Taylor & Francis
Taylor & Francis Group

International Journal of Sustainable Engineering

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tsue20

More than 10 years of industry 4.0 in the Netherlands: an opinion on promises, achievements, and emerging challenges

A. Martinetti, K. Nizamis, P. Chemweno, C. Goulas, L.A.M. van Dongen, I. Gibson, S. Thiede, E. Lutters, T. Vaneker & G. M. Bonnema

To cite this article: A. Martinetti, K. Nizamis, P. Chemweno, C. Goulas, L.A.M. van Dongen, I. Gibson, S. Thiede, E. Lutters, T. Vaneker & G. M. Bonnema (2024) More than 10 years of industry 4.0 in the Netherlands: an opinion on promises, achievements, and emerging challenges, International Journal of Sustainable Engineering, 17:1, 1-12, DOI: 10.1080/19397038.2024.2327380

To link to this article: https://doi.org/10.1080/19397038.2024.2327380

INTERNATIONAL JOURNAL OF SUSTAINABLE ENGINEERING
2024, VOL. 17, NO. 1, 1–12
https://doi.org/10.1080/19397038.2024.2327380

More than 10 years of industry 4.0 in the Netherlands: an opinion on promises, achievements, and emerging challenges

A. Martinetti*, K. Nizamis*, P. Chemweno*, C. Goulas, L.A.M. van Dongen, I. Gibson, S. Thiede, E. Lutters, T. Vaneker and G. M. Bonnema

Design, Production and Management, University of Twente, Enschede, Netherlands

ABSTRACT
The concept of Industry 4.0, as a means to move forward in the industrial ecosystem, has reached an important turning point. Where do we stand now in terms of industrial innovation and transition? This opinion paper provides an overview of the situation in the Netherlands, a reflection on what has been achieved by the Industry 4.0 paradigm, and the necessary way forward to solidify its implementation. Tentative results reveal that the pervasiveness of Industry 4.0 applications is sector-specific. This work provides industrial stakeholders and academics with useful suggestions and a possible path to move towards better integration of Industry 4.0 in company reality. In this opinion paper, we employ a mixed methods research methodology to argue that, based on our findings on industrial adaptation in The Netherlands, Industry 4.0 is the outcome of an evolutionary process and not of a revolution, as it is often claimed.

ARTICLE HISTORY
Received 28 November 2023
Accepted 28 February 2024

KEYWORDS
Industry 4.0; Smart industry; demystification; Industry 4.0 pervasiveness

1. Introduction

Industry 4.0 is often referred to as a new industrial stage, and yet since the term was coined in Germany more than 10 years have passed (Kagermann and Wahlster 2022; Kagermann, Lukas, and Wahlster 2011). There is already an effort to conceptualise industry 5.0 around the concept of sustainability, human centricity, and resilience (Directorate-General for Research and Innovation European Commission 2022; Maddikunta et al. 2022). There is even mention of Industry 6.0 inspired by the recent series of crises we are facing as humanity (COVID-19, financial crises, the tension between Russia and the EU, Brexit, the USA-China trade wars, etc.) (Annanperä et al. 0000) and the further independence of machines (Duggal et al. 2022). It is evident that the time we spend in every industrial phase is shrinking rapidly (see Figure 1). Therefore, it is a suitable time to reflect upon what has been achieved so far, which promises were met, to what extent, and what are the differences in the context of different industrial sectors. Industry 4.0 is met in different contexts with various names (for example *smart industry* in The Netherlands, *Made in China* 2025 in China, *Advanced Manufacturing Partnerships* in the USA, etc.) (Bureš 0000). However, the main characteristic of the 4th industrial revolution is the change in manufacturing enabled by cyber-physical systems (CPS) (Reyes Garcia et al. 2019), due to the integration of advances in information and communications technology (ICT), Internet of Things (IoT), sensors, computational power, robotics, and artificial intelligence (AI) (Geissbauer, Veldso, and Schrauf 2015; Xu, Xu, and Li 2018). In this work, the authors do not wish to discuss the validity of different definitions but look at those common characteristics in the context of Dutch industry.

Looking at the literature, there are many studies including review articles, and position papers on the Industry 4.0 concept. However, a closer look at articles published in highly ranked scientific journals, and international conferences shows a predominant bias towards specific application areas. Key terms mainly include: ‘digital tools/twins’, ‘serious games’, ‘technology assessment’, ‘smart factory performance’, or ‘implementation of Industry 4.0 concept’. Several publications discuss industry trends and the impact of Industry 4.0 conceptualisation on different industry sectors, for instance (Kozlovska, Klosova, and Strukova 2021) the impact on the construction industry (Fallahpour et al. 2021), the implementation of Industry 4.0 in companies providing empirical evidence, and (Dzwigol, Dzwigol–Barosz, and Kwilinski 2020) explores the formation of globally competitive enterprises. We found articles exploring Industry 4.0 trends with a few examples including (Fuertes et al. 2022) discussing the evolution of sustainability manufacturing objectives aligned to the Industry 4.0 trend (Karnik et al. 2021), discussing trends of technology enablers (Florescu and Barabas 2022), looking at development trends of production systems and lean manufacturing, and discussing the impact and trends on the food industry (Hassoun et al. 2023, 2024).

1.1. State-of-the-art and motivation for the study

As a starting point, we explored the situation of the European manufacturing landscape and especially, how different

CONTACT A. Martinetti a.martinetti@utwente.nl Design, Production and Management, University of Twente, Enschede, Netherlands
*These authors have contributed equally to this work and share the first authorship.

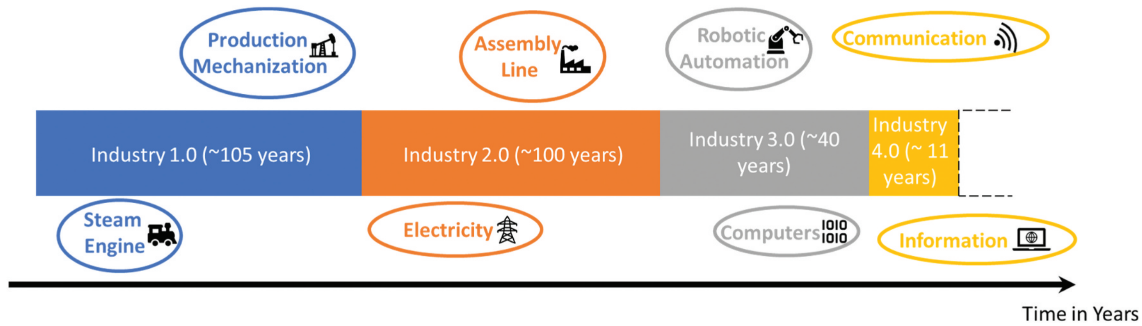

Figure 1. The (approximate) timeline of the four industrial periods. It is evident here, that the transitioning time between industrial revolutions has decreased from approximately 105 years to 11 (and counting) (Tsaramirsis et al. 2022).

industry sectors implement the Industry 4.0 concept or its variations. Based on consultancy reports, and published literature, there are limited insights on clear roadmaps for its implementation. Calabrese, Levialdi Ghiron, and Tiburzi (2020) provide glimpses into complex factors in the adoption and implementation of Industry 4.0 concepts. They are including differences in size, industrial sectors, service levels, and production portfolios, resulting in variation in how companies adopt enabling technologies. Their study focuses on SWOT analysis and interviews with companies to understand mainly the adoption of enabling technologies, including wearable technologies, cobotization, or simulation platforms for optimising productivity. A different study by Müller, Kiel, and Voigt (2018), aptly titled 'What drives the implementation of Industry 4.0: the role of opportunities and challenges in the context of sustainability', highlights the relevance of digital technological enablers from a perspective of sustainability. The authors mention similar differentiation in size, industry sectors, business context, core drivers of adaptability, and adoption of Industry 4.0 concepts. Their study nonetheless provides high-level insights on sustainability drivers relevant to industrial value addition.

