Digital Technologies Enabling Resilience in Manufacturing Networks

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Abstract. Unforeseen events have the potential to cause disruptions throughout the entire manufacturing value chain, ranging from interruptions in production processes on the shop floor level to shutdowns in the supply chain and logistics. These disruptions increase the necessity for the establishment of manufacturing networks that prioritize cooperation and circularity to strengthen resilience, predict and counteract such impacts. This paper provides an overview of the main digital technologies required to create a resilient and sustainable manufacturing network and the implementation of the Manufacturing as a Service (MaaS) approach. For each digital technology, a synthetic characterization is provided, with respect to requirements, exemplary applications and involved standards. Challenges on the use of such technologies are presented and suggestions for future developments on the integration and deployment of digital technologies with the aim of achieving resilience in manufacturing networks is described.

Keywords: Digitally integrated production · Resilience · Supply chain · Circularity · Manufacturing networks · Sustainability · Manufacturing as a service

1 Introduction

In 2020, EU trade was hit by the COVID-19 pandemic, resulting in a significant fall for exports (−9.3%) and imports (−11.5%) [1]. In a positive light, EU trade has recovered strongly in 2021 and 2022, with imports of goods growing by 23.8 and 41.3% respectively, while exports of goods increased by 12.8% in 2021 and by 17.9% in 2022. In 2021, the value of sold production in the EU amounted to €5209 billion, an increase by almost

H. Kohl et al. (Eds.): GCSM 2023, LNME, pp. 516–523, 2025.
https://doi.org/10.1007/978-3-031-77429-4_57

14% compared with €4581 billion in 2020 [2]. The manufacturing sector is critical to the EU, employing around 29.4 million persons in 2020 and generating €1880 billion [3]. The region is now seeing a strong rebound in global demand for manufactured goods. However, some sectors are still hit by severe supply shortages, particularly in high value products, with supply struggling to accommodate this surge in demand. Disruptions in the logistics industry remain and have exacerbated supply bottlenecks. Companies may face severe shortages, particularly in high value process, with manufacturers struggling to accommodate this incremental surge in demand.

Manufacturing as a Service (MaaS) will play a critical role in terms of economic and societal impact. Bruegel, the European think tank specializing in economics, highlighted the importance of making the EU manufacturing sector more competitive and this is vital to restore economic growth in Europe in a recent report. In particular, the adoption of service business models in terms of servitization or "servinomics" will enable a wider portfolio of services for manufacturers and the fact that such services will be more resilient to business cycle fluctuations and to create a differentiation. The report also found that the externalization of services is more prevalent in the USA and in the Far East such as South Korea and increasingly in China. Therefore, it is imperative that EU manufacturers close this digital gap to increase its competitiveness and to reshape the way that manufacturing firms produce and compete [4].

As a result, the establishment of manufacturing networks that prioritize cooperation and circularity to strengthen resilience and counteract such impacts becomes all the more necessary [5]. The efficient utilization of resources by combining and deploying digital technologies for different processes across the manufacturing value chain has the potential to enhance resilience and raise the level of competitiveness of the manufacturing industry, as well as improving the sustainability of production processes [6]. Increased asset utilization along with circularity and minimized waste at their core will foster sustainability and increase the utilization of resources in manufacturing supply chains across various industries. Furthermore, in the literature has been pointed out that isolated solutions offer lower efficiency compared to holistic approaches [7]. Therefore, this paper provides a holistic framework for the synthetic characterization for each digital technology along with examples, standards, challenges and suggestions for future developments on their integration and deployment.

2 Enabling the Establishment of Manufacturing Networks

Disruptions described in the context of discrete manufacturing or other production industries can be mitigated if the system is able to quickly react to external or internal influences, and to also predict and anticipate these disruptions. The disruptions can trigger specific actions covering different processes and inform the supply chain network which in turn can offer alternative solutions. Relevant stakeholders need to be provided with information and assisted for optimal decision making on how to overcome the problems when they arise. These solutions require technologies to ensure that best solution can be applied for the adapted manufacturing strategy, such as dynamic rescheduling tools for accommodating the changes as efficient as possible. Additionally, by relying on synthetic System Digital Twins (DT) of the manufacturing plant to evaluate the effect of reconfigurations, process adaptation and rescheduling in a fast and efficient way [8, 9].

