Digital Twins

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Pictures have been a valuable tool in solving complex problems throughout history. Architects and engineers have long relied on blueprints and sketches to visualize their designs, while automakers have used wooden and clay models to develop car prototypes. Over time, the use of pictures has evolved, with advancements in technology allowing for more precise and realistic 2D and 3D computer-generated models. Despite this progress, there have been inconsistencies between digital models and the physical world, and often required modifications during the construction process due to unforeseen factors like component substitutions or changes in construction needs. However, with the rise of Internet of Things (IoT), cloud computing, artificial intelligence (AI), digital reality technologies, and big data, this gap is being addressed. One of the most exciting developments in this area is the advent of Digital Twins (DT), which represented the perfect connection between the physical and digital worlds, allowing for continuous evaluations and valuable insights from operational data. DT is being increasingly utilized across various industries, including engineering, manufacturing, energy, and automotive, to design, visualize, monitor, manage, and maintain assets effectively.

Industry 4.0

Over the past few decades, the Industry 4.0 revolution has taken shape, ushering in a new era of advanced technology integration. Industry 4.0 is all about interconnectivity, and it involves the integration of cutting-edge technologies such as IoT, AI, big data analytics, and cyber-physical systems[1]. Although initially developed largely by the manufacturing sector, Industry 4.0 has evolved into a comprehensive solution that can benefit a wide range of industries[2]. By harnessing the power of real-time data, Industry 4.0 has empowered companies to optimize their operations, enhance productivity, streamline processes, and drive growth. DTs play a critical role by creating virtual replicas of physical assets, facilitating the creation, management, and maintenance of cyber-physical systems[3].

History of Digital Twins

A pairing technology was first used in National Aeronautics and Space Administration's (NASA) Apollo 13 mission in 1970. The concept was initially used to pair a spacecraft launched into outer space with its twin on earth to monitor flight conditions[4]. NASA engineers used the technology to come up with recovery strategies when the spacecraft suffered significant damage. It was only in 2002 that the term "digital twin" was first coined by Dr. Michael Grieves, a professor at University of Michigan, in his book that talked about digital transformation in Product Lifecycle Management (PLM)[5]. In recent years, the development of data

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[1] Singh, Harpreet. "Big data, industry 4.0 and cyber-physical systems integration: A smart industry context." Materials Today: Proceedings 46 (2021): 157-162.
[2] Kagermann, Henning. "Change through digitization—Value creation in the age of Industry 4.0." In Management of permanent change, pp. 23-45. Wiesbaden: Springer Fachmedien Wiesbaden, 2014.
[3] Tao, Fei, Qinglin Qi, Lihui Wang, and A. Y. C. Nee. "Digital twins and cyber–physical systems toward smart manufacturing and industry 4.0: Correlation and comparison." Engineering 5, no. 4 (2019): 653-661.
[4] Yu, Wei, Panos Patros, Brent Young, Elsa Klinac, and Timothy Gordon Walmsley. "Energy digital twin technology for industrial energy management: Classification, challenges and future." Renewable and Sustainable Energy Reviews 161 (2022): 112407.
[5] Grieves, M. "Virtually Perfect: Driving Innovative and Lean Products through Product Lifecycle." Management (2011).

acquisition technology, processing technology, artificial intelligence, and simulation technology has led to the maturity of the concept[6]. In 2010, General Electric was one of the earliest adopters of DT, called the *Digital Ghost*, in their usage of the technology in the development of jet engines[7]. In 2015, the aerospace industry utilized DT to optimize decision-making in airframe design and maintenance, vehicle capacity estimation, and fleet prognosis[8]. Today, DT is used in various fields such as electricity power generation, construction, manufacturing, and healthcare. In 2017, Gartner recognized DTs as one of the top ten strategic technology trends[9]. For a detailed evolution of DT, see Figure 1.

What are Digital Twins and How Do They Work?