Additionally, we found articles discussing possible guidelines or road maps for implementation. Several of the articles relate to implementation in the European context not only by the European manufacturing sector but also by the European Commission. Documents published, include the titled 'Industry 4.0: Digitalisation for productivity and growth' prepared as an outcome of discussions in the European Parliament. Notably, the document highlights the importance of applications of sensors, wireless communication, and intelligent manufacturing robots. Interestingly, the document also highlights challenges that we explore in this paper, including opaque business models, sectoral implementation differences and structural implementation guidelines or roadmaps.

A follow-up document by the European Economic and Social Committee titled 'Industry 4.0 and Digital Transformation: where to go' (Industry 4.0 and digital transformation: Where to go 2023) deliberated on four core topics. These include technology and platforms, standards and reference architectures, geographic cohesion and innovation hubs, and skills. Similar to the earlier report by the European Commission, aspects related to sectoral differences in the European, implementation architectures remain ambiguous. More recently, the European Commission fronted the 'European industrial strategy' aiming at integrating sustainability, climate neutrality, and digital leadership. The document also incorporated a survey of the European Manufacturing landscape and reported outcomes including decreasing turnover of SMEs, and a decline in intra-EU trade among other indicators. Notable and interesting for our paper are the need for developing transition pathways and analysis of sectors (notably the steel sector owing to its negative carbon footprint). This is aligned to the goal of this paper, as we explore more broadly aspects, including sectoral differences but more importantly, sectoral differences and potential insights on implementation roadmaps or transitional guidelines for European manufacturing companies.

From a country-specific perspective, the Netherlands manufacturing sector developed a comprehensive agenda aptly titled 'Smart Industry Implementation Agenda 2018–2021'. The Dutch government has in place a strong sectoral policy to support technology-oriented SMEs to rapidly introduce smart industry and Industry 4.0 initiatives. Perhaps notable is the 'Implementation Agenda Smart Industry for 2018–2021' for the Dutch companies, supported by the Dutch Organization for Applied Natural Sciences (TNO), the Dutch Ministry of Economic Affairs, and the Dutch Chamber of Commerce, among other sectoral players (Smart Industry Implementatieagenda 2018–2021 DUTCH INDUSTRY FIT FOR THE FUTURE 2022). This is one of the primary motivations for selecting the Dutch situation as a showcase because of the similarity of the manufacturing landscape situated in the broader European Manufacturing landscape. Moreover, the agenda contextualises the Industry 4.0 concept for the Dutch industry. The implementation agenda communicates a strong ambition by the Dutch government and industry actors in technology and manufacturing to become front runners in the 'fourth industrial revolution' or 'Industry 4.0' as a common term used. Accordingly, Dutch industry should make 'giant leaps' in ICT innovation, and automated production systems co-opting advanced robotics and smart manufacturing technologies. Looking at the 'Smart Industry Agenda' of the Netherlands, the pillars of Industry 4.0 as originally conceptualised are apparent.

At the core of the agenda, Agile Manufacturing Technologies, Digitization, and Network centricity are situated, linked to eight dimensions. Overall, close connections with pillars of Industry 4.0 are implicit, apart from dimensions such as connected factories (system integration and simulation), advanced manufacturing (3D printing), flexible manufacturing (linked to autonomous robots), digital factories and servitisation (cloud computing, augmented reality, big data, IoT, and cyber security) (Geissbauer, Veldso, and Schrauf 2015; Hulshoff 2001). The agenda goes beyond the Industry 4.0 pillars and introduces a sustainability pillar and smart working (linked more recently to Operator 4.0 concepts). Interestingly, the Dutch Smart Industry agenda also goes further by seeking a broad consensus of the Dutch industry and proposes a road map for operationalising the agenda, through a lifelong learning component supported by Smart Industry Labs or Field Labs. The latter is a component not explicitly included in the initial conceptualisation of Industry 4.0 but increasingly is recognised as an important pillar towards realising a smart industry future.

Our main motivation with this opinion paper is not only to explore achievements and opportunities in different industry sectors but also to provide a reflection on a country where the Industry 4.0 concept is expected to be mature, and pave the way for the smoother adoption of Industry 5.0. To the best knowledge of the authors, there are no similar articles. We see this as an important gap, especially limited are insights on updates of Industry 4.0 concepts, successes, pitfalls, and reflections on the next steps for different sectors.

2. Methodology

We aim to highlight recent advancements in the implementation of Industry 4.0 in the Dutch industry, understand it, and discuss a perspective based on diverse sources from various industrial sectors. As this is a rather complex endeavour, encompassing multiple disciplines, and sectors, we believe that quantitative or qualitative analysis alone would not be fit to reveal the complete picture. To achieve a comprehensive understanding, we apply methodological triangulation by combining qualitative with quantitative research, accompanied by the author's perspective (Figure 2), in a mixed methods research methodology.

We start by analysing existing sources starting from the European vision of Industry 4.0 as the context where the Dutch road map for Smart industry was developed, and finally analyse applications of Industry 4.0 aspects in different sectors (Section 2 – Qualitative Analysis). Next, we investigate the pervasiveness of the concept in the Dutch context, by analysing an existing survey involving 30 companies in the Netherlands (Section 3 – Quantitative Analysis). Lastly, we offer our perspective, based on the information given in Sections 2 and 3. We attempt to demystify the implementation of Industry 4.0 in the Netherlands, discuss our insights for future barriers and enablers.