As described in Fig. 1, the architecture of a manufacturing network needs to be constructed in a way that the data can be shared horizontally and vertically in each layer. Starting from the bottom, the resources of the network participants, e.g. machine tools, materials or manufacturing capacities etc., must be able to provide actual information to all manufacturing entities. The data can be used to effectively communicate available resources across other network participants and at the same time inform decisions at an application level, e.g. for decision making, business approaches etc.

2.1 Dynamic Models and Digital Twins

Functional and geometrical models of products/components will need to be developed to contribute to the product-process matchmaking. The process planning should consider:

1. physical constraints such as process workspace or payload requirements,
2. operational capabilities and capacities,
3. level of automation available and
4. technological constraints.

The provision of models and simulators based on physics, technological features and real-time data to describe process capabilities and product requirements in the network is essential. It allows the implementation of actionable Digital Twins (DTs) that provide the exchange of information flow of manufacturing processes at network level and the identification of robust manufacturing strategies in the context of MaaS.

2.2 Networked Distributed Components

Industrie 4.0 with the implementation of Cyber Physical Systems (CPS) gives the ability to create highly automated digital factories, closing the gap between Operation Technology and Information Technology [10]. This integration ensures that information from different entities across the manufacturing value chain can reach potential or intended parties efficiently. Modular architectures incorporating concepts of DT and Asset Administrations Shells (AAS) assist in creating virtual representation of physical assets in a standardized way and will bring homogeneity in a heterogeneous interface field [11]. Such modular distributed Industrial Internet of Things (IIoT) architectures of production systems are often made of self-contained production modules. Every module must have the required capability for local control, to manage all operations that need to be performed within the entity, e.g. part reception, transformation operations start, termination etc. Furthermore, monitoring of process quality, equipment health status, faults, energy consumption, as well as part tracing, are all capabilities the module should include. Approaches that deploy Multi Agent Systems (MAS) can provide methods for distributed production control that enables production entities in the form of agents to securely exchange information within the network and to lead towards optimal decision-making regarding capacity utilization, complying with delivery dates and to account for real-time disruptive events and simulating different scenarios affecting production [12].

2.3 Data Driven Approaches and Analytics

Data driven Artificial Intelligence (AI) has created unprecedented opportunities for improvements in predictive analytics. This in turn helps improve efficiency in planning, forming the backbone of Industrie 4.0. Accurate predictions on quality outcomes help optimize process parameters and buffers, energy use, optimizing scheduling, suggesting predictions on machine operational lifespan, recommending times for service interventions, and making reliable predictions on supply stock and supply chain configuration. The implementation of effective analytical approaches is critical to the operation of a manufacturing network. Network participants must deploy various models across the entire organization to enable the generation of accurate information for stakeholders.

2.4 Human-Centered Value Chains

Businesses seek to boost efficiency in the value chain while also enhancing the quality and uniformity of their products. Human operators are being used for both quality control and at the same time are expected to be responsible for decision-making processes at the production level as well as at the value chain level. In some scenarios such as dealing with single or multiple unexpected disruptions, human operators may be unable to cope efficiently with the assigned tasks without any human centric assistive tools, purely because of human limitations in terms of cognition and mental processing. The new value chains should be characterized through cooperation between humans and machines, and they should be created to enhance and optimize, rather than to fully replace the knowledge and skills of human workers [13]. Beyond the traditional human factors that only help organizations to manage the workload safely and healthily, the design of these technologies must be centered around the human worker. Therefore, the design solution should advance to a more humanistic level, considering aspects of human experience, individual expertise and job satisfaction. This includes ensuring that the interface between Man and Machine, or the Graphic User Interface should be easy to understand and sufficiently intuitive to operate [14].

2.5 Cross Organization Data Exchange

The Internet and the services delivered by it are increasingly centralized on available platforms. Current frameworks are created to cater for increasing returns to scale and to deploy a business model with asymmetries between users and services. Existing multi-agent and agent architectures have seen no significant adoption outside niche applications. Consequently, the necessary agent frameworks need to be designed to allow for decentralized approaches, where each individual and organization can be represented by an autonomous entity with its own independent agency. Such an approach would bridge the gap between existing applications and new advancements in this field, such as by employing distributed ledger technologies as core parts of its construction. Other approaches such as decentralized Web 3.0 and Distributed Ledger Technologies, specifically Bitcoin or Ethereum, can be deployed to create decentralized systems for manufacturing networks.