Digital twins are virtual representations of physical objects, processes, or services, which are widely used across industries but lack a universal definition[10]. However, the vast and growing DT literature have always touched on similar sets of business and engineering principles. For the bibliometric analysis, see Figure 2. Experts agreed that DTs can replicate physical objects or systems, from wind turbines and airplanes to buildings and rail systems, and simulate their behaviors and states for predictive analysis[11]. DTs are created through a mathematical model that incorporates operational data and physics and are connected to sensors from the physical object to mimic it in real time[12]. DTs can be used as a prototype to provide real-time feedback during product development or be used as a standalone tool for product research[13]. In general, a technology is classified as a DT when it represents a real physical object, simulates its behaviors and states, is unique to a specific instance of the physical object, updates itself based on the object's state, and provides visualization, optimization, analysis, or prediction[14].

Hierarchy and Types of Digital Twins

Good systems engineering involves managing complexity through strategies such as abstraction and hierarchy[15]. This is important because systems often comprise multiple layers of subsystems, assemblies, and subassemblies, known as constituent elements[16]. Complex but comprehensible systems require

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[6] Alexopoulos, Kosmas, Nikolaos Nikolakis, and George Chryssolouris. "Digital twin-driven supervised machine learning for the development of artificial intelligence applications in manufacturing." International Journal of Computer Integrated Manufacturing 33, no. 5 (2020): 429-439.
[7] Fournaris, Apostolos P., Andreas Komninos, Aris S. Lalos, Athanasios P. Kalogeras, Christos Koulamas, and Dimitrios Serpanos. "Design and run-time aspects of secure cyber-physical systems." Security and Quality in Cyber-Physical Systems Engineering: With Forewords by Robert M. Lee and Tom Gilb (2019): 357-382.
[8] Phanden, Rakesh Kumar, Priavrat Sharma, and Anubhav Dubey. "A review on simulation in digital twin for aerospace, manufacturing and robotics." Materials today: proceedings 38 (2021): 174-178.
[9] CeArley, David, Brian Burke, Samantha Searle, and Mike J. Walker. "Top 10 strategic technology trends for 2018." The Top 10 (2016): 1-246.
[10] Liu, Mengnan, Shuiliang Fang, Huiyue Dong, and Cunzhi Xu. "Review of digital twin about concepts, technologies, and industrial applications." Journal of Manufacturing Systems 58 (2021): 346-361.
[11] Ibid.
[12] Tao, Fei, Bin Xiao, Qinglin Qi, Jiangfeng Cheng, and Ping Ji. "Digital twin modeling." Journal of Manufacturing Systems 64 (2022): 372-389.
[13] Lo, C. K., C. H. Chen, and Ray Y. Zhong. "A review of digital twin in product design and development." Advanced Engineering Informatics 48 (2021): 101297.
[14] Qi, Qinglin, Fei Tao, Tianliang Hu, Nabil Anwer, Ang Liu, Yongli Wei, Lihui Wang, and A. Y. C. Nee. "Enabling technologies and tools for digital twin." Journal of Manufacturing Systems 58 (2021): 3-21.
[15] Kossiakoff, Alexander, Steven M. Biemer, Samuel J. Seymour, and David A. Flanigan. Systems engineering principles and practice. John Wiley & Sons, 2020.
[16] Ibid.

manipulating the lowest level element and then reassembling the system[17]. Similarly, DT operate on a bottom-up approach, with the lowest level containing the least function and information, and each subsequent layer becoming more sophisticated and diverse[18]. DTs' hierarchical structure includes parts, product, system, and process twinning[19]. Parts twin are virtual representations of physical, mechanical, and electrical properties for engineers to study, and computer-aided design/manufacturing can analyze static and thermal stress to enhance durability. Product twin tests the interoperability of different parts, and understanding interactions among them allows for optimization of constituent parts. System twin enables engineers to maintain fleets of various products that function together on a system level, such as energy grids or traffic control systems. Process twin is a virtual copy of workflows and procedures, and it can be used to optimize manufacturing processes or business workflows without affecting existing ones. DT can also be classified based on the stage of development of the physical counterpart. These three types are DT prototype, DT instance, and DT aggregate[20]. The DT prototype is created before the physical object to test various scenarios[21]. DT instance is done once the physical product is created to run tests on different usage and future scenarios[22]. Lastly, the DT aggregate determines the product's capabilities based on the DT instance and runs prognostics to test various operating parameters[23].

