufacturing technologies found its applications in aerospace and defense industry in manufacturing lightweight parts with geometric and material complexities necessary to ensure safe travel in stringent conditions. From design concept to end life repairs, aerospace and defense industries incorporated AM technologies in every step of manufacturing to take full advantage of the technology (Hiemenz, 2014). Electron Beam Technology (EBM) is used to manufacture complex aerospace components (Dehoff et al., 2013). Figure 5 shows the additively manufactured Ti-6Al-4V Bleed Air Leak Detect bracket. Additive technologies with a digital link enable to maintain digital models of the spare parts reducing the expenses of physical warehousing and increase the availability of parts at the point of use. The advantages of AM in aerospace and defense industry include reduced time to market, the design of complex tools and parts at low cost, waste reduction and part simplification (Coykendall, Cotteleer, Holdowsky, & Mahto, 2014).

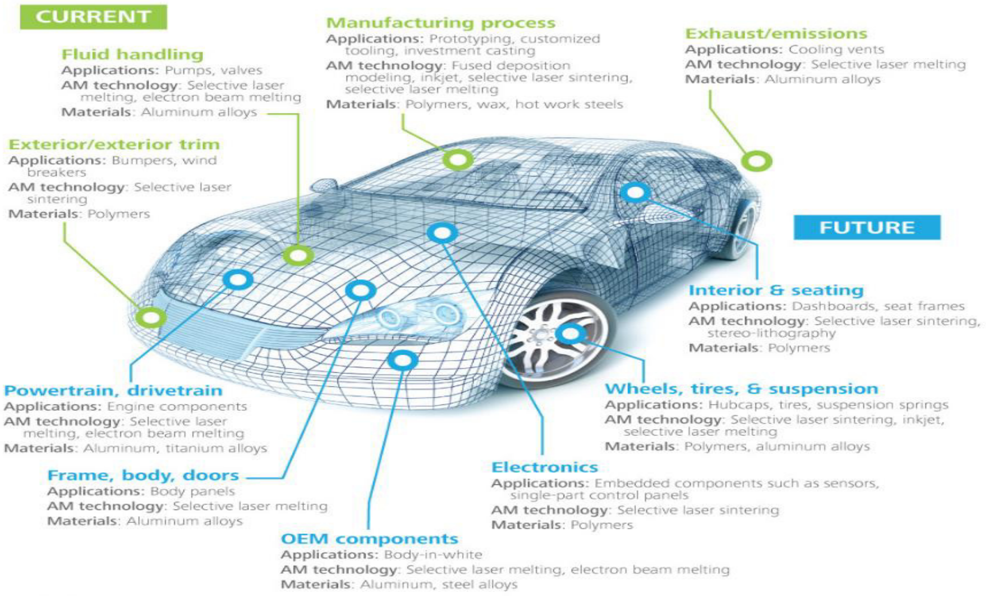

Figure 4: Applications of additive manufacturing in automotive industry *(Cotteleer, Holdowsky, & Mahto, 2014; Giffi, et al., 2014)*.

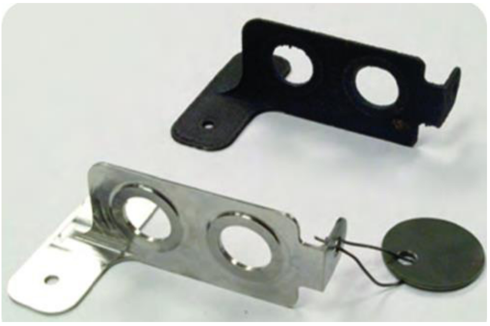

Figure 5: Ti-6Al-4V Bleed Air Leak Detect bracket produced by additive manufacturing *(Dehoff, et al., 2013)*.

6.3 Chemical compounds and Material microstructures

3D printing a versatile means of providing cost-effective and customized products is revolutionizing all sort of industries from kitchenware to food manufacturing. Startling technological advancements of 3D printing includes chemical design and production by the use of supercomputers to virtually analyze several chemical compounds for generating and manufacturing novel chemical compounds (Kurzrock & Stewart, 2016). 3D printed devices found their application in the field of synthetic chemistry in the area of fluidic reactors (Capel et al., 2013) and reactionware for chemical synthesis (Kitson et al., 2016). The ability of the additive manufacturing processes to manufacture process-dependent material microstructures, freely mix and fuse multiple microstructures, and produce a variety of material architectures perceived the emergence of a new paradigm in the modeling of material structures with different architectures (Regli, Rossignac, Shapiro, & Srinivasan, 2016). This technique offers an attractive pathway to mimic the microstructure of materials featuring complex heterogeneous architectures inspired by biological systems, using novel technologies including PolyJet printing, direct ink writing (DIW), 3D magnetic printing, multimaterial magnetically-assisted 3D printing (MM-3D printing) and magnetically-assisted slip casting (MASC) (Studart, 2016). Selective laser sintering (SLS), one of the most popular additive manufacturing technique is used to manufacture 3D samples with internal cracks of different orientations to study the fracture behavior of complex parts (Brugo et al., 2016). 3D laser microfabrication techniques allow generation of patterns, structures, and devices not feasible with traditional photolithographic processes. Additive laser –direct –write techniques like Microsteriolithogarphy (μSLA), Two-Photon Polymerization (TPP), Laser Chemical Vapour Deposition (LCVD), (Pique, Auyeung, Kim, Charipar, & Mathews, 2016) Lased Induced Forward Transfer (LIFT) are applied to generate 3D microstructures and nanostructures based on a digital design (Delaporte & Alloncle, 2016).