3. Vision on industry 4.0: a top-down perspective from Europe to sector-specific

The EU supports industrial change through its industrial policy and research, and infrastructure funding. However, challenges remain. The need for investment, changing business models, data issues, legal questions of liability and intellectual property, standards, and skill mismatches are among the challenges that must be met if benefits are to be gained from new

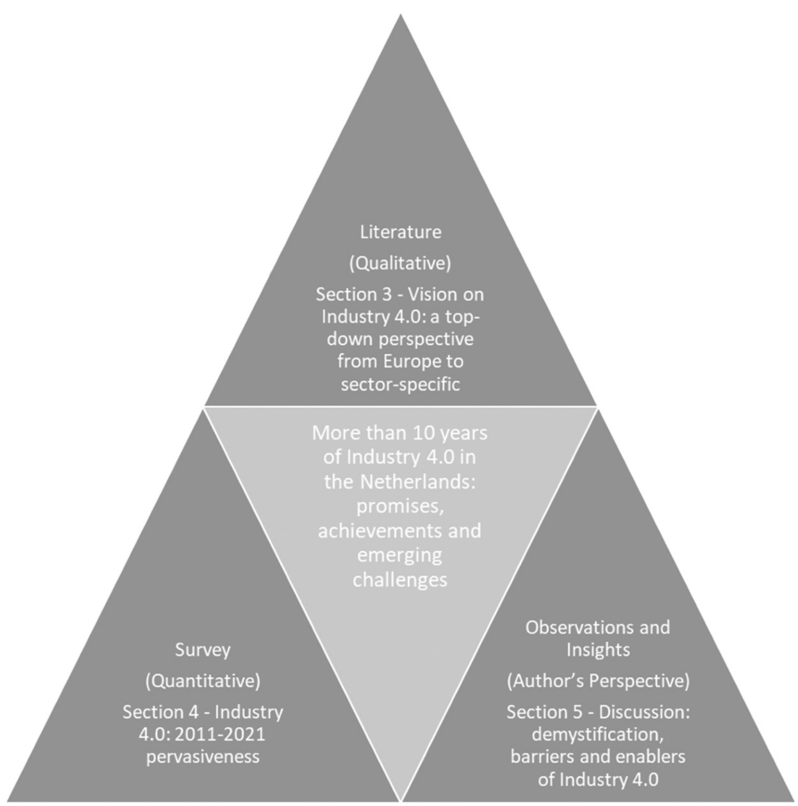

Figure 2. Graphical representation of the methodology used in the paper. Each edge of the triangle represents the methodology used per section.

industrial technologies. If these obstacles can be overcome, Industry 4.0 may help to reverse the past decline in industrialisation and increase total value-added from manufacturing to a targeted 20% of all value-added in the coming years. Not every observer is convinced of the value that Industry 4.0 will add. Some feel that Industry 4.0 as a concept is poorly defined and suffers from exaggerated expectations; others believe that fully digitised products and value chains are still a 'pipe dream' (Davies 2015).

3.1. Motivation for analyzing the Dutch situation

The Netherlands is well-known for its robust small and medium-scale manufacturing enterprises (SMEs). This tradition stems from a culture of establishing family businesses, that goes back several decades and continues to contribute significantly to the Dutch economy (Hulshoff 2001). Traditionally, Dutch family businesses span both small, medium, and large enterprise sectors and according to estimates, over 50% of Dutch enterprises employing between 2 and 249 employees are family businesses. More interestingly, the share of family businesses in the SME sector is estimated conservatively at 80%. Moreover, the growth of SMEs has been robust with 1,300 new enterprises between 2019 and 2020. In total, their contribution to the Dutch economy was in the order of magnitude of 220 billion Euros in 2017 according to the most recent survey by the European Commission.

This underscores the importance of Dutch SMEs to the future economic outlook of the Netherlands. Besides, the Netherlands is one of the most prominent countries in Europe for start-ups, with year-to-year growth rates judged in terms of raising venture capital funds peaking at $3.8 bn in 2021 alone. Looking at the sectoral spread, manufacturing-related SMEs as of 2020 stood at 71,566 companies constituting slightly larger than 6% of non-financial businesses in the Netherlands. From the sectoral analysis by the European Commission, this proportion is larger once the contribution of other sectors, including technical services, construction, transportation and storage, and water supply and energy services. In a much broader sense, technical services contribute significantly to a large industry portfolio considering the Netherlands is a prominent manufacturer with well-known industries, including Philips, Tata steel, DAF trucks, VDL, and Royal Dutch Shell and a manufacturing base of major international names. Technical services are also a major player in the logistics and transportation industry, with major players including the Netherlands Railways and the port of Rotterdam.

3.2. Status of implementation of the smart industry agenda by Dutch industry

There are already concerted efforts by the Dutch Industry to integrate the dimensions of the smart industry agenda. The progress and successes so far seem sectoral-wide, with some of the dimensions implemented to a mature level compared to others. A few use cases are noteworthy to mention, from a sectoral perspective categorised on the nature of the business, turnover and number of employees. Key Dutch industries and potential adopters of the smart industry agenda include agrifood, information technology, chemicals, high-tech systems and materials, energy, and logistics as some examples. Each sector/industry is further characterised by manufacturing or value additional components, for instance, with the agrifood sector focusing on agri-processing and innovations in logistics and supply chains. The logistics sector is wide in scope, covering among others road, rail, and air transport. Prominently, the rail infrastructure and rolling stock operator is widely discussed as an adaptor of smart industry initiatives owing to their unique capital, safety, and maintenance-intensive business.

The high-tech systems and materials industry is another prominent initiator of smart industry developments, extending to robotics and AI and consists of numerous start-ups and SMEs. Intuitively, the business model leveraging multidisciplinary crossovers between technologies presents unique opportunities to the sector as it cuts across several pillars such as flexible and advanced manufacturing, sustainable and digital factories, smart working, and smart products. Lastly, numerous actors focus on manufacturing, specifically machine tools, components, and industrial equipment, and consist of small, medium, and large enterprises.

The next section explores examples of the implementation status of the smart industry agenda by two sectoral actors:

Railway infrastructure.
Manufacturing

3.2.1. Railway infrastructure

After the liberalisation of the rail market in the Netherlands, two divisions were created for the rail operator. The first is a technician division responsible for operating train services on all mainline railways, with a fleet of around 3000 coaches, each coach having an average life cycle of 30 to 40 years (van Dongen 2015). Often the coaches are modernised halfway through this life cycle and undergo rigorous maintenance, creating opportunities for efficiency enhancement through smart industry development such as predictive maintenance, and design for maintenance (Research & Development, R&D).

To highlight a few examples, projects were initiated to develop eco-design tools to reach sustainability targets for the maintenance function of the operator. Importantly, the tools link to the sustainability pillar of the smart industry and consider the different project phases of modernising coaches to extend their operational life. The eco-design framework considers important eco-design aspects, including design for the environment, where predictive maintenance, circularity, life cycle assessment and systems engineering play critical roles (Haanstra et al. 2020). A second case considers the innovative use of augmented reality for railway maintenance operations. This extends to supporting maintenance procedures and improving decision-making. Using AR is one of the important pillars of Industry 4.0 and the Smart Industry agenda of the Netherlands (Scheffer et al. 2021).

The innovative tools extend to innovative 'digital twinning' focusing on developing simulation-based modelling approaches for improving overhaul and repair (O&R) processes within a rolling stock repair hub (Qi et al. 2021; Singh et al. 2021; Tao et al. 2022). For this specific example, agent and discrete-event simulation presented opportunities for mimicking actual operations at the O&R facility and using the simulation to gain insights into operational bottlenecks. Improvements were thereafter formulated to improve the O&R processes. These examples present glimpses of the maturity level of the Dutch railway sector. In this sector, the organisational readiness in the introduction of these new technologies appeared to be a prerequisite.