How Digital Twins Create Value

Digital Twins offer a wide range of applications, and the value they can provide to businesses is highly dependent on the specific use case. There are four main categories of value: descriptive, predictive, diagnostic, and analytical[24]. Descriptive value allows businesses to visualize the real-time status of assets, such as turbines, spacecraft, and power stations[25]. Predictive value enables companies to predict the future state of their assets, including wind farms and power output[26]. Diagnostic value helps determine the root cause of asset behavior or states, while analytical value optimizes both existing and future assets[27]. The benefits of using DT are manifold, including data-driven decision making, streamlined business processes, and new business models. By providing real-time data and advanced analytics, DT facilitates smarter and faster decision making, while automating error-prone activities such as inspection, testing, analysis, and reporting streamlines business processes[28]. Ultimately, this could lead to higher productivity, operational efficiency, and improved business profitability. Furthermore, companies can

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[17] Ibid.
[18] Kulkarni, Vinay, Souvik Barat, and Tony Clark. "Towards adaptive enterprises using digital twins." In 2019 winter simulation conference (WSC), pp. 60-74. IEEE, 2019.
[19] Michael Parks, “Digital Twins Are Being Developed for Parts, Products, Processes, and Entire Systems.,” Mouser (Mouser Electronics, February 19, 2019), https://www.mouser.com/applications/digital-twinning-types/.
[20] Jones, David, Chris Snider, Aydin Nassehi, Jason Yon, and Ben Hicks. "Characterising the Digital Twin: A systematic literature review." CIRP Journal of Manufacturing Science and Technology 29 (2020): 36-52.
[21] Ibid.
[22] Ibid.
[23] Ibid.
[24] Kassim, Nazirul Fariq Mohd. "Digtal Twin: What it means for future construction." Universiti Teknologi Malaysia, Johor Bahru, Malaysia (2020): 17-19.
[25] Ibid.
[26] Ibid.
[27] Ibid.
[28] Ohnemus, Thomas. "The digital twin–a critical enabler of industry 4.0." Zeitschrift für wirtschaftlichen Fabrikbetrieb 115, no. s1 (2020): 23-25.

leverage usage data in DT to diversify pricing and access many types and subtypes of customer segments, leading to higher market share and profitability[29].

Digital Twins and Product Lifecycle Management

Digital Twins have always been closely related to PLM[30]. Over the years, DT has been increasingly applied to different stages of a product's life cycle, including design, manufacturing, launch, distribution, operation, servicing, and decommissioning[31]. DT has been particularly useful in product development, production, operation and service, and end-of-life stages[32]. In product development, data from previous product versions' DTs are leveraged to detect conflicting components, assess ergonomics, and simulate product behavior under future circumstances and conditions[33]. This helps to reduce costs, speed up time to market, and improve product reliability[34]. In production, DT is used to communicate specifications to suppliers and optimize designs for manufacturing and shipping[35]. Each component in the DT has data on materials used, configuration selection by end-users, and production process conditions. During the operation stage, DT collects data upon installation by the end-user[36]. This data is used to plan maintenance, optimize product performance, troubleshoot issues, and inform future designs[37]. Multiple DTs by end-users can also be used to identify product usage trends[38]. Finally, when a product with DT reaches end-of-life, data collected by the DT is used to guide end-of-life actions. The DT recommends specific components to be recycled, reused, or disposed of[39].

Application Across Industries

Manufacturing

Digital Twin technology has gained much attention due to its operationalization in the manufacturing industry, which is uniquely positioned to benefit from this technology. The reason behind this is the data-rich nature of physical assets' production in manufacturing[40]. With the advancements in technologies such as IoT, automation, and robotics, manufacturing has become smarter and more automated. This automation does not have to come at the cost of accuracy, as even the smallest improvements in throughput, quality, and equipment uptime can result in a significant increase in profit for manufacturing companies[41]. CNH Industrial, a global producer of vehicles for agricultural, industrial, and commercial use,