2.6 Business Decisions

MaaS is part of a family of business models that are broadly summarized under the term servitization. In this context, "as-a-service" refers to the provision of a specific capability, and in the case of manufacturing industries, it means having an all-inclusive fee compared to selling equipment, solutions and services as separate transactions. Servitization therefore allows manufacturing companies to go beyond just selling products and instead offering a range of services that add value for customers. These services can include maintenance, spare parts management, process optimization, system integration, financing etc. [15]. In today's increasingly complex technological landscape, product differentiation alone may not suffice for a competitive advantage [16]. By leveraging their existing knowledge and expertise, companies can be faster to react to the market, develop and offer solution packages that set them apart from their competitors. This requires not only technical capabilities such as maintenance and repair, but also service-related skills such as data processing, risk assessment, and financing [17].

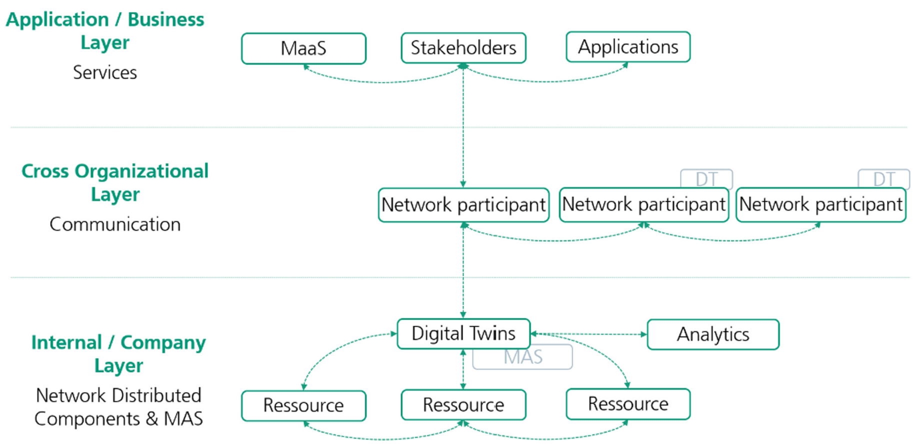

Fig. 1. Reference architecture for manufacturing networks

3 Challenges and Suggestions

Effective cross organizational communication requires a common language for all participating entities. Each organization, from the supply chain to the factory floor level uses different ontologies to describe common scenarios, applications and problems. Information included in various architectures of DTs differs significantly, thus making it increasingly difficult to relay the appropriate information when required. In manufacturing scenarios, common descriptions between machine tool capabilities and product requirements will need to be established, in order for appropriate matching to take place. This includes standardized translations of product designs to manufacturing specifications.

Key issues also arise in the data driven approaches. Deployed models typically suffer from data imbalance, due to the limited availability of historical data. Increased data sharing and collective decision making could consequentially improve predictive power. Such approaches have been extremely limited as organizations fear that sharing sensitive information such as process vulnerabilities, capacity and excess stock can be used opportunistically by others for cost reduction or for unfair competition [18].

4 Conclusion

This paper presents an overview of the main digital technologies required to create resilient and sustainable manufacturing networks. This starts from building upon the networked aspects of Industry 4.0, where all devices and components already possess cyber-physical capabilities and using agile resource exchange to solve real-world industry problems. A holistic and structured approach is necessary to build an organized hierarchical structure of assets that can be utilized within the manufacturing network. Data captured from sensors and machine tools during production processes should be integrated and translated into useful dynamic models, to be proactively used to control subsequent production processes and to flexibility adapt to existing production supply chains. The interconnected elements of the described architecture include dynamic models and digital twins, networked distributed components, data driven approaches and analytics, human-centered value chains, cross organization data exchange and business decisions. Cooperation among companies will improve asset utilization, thus reducing expected material and energy waste, reduce production costs by identifying optimal solutions at network level and foster proactive circular approaches. These technologies will allow the adaptation of logistics and production to varying external conditions, improving the resilience of the industrial systems and value chains. Such a shift from linear approaches to closed-loop, circular processes that also minimize waste will therefore ensure resilience, sustainability and relevance of manufacturing supply chains.

Acknowledgments. We thank our colleagues from TTTech Computertechink AG, Fetch.ai Research and Development GmbH, Servitize UG, M&M Group, EIT Manufacturing East GmbH and EIT Manufacturing South East who provided insight and expertise that greatly assisted this research.

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