3.2.2. Manufacturing

The Netherlands is also renowned for its resilient small and medium-scale manufacturers of a wide range of industrial and household tooling, appliances, and machinery/equipment (Boutris and Salimi 2023). Innovation in automation readiness is deemed mature, especially as far as implementing legacy technologies including industrial robots, automated storage, and material handling systems (Phan Vo, Wolters, and Chi Vo 2021). This motivation is intuitive – the need to remain competitive in a labour cost environment compared to large manufacturing hubs in Asia and particularly China (Acemoglu, Koster, and Ozgen 2023). More recently, there is a drive towards integration smart AI-driven tools to support innovation for product development, as well as design of flexible and agile manufacturing systems. This includes innovations in collaborative robotic manufacturing, automated material handling systems, and digitisation technologies. These technologies integrate the so-called human-in-the loop, thereby driving innovations in areas of sensing technologies, ergonomics, and human factor analysis (Bokhorst et al. 2022).

To support seamless manufacturing and mitigate supply chain disruptions, there is evidence of interest and investment in information technologies including enterprise resource planning and manufacturing execution systems (Tedaldi and Miragliotta 2022). These systems aid production planning, control, and execution and lately, rely on smart AI tools to dynamically adapt manufacturing to better cope with changes in order patterns, and supply chain disruptions (Pulikottil et al. 2021). Such AI tools are increasingly used to harness 'big data' to better gain insights on order patterns, production bottlenecks, and integrating market forecasts as a productivity efficiency driver (Pulikottil et al. 2021).

Digital simulation tools are increasingly used for decision making in manufacturing and service environments characterised by complex trade-offs. This includes factory 'digital twins' to help companies better visualise production flow and anticipate impact of changes in planning or manufacturing new products (Chemweno and Torn 2022). Potentially, linking simulation platforms to digitisation platforms (manufacturing executions systems and supervisory control and data acquisition) is an emerging trend, but still nascent in Dutch manufacturing. This integration extends to using factory simulation to identify automation opportunities on the manufacturing shop floor (Chemweno and Torn 2022).

4. Industry 4.0: 2011–2021 pervasiveness

Industry 4.0 arrived with some initial promises and created certain expectations for improvements compared to the previous situation (Dalenogare et al. 2018), [39]. Creating smarter, more efficient workplaces and increasing process quality would expedite faster production. Seamless interconnections within factories, sectors and cross-sectors using data utilisation, not just for gathering data, but also for extracting useful insights and patterns that may help achieve cost reduction, and boost revenues. After all, Industry 4.0 has created a vast potential for enabling more sustainable industrial practices (Hilty and Aebischer 2015).

Following in this section we will perform an analysis of the current degree of realisation of Industry 4.0 processes, practices, and technologies in the Dutch industry, from available data. In the next section, we will reflect on and discuss how many of those were realised and how we can expedite their implementation in practice.

The current Dutch situation in terms of Industry 4.0/Smart Industry pervasiveness was analysed taking into consideration three key sectors for The Netherlands: manufacturing, energy, infrastructures, telecommunication, financial and consumer goods.

Thirty companies in total were interviewed. The companies were chosen based on their size (SME and large companies) and their products to have as much as possible a fair representation of the companies' population. Table 1 provides an overview of the industrial domains to which the companies belong.

Table 1. Industrial domain of the companies included in the survey.

Company	Industrial Domain	Company	Industrial Domain
C1-Manufacturing	Electronics production	C19-Telecommunication	Electronics production
C2-Manufacturing	Steel production	C20-Telecommunication	Steel production
C3-Manufacturing	Avionic components' production	C21-Telecommunication	Avionic components' production
C4-Manufacturing	Metal production	C22- Telecommunication	Metal production
C5-Manufacturing	Agrotechnical machine production		
C6-Manufacturing	Defence systems		
C7-Energy	Energy production	C23-Financial Institutions	Bank
C8-Energy	Energy distribution	C24-Financial Institutions	Bank
C9-Energy	Energy distribution	C25-Financial Institutions	Bank
C10-Energy	Oil and gas	C26-Financial Institutions	Investment fund
C11-Energy	Energy production	C27-Financial Institutions	Investment fund
C12-Energy	Energy production		
C13-Infrastructures	Asset maintenance and management	C28-Consumer Goods	Food & Beverage
C14-Infrastructures	Infrastructures management	C29-Consumer Goods	Food & Beverage
C15-Infrastructures	Infrastructures construction	C30-Consumer Goods	Food & Beverage
C16-Infrastructures	Infrastructures management		
C17-Infrastructures	Shipping		
C18-Infrastructures	Infrastructures construction		

The authors acknowledge that the number of companies involved in the study is not 'statistically relevant' and it offers a limited perspective on the Dutch market. However, it is valuable to point out that statistical significance was never meant to imply scientific importance and, as it is not worth believing that an association or effect exists just because it was statistically significant, it is also not worth believing that an association or effect is absent just because a dataset is not statistically significant (Wasserstein et al. 2019).

Firstly, the interviewed companies had to reflect on how much Industry 4.0/Smart Industry has entered the market in terms of application. After the brainstorming session, a survey based on eight main technologies of the Industry 4.0/Smart Industry (Augmented Reality, Robotics/Automation, Biointegration/Mobile Technologies, Additive Manufacturing, Big Data/AI, Cloud Computing, Cybersecurity, Digital Twin/Simulation) was provided. The technologies were selected based on (Vaidya, Ambad, and Bhosle 2018) and adapted for the Dutch industry according to their relevance. The interviewees were asked to rank them using a Likert scale ranging from 0 to 5, where 0 represents the lowest introduction grade of a specific aspect in the industry. Figure 3 offers an overview of the result of the survey. Finally, the companies were asked to rank the highest grade (5) only the elements that are 'permanently' embedded in their workflow.

As it is possible to notice from Figure 3, the implementation and acceptance of the Industry 4.0/Smart Industry elements are far from being over or even close to a desirable level. Augmented Reality and Additive Manufacturing are now, quite under (or not at all) implemented amongst industries of the three selected sectors with respectively an overall mean value of 2.10 and 1.11 out of 5. On a positive note, the companies included in the survey claim to have integrated their workplace's Big Data/AI, Cybersecurity and Biointegration/Mobile Technologies in more structured ways (mean values of 2.64, 2.89 and 2.62).

These results are also supported by the outcomes of the Gartner Hype Curves published in the last decades (Gartner Hype Cycle 2022). Even though it is difficult to create a Gartner Hype Curve for the whole Industry 4.0 ecosystem, it is possible to notice that most of the Industry 4.0 elements are entering or moving through the 'Trough of Disillusionment' phase (Figure 4). It means that, overall, less than 5% of the potential audience has adopted fully Industry 4.0. But it also means that to climb the 'Slope of Enlightenment' phase and reach the so-called 'Plateau of Productivity', methodologies and best practices (Steinert, Leifer, and Leifer 2010) need to be developed.