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[29] Ibid.
[30] Silva, Henrique, Tomás Moreno, António Almeida, António Lucas Soares, and Américo Azevedo. "A digital twin platform-based approach to product lifecycle management: Towards a transformer 4.0." In Innovations in Industrial Engineering II, pp. 14-25. Cham: Springer International Publishing, 2022.
[31] Ibid.
[32] Ibid.
[33] Ibid.
[34] Ibid.
[35] Ibid.
[36] Ibid.
[37] Ibid.
[38] Ibid.
[39] Ibid.
[40] Lu, Yuqian, Chao Liu, I. Kevin, Kai Wang, Huiyue Huang, and Xun Xu. "Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues." Robotics and Computer-Integrated Manufacturing 61 (2020): 101837.
[41] Ibid.

is a prime example of the benefits of DT in manufacturing. CNH used DT to optimize the usage of the lamellar pack, a component that delivers electric current to their welding heads[42]. Mismanagement of the lamellar pack can cause damage to the robot and disrupt operations due to its volatile nature and finite shelf life[43]. By using DT to monitor and optimize its use, CNH Industrial increased efficiency, reduced costs, and ensured uninterrupted operations.

Industrial Production

The use of Digital Twins in industrial production has enabled manufacturers to pursue servitization strategies, providing visibility into their products even when in the hands of customers[44]. This enhanced remote diagnostics and targeted repair, contributing to the approximation of product uptime[45]. Additionally, usage data collected by the DT has the potential for future product development[46]. For instance, aero engine manufacturers such as GE and Rolls-Royce leveraged DT for product development by monitoring and supporting engines installed in customer aircraft[47]. Kaesar Compressoren (Kaesar), a compressed air systems manufacturer, used DT throughout the sales and product support lifecycle[48]. The company stored data on specifications and tendering for new installations, offers post-sales monitoring, and predictive maintenance features[49]. Additionally, Kaeser began providing air-as-a-service, where customers only pay for their portion of compressor use[50]. Similarly, Tesla collected usage information for every car and creates a DT for each[51]. This became the gateway for real-time servicing in the form of updates and helped Tesla engineers consider all the data gathered for future versions of their cars[52].

Healthcare

Digital Twins have caused a stir in the healthcare industry as researchers and clinicians alike are fascinated by their potential. Instead of relying on traditional machines, body parts are now digitally modeled, providing doctors with a detailed understanding of the body while reducing the need for invasive procedures[53]. In addition, DTs made *in silico* evaluations of new drug treatments possible, providing

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[42] Pires, Flávia, Ana Cachada, José Barbosa, António Paulo Moreira, and Paulo Leitão. "Digital twin in industry 4.0: Technologies, applications and challenges." In 2019 IEEE 17th International Conference on Industrial Informatics (INDIN), vol. 1, pp. 721-726. IEEE, 2019.
[43] Ibid.
[44] Rabah, Souad, Grégory Zacharewicz, and Vincent Chapurlat. "Digital Twin for services (DT4S): Conceptual strategy." IFAC-PapersOnLine 55, no. 10 (2022): 3256-3261.
[45] Ibid.
[46] Ibid.
[47] Qi, Qinglin, Fei Tao, Tianliang Hu, Nabil Anwer, Ang Liu, Yongli Wei, Lihui Wang, and A. Y. C. Nee. "Enabling technologies and tools for digital twin." Journal of Manufacturing Systems 58 (2021): 3-21.
[48] Augustine, Peter. "The industry use cases for the digital twin idea." In Advances in Computers, vol. 117, no. 1, pp. 79-105. Elsevier, 2020.
[49] Ibid.
[50] Ohnemus, Thomas. "The digital twin–a critical enabler of industry 4.0." Zeitschrift für wirtschaftlichen Fabrikbetrieb 115, no. s1 (2020): 23-25.
[51] Condori, Pedro Pablo Chambi. "Digital Twin in Development of Products." Digital Twin Technology: Fundamentals and Applications (2022): 205-218.
[52] Ibid.
[53] Alazab, Mamoun, Latif U. Khan, Srinivas Koppu, Swarna Priya Ramu, M. Iyapparaja, Parimala Boobalan, Thar Baker, Praveen Kumar Reddy Maddikunta, Thippa Reddy Gadekallu, and Ahamed Aljuhani. "Digital twins for healthcare 4.0-recent advances, architecture, and open challenges." IEEE Consumer Electronics Magazine (2022).