6.4 Medical Applications

As we are in the middle of paradigm shift the health care industry has perceived transformation in biopharmaceuticals, medical technology, and surgical procedures. Additive manufacturing technologies are mainly used in surgical and diagnostic aids, prosthetics development, tissue engineering etc. The recent research in the medical field has strengthened the capability of generating intricate shapes in the biomedical implants such as craniofacial, dental prosthetics; tissue engineering (Gao & Cui, 2016). Digital manufacturing has also been expanding in the areas of regenerative medicine, drug delivery systems, cancer therapies, bioprinting (Morouco, Carla Moura, & Alves, 2015). The current advancements in AM technologies shifted the mass fabrication of implants to the personalized pre-operative manufacturing of implants based on a digital 3D model of the patient.

6.5 Food

The decrease in the price of 3D printers and sophisticated technologies enabled the application of AM in the food industry. Since food processing involves labor intensive and repetitive operation, automation in food manufacturing increases efficiency and quality. Food printing , a digital food manufacturing process allows customized color, shape, flavor, texture etc to a cookie (Sun, Zhou, Huang, Fuh, & Hong, 2015). A 3D Foodini printer by Natural Machines can print sweet and savory dishes like pizza, spaghetti, mini burgers, and chocolates etc. of specific calorie portions where the user have to cook the food (Keating, 2014). Figure 6 a) & b) shows the advancements in 3D food printing processes. The main advantage of edible printing is less shelf time of food compared to traditionally and centrally manufactured items. However, handling multiple ingredients without out compromise in quality is still a challenge (Kim Porter, Jarrod Phipps, Adam Szepkouski, & Abidi, 2015) .

(a) (b) (c)

Figure 6: ***a)*** **3D food printing process** ***of a customized cookie (Sun, et al., 2015), b)*** **Printed Pizza by 3D Foodini printer** ***(Keating, 2014) c)*** **3D printed building model** ***(Meijs, 2013).***

6.6 Construction Engineering

Creating architectural models by hand techniques prior to actual construction is a usual practice followed by architects to demonstrate the models to the customers. The hand build models require a lot of time and money with details missing in the complex designs making it difficult to convince the customers about the merits of the design. Additive manufacturing technologies enable the architects to build 3D models of the complex designs from a CAD model faster and cheaper with an aesthetic look. Rietveld Architects is able to reduce the time from two months of two employers to just a few hours of single employee time and expense of creating detailed and accurate architectural models with the use of Object Eden 350 printing system as shown in Figure 6 c) (Meijs, 2013). Digital technologies are also offering a wide range of possibilities in architectural construction enabling architects, engineers, and constructors to design and build complex structures. Smart Dynamic Casting (SDC), a robotic based novel technology is developed by linking digital design, additive fabrication and material properties for complex concrete construction with low wastage and sustainability(Lloret et al., 2015).

7. Conclusions and Future scope

Over the past few decades, tremendous progress in science and technology transformed the way a product is manufactured. Digital manufacturing is a novel technology that creates designs and manufactures sustainable products at speeds beyond imagination! The more complex a product and its manufacturing operations are the more valuable is the digital manufacturing.

Additive manufacturing, a digital manufacturing technique has undergone significant development and found its applications in various sectors like automobile, aerospace, medical, materials, architecture, construction, food, fashion etc. In aerospace industry AM is advantageous to manufacture geometric and material complex lightweight high-performance products. Automotive industry exploited AM technologies to develop new products quickly, and efficiently thereby reducing the product development cost. Biomedical applications of AM are manifold. Manufacturing of customized implants and prosthetics, medical and diagnostic aids, tissue engineering, regenerative medicine etc. are few of them. AM technologies are also capable of printing different chemical compounds and materials with complex architectures which are difficult by traditional manufacturing. Architects took the leverage of AM in printing complex models to be presented to the customers with an aesthetic look. Construction engineering, with the help of robotic technology, is using AM to print large structures. The food industry is also using AM technologies to print chocolates, cookies, and cakes etc.

Despite, a significant development in additive manufacturing technology, it still requires more insight into the microscopic and macroscopic aspects of manufacturing processes as well as systems. Additionally, novel AM systems and standard processes need to be developed with a focus on the design of complex multimaterial structures, materials with multifunctional properties, electrically conductive materials, bio-applications using cells and biomaterials, micro and nanoengineering, energy and sustainability implications in manufacturing in order to elevate it as a middle-of-the-road technology. Also, there is a need for AM systems that can produce large parts for automobile and aerospace industries. Apart from the core industries like aerospace, military, automobile, medical, and consumer products, in the near future, AM technology will drive various other industries including dental, food, construction, architecture, fashion, toys, furniture, home accessories etc. with a digital link. With the present pace of ongoing research, new applications are likely to develop in printing customized biocompatible implants and biological tissues, edible foods, customized outfits, and jewelry, dream toys for kids, embedded electrically conductive parts enabling part simplifications etc. Therefore, digital manufacturing is widely believed as a frontier for new innovations and technology start-ups which will become the state- of- the- art technology in which a wide range of products will be developed virtually, and customized manufacturing is vogue.

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