In the Netherlands, successful examples of companies that employ Systems Engineering (SE) to deal with complex product development and ongoing digital transformation are ASML and Phillips. From its start in the 1980s, ASML has taken a systems approach. While the organisation of the systems engineers has changed over time, from individuals to a focused systems group, to an SE department and so on, the common thread has been to balance the systems' performance with business aspects like the time-to-market. System budgets have been a central point for developing new and improved systems. For instance, overlay (=position accuracy), throughput and imaging performance all have their budget. These budgets are used for dividing overall system performance over the subsystems and components. The importance of communication in decision-making is visible in the focused four o'clock sessions where people from various departments and disciplines have the chance to discuss things together. Philips Medical Systems (now Philips Healthcare) also has a history in Systems Engineering. The CAFCR (Customer Objectives, Application, Functional, Conceptual, Realisation) method (Muller 2004) originates from Philips practice, as do the A3 Architecture overviews (Juzgado 2010). Both cases show the importance of interdisciplinary communication which is a core component of Industry 4.0.

5. Discussion: demystification, barriers, and enablers of industry 4.0

What can we learn from the information gathered and analysed? Based on the results of the survey, some interesting conclusions can be derived to highlight the achievements that were reached by adopting Industry 4.0 solutions, especially in the Dutch market and the barriers and gaps that are still constraining the full adoption of Industry 4.0.

5.1. Demystification of industry 4.0

As mentioned, the deployment of Industry 4.0 is far from being achieved in cross-sectors and far from being embraced by both SMEs and large companies. With its arrival, the industrial world was seduced to believe that in a few years, production would have become faster and cheaper, the revenues would have been boosted and the market agility would have increased (Kranz 2016). As mentioned by several authors, it is a hit rather than hype (Ardito et al. 2019; Buer, Strandhagen, and Chan 2018; Schroeder et al. 2019). Unfortunately, not all these expectations match the current reality. As pointed out in Section 4 a very limited number of companies (and the number is even smaller if SMEs are considered), can introduce and master some of the Industry 4.0 features.

Analysing these difficulties, five main aspects of Industry 4.0 need to be demystified to understand how to proceed in the coming decades, maximising the opportunities offered by the available technology as the foundation of Industry 4.0.

5.1.1. Faster production

Now, a 'leap' change in the production speed has not happened yet. Companies are unable to translate technology into meaningful actions and processes to optimise production lines. None or little effort has been deployed to increase the ability of the operator to keep up with technological innovations introduced by Industry 4.0. This situation generates a 'flying wheel' effect that increases the gap between the operator and technology. Moreover, even though digitalisation often allows more flexibility in the processes, the decision-making process becomes more complicated due to a large variety of options. Finally, there is a high degree of underutilisation of capabilities of the new technology adopted such as collaborative robots;

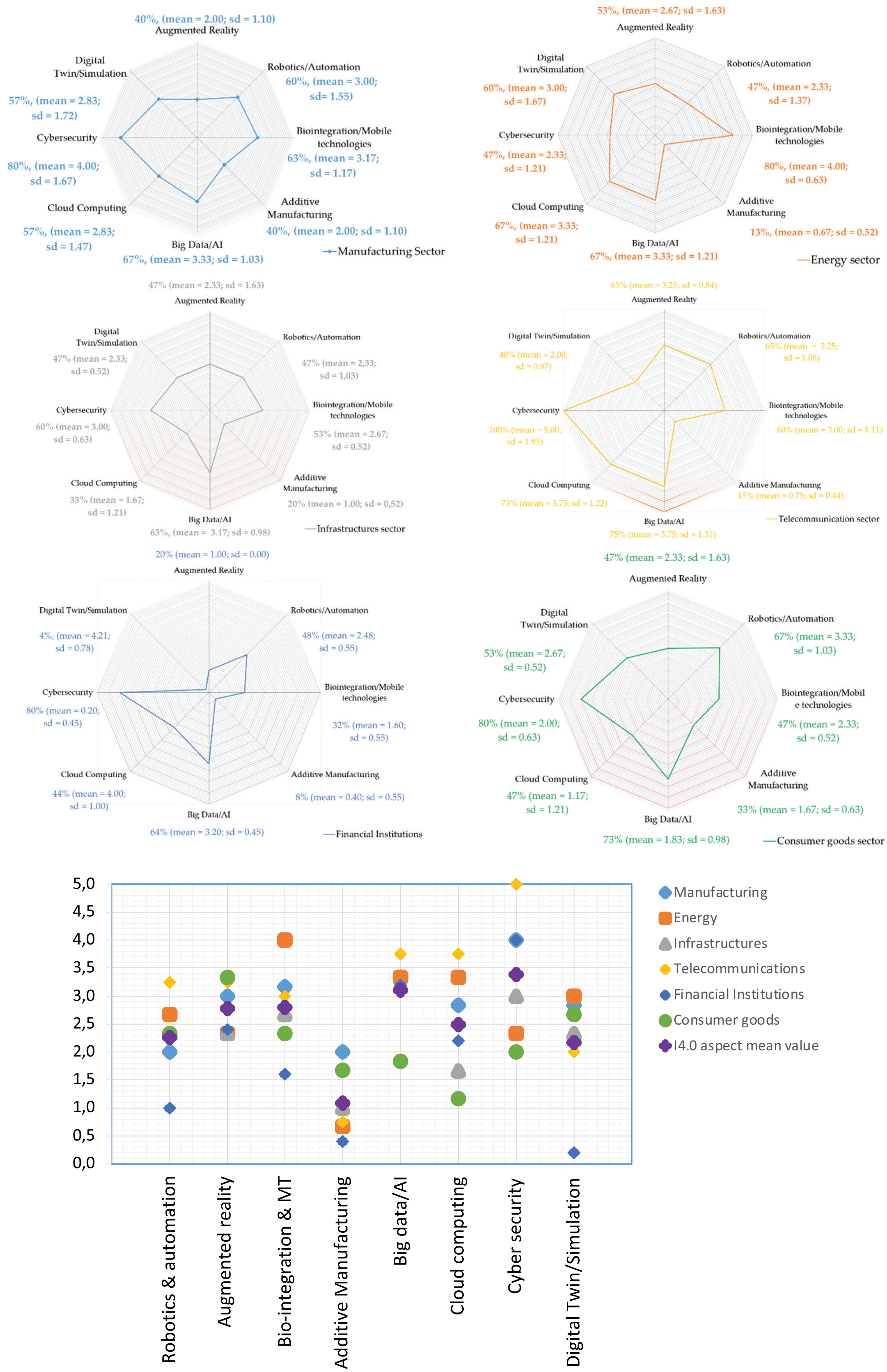

Figure 3. Information about the manufacturing, energy, infrastructures, telecommunication, financial and consumer goods sectors regarding the introduction of industry 4.0/Smart industry elements. (Upper part) the radar plots offer both the mean value (mean) and the standard deviation (sd) per sector. (Lower part) the graph shows the overview of all sectors per industry 4.0 aspect. The mean value for each technology is noted.