doctors with valuable insights before administering the treatment in the physical world[54]. Siemens Healthineers, a leader in healthcare technology, has taken DT development to the next level by creating a DT of the human heart[55]. This model simulated the mechanical and electrical activities of the heart and enabled doctors to create patient-specific treatments using electrocardiogram and imaging data[56]. In a recent trial phase of the technology, Siemens successfully tested the DT on a record number of 100 patients[57]. The future of DTs in healthcare is bright, promising advancements not only in rehabilitative care but also in diagnosis and treatment planning[58].

Energy

Digital Twins have emerged as a game-changer in the energy sector due to its ability to tackle big and complex processes in assets in remote locations[59]. These remote locations include oil and gas wells, transmission and distribution lines, power plants, wind farms, solar parks, pipeline networks, and offshore platforms[60]. This technology is seen as a key tool in enhancing operational efficiency, reducing costs, and ensuring safety in the industry[61]. Siemens analytics technology has allowed Aker BP to leverage DT successfully in its Ivar Aasen project located off the Norwegian Coast[62]. Through DT, Aker BP was able to optimize its equipment maintenance schedules and reduce manpower requirements[63]. The successful implementation of DT in energy production highlighted its potential to drive transformational change in the industry through improved performance, reduced downtime, and enhanced safety.

Consumer Products

Digital Twins are used in consumer product tracking within the supply chain[64]. This technology has been particularly useful for simpler objects, where aggregated data provided valuable insights[65]. Dassault Systemes, a 3D modeling and DT technology company, partnered with Sony Electronic Systems to create a DT of a store[66]. This digital store is connected to the inventory and point-of-sale systems, providing real-time updates on sales and stock levels[67]. Customers are also seen to benefit from this technology by easily

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[54] Ibid.
[55] James, Lindsay. "Digital twins will revolutionise healthcare: Digital twin technology has the potential to transform healthcare in a variety of ways–improving the diagnosis and treatment of patients, streamlining preventative care and facilitating new approaches for hospital planning." Engineering & Technology 16, no. 2 (2021): 50-53.
[56] Ibid.
[57] Ibid.
[58] Ibid.
[59] Borowski, Piotr F. "Digitization, digital twins, blockchain, and industry 4.0 as elements of management process in enterprises in the energy sector." Energies 14, no. 7 (2021): 1885.
[60] Borowski, Piotr F. "Digitization, digital twins, blockchain, and industry 4.0 as elements of management process in enterprises in the energy sector." Energies 14, no. 7 (2021): 1885.
[61] Ibid.
[62] LaGrange, Elgonda. "Developing a digital twin: The roadmap for oil and gas optimization." In SPE Offshore Europe Conference and Exhibition. OnePetro, 2019.
[63] Ibid.
[64] Srai, Jagjit, and Ettore Settanni. "Supply chain digital twins: Opportunities and challenges beyond the hype." (2019).
[65] Ibid.
[66] Michael Parks, "Digital Twins Are Being Developed for Parts, Products, Processes, and Entire Systems.," Mouser (Mouser Electronics, February 19, 2019), https://www.mouser.com/applications/digital-twinning-types/.
[67] Ibid.

locating items on their shopping list[68]. In the retail and e-commerce industries, DT is poised to become the next level of sophisticated models of consumer behavior[69]. By analyzing past purchases, browsing behavior, and social media activity, DT can help businesses predict consumer behavior and influence purchase decisions[70].

Other Industries

Digital Twins have proven to be a valuable tool in various fields, including materials science and transportation. DTs are used to predict the performance of physical products based on their material components, allowing for a better understanding of how certain materials impact product performance[71]. For example, DTs were used to determine how the strength and weight of materials affect fuel consumption in cars and trains[72]. In addition, DT has been integrated into maintenance operations in the transportation sector. Alstom, a UK-based rail equipment company, used DT in its train maintenance operations on the West Coast Main Line, that connects London to Glasgow and Edinburgh through major cities in the North West and Midlands of England[73]. By incorporating DT into its maintenance procedures, Alstom was able to optimize its operations, improve safety, and reduce costs.

Looking Ahead

Digital Twin will undoubtedly have a massive impact on various industries. Many DT projects are still under construction due to the complexity of the technology, but we can expect to see millions of objects with their DTs in the foreseeable future. In a way, DTs are depicted as building blocks of virtual ecosystems within the IoT and their usefulness is expected to evolve over time. While it is difficult to predict the exact growth of DT in the coming years, many experts anticipate its mainstream adoption in areas such as collaborating twins, corporate innovation, and as a supplementary technology for a multiplier effect[74]. Collaborating twins enable DTs to share information with each other in a non-siloed manner, which can lead to fully autonomous car grids and conscious cities[75]. DTs can also connect an enterprise's information, providing a bird's-eye view of operations and allowing for tactical improvements[76]. Additionally, DTs can be combined with virtual reality to enable simulations, rapid-pace design, and mimicked actions by

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[68] Ibid.
[69] Vijayakumar, D. Sudaroli. "Digital twin in consumer choice modeling." In Advances in Computers, vol. 117, no. 1, pp. 265-284. Elsevier, 2020.
[70] Ibid.
[71] Tao, Fei, Fangyuan Sui, Ang Liu, Qinglin Qi, Meng Zhang, Boyang Song, Zirong Guo, Stephen C-Y. Lu, and Andrew YC Nee. "Digital twin-driven product design framework." International Journal of Production Research 57, no. 12 (2019): 3935-3953.
[72] Bhatti, Ghanishtha, Harshit Mohan, and R. Raja Singh. "Towards the future of smart electric vehicles: Digital twin technology." Renewable and Sustainable Energy Reviews 141 (2021): 110801.
[73] Schislyaeva, Elena Rostislavovna, and Egor Alexandrovich Kovalenko. "Innovations in logistics networks on the basis of the digital twin." Academy of Strategic Management Journal 20 (2021): 1-17.
[74] Ray Eitel-Porter Mark Purdy, "How Digital Twins Are Reinventing Innovation," MIT Sloan Management Review, January 14, 2020, https://sloanreview.mit.edu/article/how-digital-twins-are-reinventing-innovation/.
[75] Ibid.
[76] Ibid.

robots[77]. The DT market is set to grow beyond 40% annually from 2022 until 2029, driven by demand for IoT and cloud-based platforms and the desire of companies to stay competitive[78].

Conclusion

Industries such as engineering, automotive, manufacturing, and energy are among the pioneers in utilizing DT to manage their most critical assets, with other sectors such as the public sector, healthcare, and consumer retail not far behind. As the technologies required to implement DT become more prevalent, we can expect it to become increasingly mainstream across different industries. DT serves as a tool that provides insights into the current and future state of an object, allowing for more proactive decisions in terms of development, deployment, and maintenance. However, for DT and their physical counterparts to work seamlessly together, companies must prioritize the improvement of data quality, availability, integration, security, governance, and analytics in their immediate operations[79]. While many DT applications are still in the development stage due to their complexity, companies that fail to invest in this technology will run the risk of falling behind. The potential applications of DT are vast, and its benefits cannot be overstated, making it a technology worth exploring for any industry and company seeking their next big growth.

[77] Ibid.

[78] "Digital Twin Market Size, Share & Covid-19 Impact Analysis, by Type (Parts Twin, Product Twin, Process Twin, and System Twin), by End-User (Aerospace & Defense, Automotive & Transportation, Manufacturing, Healthcare, Retail, Energy & Utilities, Home & Commercial, It and Telecom, and Others), and Regional Forecast, 2022-2029," Digital Twin Market Size, Forecast Value | Growth Report [2029], accessed March 29, 2023, https://www.fortunebusinessinsights.com/digital-twin-market-106246.

[79] Author Ramesh Dontha et al., "Data and Trending Technologies: Role of Data in Digital Twin Technology," TDAN.com, November 1, 2015, https://tdan.com/data-and-trending-technologies-role-of-data-in-digital-twin-technology/23630.