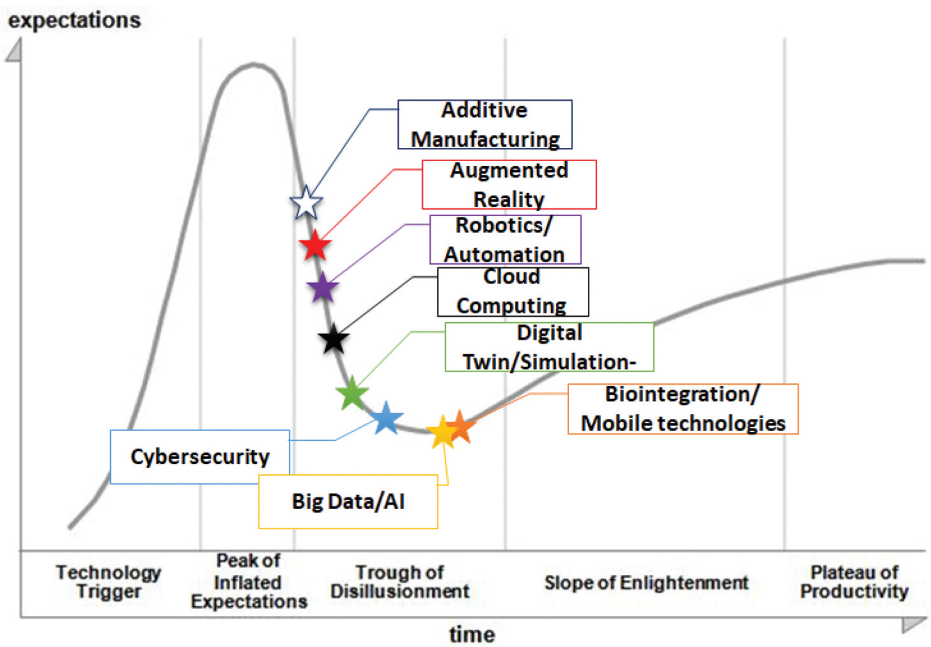

Figure 4. Gartner Hype Circle for Industry 4.0 elements based on the conducted survey (adapted from (Gartner Hype Cycle 2022)).

due to the ongoing low readiness level in technology's introduction, several opportunities offered by the technology itself remain unexplored and unused, limiting the possible positive impacts. For example, the use of Additive manufacturing, which is a technology that promises to shorten lead times and make production faster, is under-adopted within our sample of manufacturing companies.

5.1.2. Data gathering vs insight gathering

Industry 4.0 brought several data options for industries to improve the connectivity between machine-machine and machine-operator. However, this increased available connectivity is stimulating a vicious phenomenon where companies are striving to gather more data often without a clear strategy. This causes a 'strange' correlation where more data does not mean more insights.

Part of this problem is the paradigm of Fear of Missing Out (FoMO) in combination with Faith in Future Opportunities (FiFO). These aspects are shifting attention to the wrong point for the companies making data collection and data management the goal and not the means to reach a solution.

5.1.3. Cost reduction, boosted revenues and enable market agility

The introduction of new technologies does not *per se* mean cost reduction, operation optimisation or boosting revenues. Digitalisation and IoT come with extra cost such as storage cost for data, elaboration cost and communication cost not contributing to efficiency in this way. To contribute to cost increase there is the underutilisation of introduced technology; indeed, this already mentioned factor does not contribute to the overall financial efficiency of the manufacturing processes.

Moreover, the speed of primary processes did change due to the Industry 4.0 introduction: Computer numerical control (CNC) or milling machines do not work faster if there is a Digital Twin deployed in the factory that collects and analyzes information about the health of the system. The latter originated from a deep misalignment between operation and strategic levels in terms of expectations with operators at workshop levels conscious from the beginning that this manufacturing process speed acceleration would not happen.

Finally, and closely related to boosted revenues, the perception that Industry 4.0 features would have increased the marker agility quickly became unrealistic because all competitors have access to the same new technology, highlighting how smart engineering solutions based on proper design can usually make the difference over the technology adoption. This can be summarised as follows: companies often focus too much on doing things right rather than doing the right thing.

5.1.4. Process quality and industry 4.0

Like cost reduction, boosted revenues and enabled market agility, the quality did not improve just because of the arrival of Industry 4.0. Quality is not driven by information but facilitated by that; therefore, the Industry 4.0 introduction could not generate a 'flawless' production with enhanced quality. The introduction of specific instruments, such as manufacturing monitoring sensors to adjust in real-time the production characteristics, can only support a better process quality by offering the operators information for adjusting parameters.

5.1.5. Environmental sustainability

Environmental sustainability is an important change driver for the industry, fostered by social awareness and pressure (Rödger et al. 2021). Several studies claimed that Industry 4.0 would have a major role in enhancing the environmental sustainability of manufacturing and reducing the possible impacts of current manufacturing productions. However, this is not an automatic and easy objective to reach, positioning digitalisation as part of the solution but also part of the problem (Hilty and Aebischer 2015; Thiede 2021; Thiede, Damgrave, and Lutters 2022).

5.2. The way forward to fill the gaps

The transition towards Industry 4.0 requires the integration of various innovative technologies (such as CPS, manufacturing systems, smart factories, higher automation, etc.), new product development methods, new processes, and all these with human needs, safety, and socio-ethical responsibility in mind (Berx, Decré, and Pintelon 2022; Kapeller et al. 2021; Martinetti et al. 2021). Additionally, Industry 4.0 comes with the integration of multiple disciplines in the workplace. Several types of engineers, information specialists, designers, psychologists, and business experts come together to deal with complex projects. This is very evident in recent years not only in manufacturing but also in the field of medical robotic technologies, which integrate an ever-increasing number of technologies and disciplines that, however, did not yet converge towards healthcare 4.0 (Nizamis et al. 2021,). Overall, this may lead to the rise of complexity and the need for easier multidisciplinary communication and a holistic system view. In our research, we observed several successful enablers and existing barriers:

5.2.1. Successful enablers

Transitioning towards Industry 4.0 for an enterprise is a complex task and is not only technological but also linked with humans, processes, and various intertwined economic and social aspects. Thus, developments stemming from SE, such as model-based SE (MBSE) (Mandel et al. 2020), can be helpful for the transition towards digital transformation (Kenett, Swarz, and Zonnenshain 2022; Samaras 2022). SE constitutes a young engineering discipline (that itself transcends all other disciplines, fields, and sectors) that aims to facilitate multidisciplinary communication, integration towards a common goal (a working system), dealing with complexity, and many more (SEBoK 2022). It can be seen as a combination of processes (vee, spiral, and waterfall models, etc.) (SEBoK 2022), tools (context, N2, and functional flow diagrams, etc.), and thinking (Bonnema and Broenink 2016), that together can help the design and organisation of complex systems (Bonnema, Veenvliet, and Broenink 2016; SEBoK 2022).

5.2.2. Current barriers

One of the main challenges in the implementation and integration of multiple Industry 4.0 elements is the skills transformation of the workforce (L. Li 2022). To transition from the current situation into the full adaptation of the promises and opportunities that Industry 4.0 offers we need to consider the place of the human in the transition (Romero, Stahre, and Taisch 2020). This was identified and added as an extra dimension in the definition of Industry 5.0 (Leng et al. 2022; Romero, Stahre, and Taisch 2020). Romero et al. have identified this as operator 4.0 or 5.0 (Directorate-General for Research and Innovation European Commission 2022). This is a new type of worker whose skills are augmented by technology, and at the same time requires a different mindset than the existing one to become a knowledge worker and learn how to process large amounts of information (Fitsilis, Tsoutsa, and Gerogiannis 2018; L. Li 2022; D. Li et al. 2022). Until the new generation of operators acquires this skillset via education or practice, we identify a gap in time and skills, where the existing workforce needs to acquire all or some of these skills. Fostering the development of such skills via continuous professional development (CPD) (Vodenko, Komissarova, and Kulikov 2019) may remove this barrier and result in this new type of operator becoming an enabler for transformation.