APPENDIX

Figure 1 Development of Digital Twins over the Years[80]

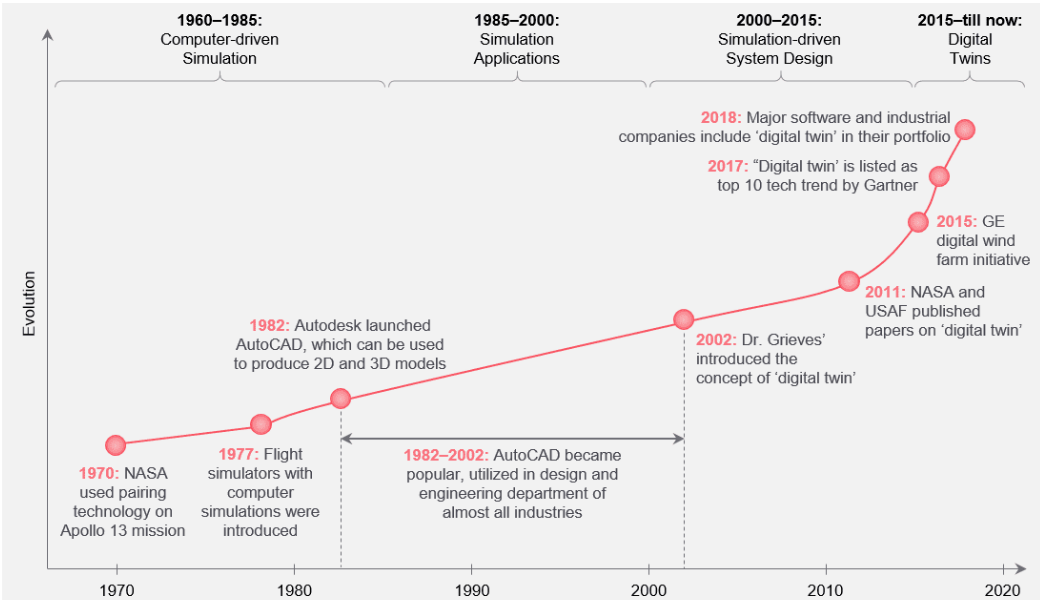
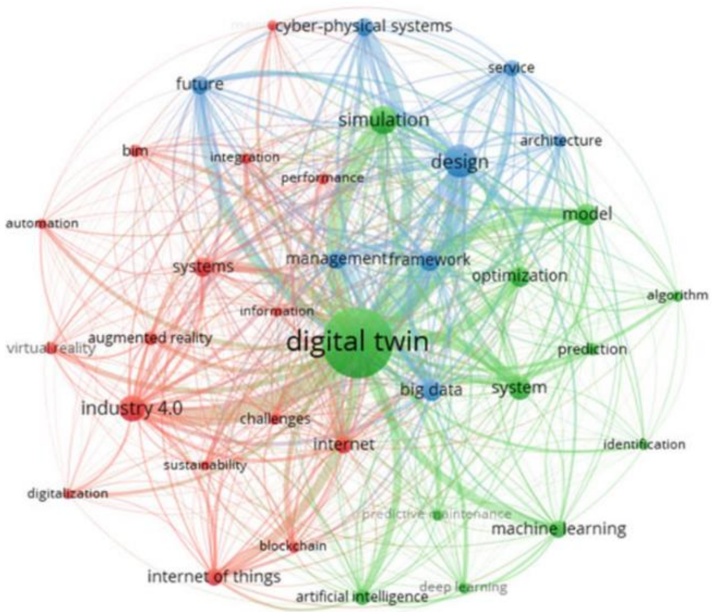


Figure 2 **Bibliometric Analysis of DT Literature in Web of Science[81]**



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[80] FutureBridge. "Application of Digital Twin in Industrial Manufacturing." FutureBridge, 2021, https://www.futurebridge.com/industry/perspectives-mobility/application-of-digital-twin-in-industrial-manufacturing/.

[81] Kumar, Vikas. Digital Transformation in Industry: Digital Twins and New Business Models. Vol. 54. Springer Nature, 2022.