5.2.3. Industry 4.0: is it a revolution?

It is often argued that Industry 4.0 has revolutionary characteristics because it has the potential to radically change the way we work but also society. 10 years after it was first established as a term, we have observed small steps in its adoption in highly competitive sectors, primarily in the Western world. It has largely left the way many industrial sectors work largely unaffected. The timeframe of technological adoption in mainstream industrial domains has shortened but remains quite long to claim that it is a revolution. Further, in summary, the reasons that indicate that Industry 4.0 has an evolutionary character are seen below:

(1) Gradual evolution: Industry 4.0 is seen as a gradual evolution of the previous industrial revolutions, rather than a sudden, transformative revolution. The advancements made in Industry 4.0 build on the technologies and processes developed during the previous industrial revolutions.
(2) Continuity of principles: Industry 4.0 is built on the same principles that drove the previous industrial revolutions, such as the use of automation, mass production, and standardisation. Rather than introducing entirely new concepts, Industry 4.0 builds on these existing principles to create a more advanced and efficient system.
(3) Incremental improvements: Industry 4.0 represents incremental improvements and advancements in technology, rather than a radical departure from the past. Many of the technologies and processes that make up Industry 4.0 have been in development for decades and have gradually become more sophisticated over time.
(4) Adoption over time: The implementation of Industry 4.0 technologies and processes is likely to occur over a long period, as businesses gradually adopt new technologies and processes. This slow adoption is characteristic of an evolutionary process, rather than a revolutionary one.

6. Limitations of the study

The selection of the mixed methods research methodology, instead of a standalone qualitative or quantitative research methodology, was motivated by our intention to discuss the authors' opinion on the implementation of Industry 4.0 in the Netherlands in a more broad, flexible, and comprehensive way.

This methodological triangulation allowed us to assume multiple viewpoints and approach the same topic from multiple angles. On the other hand, the choice of such a methodology in combination with the author's perspective may result in conclusions that are hard to replicate and need to be treated with caution. Another limitation may be the difficulty of comparing or combining results from both qualitative and quantitative analyses.

7. Conclusion

Industry 4.0 brought the challenge of introducing ICT solutions to raise efficiency and quality in all industrial domains. Despite the efforts to implement a part of Industry 4.0, there are still several challenges and issues that need to be addressed and solved to call this industrial revolution a success.

This opinion paper analyses the pervasiveness of Industry 4.0 elements in the heavily industrialised Dutch market, taking into consideration three main sectors: manufacturing, energy, and infrastructure. The survey outcomes were displayed through radar plots for each sector. Based on these results, a Gartner Hype Circle for Industry 4.0 elements was created to show the position of every single element in its lifetime phase and identify the challenges for the implementation of Industry 4.0.

Differently from other Industry 4.0 papers this paper proposes a demystification of Industry 4.0 to deeply understand why some of the promises and expectations a decade ago were not supported by industrial results and significant improvements. Amongst others, faster production and cost reduction boosted Revenues and enabled market agility.

Finally, the paper aims to create the foundation for a smoother transition to I5.0 by alleviating similar bottlenecks and by reflecting on existing challenges. Therefore, other similar contexts can be inspired and motivated in addressing such challenges timely

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors

A. Martinetti (1985) is an Associate Professor at the department of Design, Production and Management (DPM) of the University of Twente. With a Ph.D. in Occupational Safety (2013) his research lines focus on Maintenance Engineering and Humanitarian Engineering to improve the living conditions of underserved communities.

K. Nizamis was born in 1988 in Kavala, Greece. Since 2019 he is an Assistant Professor in Multidisciplinary Design at the Design, Production, & Management (DPM) department at the University of Twente. He has a Master of Engineering in Electrical and Computer Engineering from Democritus University of Thrace in Xanthi, Greece, and a Master of Science in Biomedical Engineering from the University of Twente, where he also performed his Ph.D. research in Biomechanical Engineering.

P. Chemweno is an Assistant Professor in Advanced Manufacturing and Humanitarian Engineering. His research focuses on organizational and management factors influencing the transition from traditional manufacturing to the 'Industry of the Future' where increased roles are anticipated for automation and robotics.

C. Goulas is an Assistant Professor at the University of Twente's Faculty of Engineering Technology. Dr. Goulas is a Metallurgical Engineer & Materials Scientist, currently leading research in the field of 3D printing processes for large scale applications and novel materials for 3D printing. He holds a PhD in Materials Science and Engineering from Delft University of Technology and a Diploma (MSc) in Mining & Metallurgical Engineering from National Technical University of Athens.

L.A.M van Dongen (1954) has worked for the Netherlands Railways (NS, 100% state owned) for 35 years. He retired as Chief Technology Officer (CTO), responsible for the asset management of the rolling stock fleet, workshops and maintenance equipment in August 2019. Since 2010 he is also professor in Maintenance Engineering at the faculty of Engineering Technology, in the Department of Design, Production and Management of the University of Twente.

I. Giboson is best known for his work in the area of Additive Manufacture or 3D Printing. He as been working in this field for over 25 years; long before it was considered 'çool'. As well as Professor in Design Engineering, he is Scientific Director of the University's Fraunhofer Project Centre in complex systems engineering.

S. Thiede is the chairman for the department Design, Production and Management (DPM) in the Engineering Technology faculty of the University of Twente. He is Professor and chiar in Manufacturing Systrems and his interested is in the planning and operation of manufacturing systems/factories. This includes the interaction of different processes over the process chain but also with other factory elements like technical building services.

E. Lutters being educated as a Mechanical Engineer while having an keen interest in product design, teaches subjects related to product development as the linking pin between design and (production) engineering. This ranges from production techniques & systems, via design methodology to information management and virtual reality. He is Professor and chair of Information driven Product Development & Engineering.

T. Vanaker is an Associate Professor in the AMSPES group of the department Design, Production and Management (DPM) at the University of Twente. His main research interests are 3D printing/ Additive Manufacturing (Design for AM, development of AM processes, research and improvement of mainstream AM processes) and Industrial Robotics (factory automation strategies, smart manufacturing). He is the program director of the EngD Robotics and he is a member of CIRP.

G. M. Bonnema is Professor and chair in Systems Engineering And Multidisciplinary Design at the department of Design, Production and Managment (DPM) of the University of Twente. His goal is to improve the adoption of Systems Engineering in multidisciplinary development environments. A holistic approach as provided by Systems Engineering is needed to bind together findings in various engineering fields to develop well-designed, well-balanced and purposeful products and systems.

Data availability statement

Data available on request from the authors. The data that support the findings of this study are available from the corresponding author [Alberto Martinetti, a.martinetti@utwente.nl].

References

Acemoglu, D., H. R. A. Koster, and C. Ozgen, "Robots and Workers: Evidence from the Netherlands," 2023. https://ssrn.com/abstract=4387930.

Annanperä, E. M. Jurmu, J. Kaivo-Oja, P. Kettunen, M. Knudsen, T. Lauraéus, J. Majava, J. Porras, "FROM INDUSTRY X TO INDUSTRY 6.0 : ANTIFRAGILE MANUFACTURING FOR PEOPLE, PLANET, AND PROFIT WITH PASSION." http://hdl.handle.net/10138/335672.

Ardito, L., A. M. Petruzzelli, U. Panniello, and A. C. Garavelli. 2019. "Towards Industry 4.0: Mapping Digital Technologies for Supply Chain Management-Marketing Integration." *Business Process*

Management Journal 25 (2): 323–346. https://doi.org/10.1108/BPMJ-04-2017-0088.

Berx, N., W. Decré, and L. Pintelon. 2022. "Examining the Role of Safety in the Low Adoption Rate of Collaborative Robots." *Procedia CIRP* 106:51–57. https://doi.org/10.1016/J.PROCIR.2022.02.154. Jan.

Bokhorst, J. A. C., W. Knol, J. Slomp, and T. Bortolotti. 2022. "Assessing to What Extent Smart Manufacturing Builds on Lean Principles." *International Journal of Production Economics* 253:108599. https://doi.org/10.1016/j.ijpe.2022.108599.

Bonnema, G. M., and J. F. Broenink. 2016. "Thinking Tracks for Multidisciplinary System Design." *Systems* 4 (4): 36. https://doi.org/10.3390/SYSTEMS4040036.

Bonnema, G. M., K. Veenvliet, and J. F. Broenink. 2016. *Systems Design and Engineering : Facilitating Multidisciplinary Development Projects*. London: CRC Press.

Boutris, G., and N. Salimi. 2023. *Identifying Impact of the Entrepreneurship Ecosystem on the Success of Entrepreneurial Start-Up Firms* 129–145. https://doi.org/10.1007/978-3-031-24816-0_11.

Buer, S. V., J. O. Strandhagen, and F. T. S. Chan. 2018. "The Link Between Industry 4.0 and Lean Manufacturing: Mapping Current Research and Establishing a Research Agenda." *International Journal of Production Research* 56 (8): 2924–2940. https://doi.org/10.1080/00207543.2018.1442945.

Bureš, V., "Industry 4.0 from the Systems Engineering Perspective: Alternative Holistic Framework Development," pp. 199–223, https://doi.org/10.4018/978-1-5225-3468-6.CH011.

Calabrese, A., N. Levialdi Ghiron, and L. Tiburzi. 2020. "'Evolutions' and 'revolutions' in manufacturers' implementation of industry 4.0: a literature review, a multiple case study, and a conceptual framework." *Production Planning & Control* 32 (3): 213–227. https://doi.org/10.1080/09537287.2020.1719715.

Chemweno, P., and R. J. Torn. 2022. "Innovative Robotization of Manual Manufacturing Processes." *Procedia CIRP* 106:96–101. https://doi.org/10.1016/J.PROCIR.2022.02.161. Jan.

Dalenogare, L. S., G. B. Benitez, N. F. Ayala, and A. G. Frank. 2018. "The Expected Contribution of Industry 4.0 Technologies for Industrial Performance." *International Journal of Production Economics* 204:383–394. https://doi.org/10.1016/J.IJPE.2018.08.019. Oct.

Davies, R. 2015. Industry 4.0 Digitalisation for Productivity and Growth. https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2015)568337.

Directorate-General for Research and Innovation (European Commission), "Industry 5.0." Accessed November 21, 2022. https://research-and-innovation.ec.europa.eu/research-area/industrial-research-and-innovation/industry-50_en.

Duggal, A. S., P. K. Malik, A. Gehlot, R. Singh, G. S. Gaba, M. Masud, J. F. Al-Amri, et al. 2022. "A sequential roadmap to Industry 6.0: Exploring future manufacturing trends." *IET Communications* 16 (5): 521–531. https://doi.org/10.1049/CMU2.12284.

Dzwigol, H., M. Dzwigol–Barosz, and A. Kwilinski. 2020. "Formation of Global Competitive Enterprise Environment Based on Industry 4.0 Concept." *International Journal of Entrepreneurship* 24 (1). https://www.abacademies.org/articles/formation-of-global-competitive-enterprise-environment-based-on-industry-40-concept-9079.html.

Fallahpour, A., K. Y. Wong, S. Rajoo, A. M. Fathollahi-Fard, J. Antucheviciene, and S. Nayeri. 2021. "An Integrated Approach for a Sustainable Supplier Selection Based on Industry 4.0 Concept." *Environmental Science and Pollution Research International*. https://doi.org/10.1007/S11356-021-17445-Y.

Fitsilis, P., P. Tsoutsa, and V. Gerogiannis. 2018. "INDUSTRY 4.0: REQUIRED PERSONNEL COMPETENCES." Industry 4 0 3 (3): 130–133.

Florescu, A., and S. Barabas. 2022. "Development Trends of Production Systems Through the Integration of Lean Management and Industry 4.0." *Applied Sciences* 12 (10): 4885. https://doi.org/10.3390/APP12104885.

Fuertes, G., J. Zamorano, M. Alfaro, M. Vargas, J. Sabattin, C. Duran, R. Ternero, and R. Rivera. 2022. "Opportunities of the Technological Trends Linked to Industry 4.0 for Achieve Sustainable Manufacturing Objectives." *Sustainability (Switzerland)* 14 (18): 11118. https://doi.org/10.3390/su141811118.

"Gartner Hype Cycle 2022 for Emerging Technologies | by Kamala Kanta MISHRA (Kamal) | Medium." Accessed November 21, 2022: https://medium.com/@mishra.kamal/gartner-hype-cycle-2022-for-emerging-technologies-59adca55295d.

Geissbauer, R., J. Veldso, and S. Schrauf. 2015. "Industry 4.0: Building the digital enterprise." https://www.pwc.com/industry40 .

Haanstra, W., A. Martinetti, J. Braaksma, and L. van Dongen. 2020. "Design of a Framework for Integrating Environmentally Sustainable Design Principles and Requirements in Train Modernization Projects." *Sustainability* 12 (15): 6075. https://doi.org/10.3390/SU12156075.

Hassoun, A., A. Aït-Kaddour, A. M. Abu-Mahfouz, N. B. Rathod, F. Bader, F. J. Barba, A. Biancolillo, et al. 2023. "The Fourth Industrial Revolution in the Food Industry—Part I: Industry 4.0 Technologies." *Critical Reviews in Food Science and Nutrition* 63 (23): 6547–6563. https://doi.org/10.1080/10408398.2022.2034735.

Hassoun, A., A. E.-D. Bekhit, A. R. Jambrak, J. M. Regenstein, F. Chemat, J. D. Morton, M. Gudjónsdóttir, et al. 2024. "The Fourth Industrial Revolution in the Food Industry—Part II: Emerging Food Trends." *Critical Reviews in Food Science and Nutrition* 64 (2): 407–437. https://doi.org/10.1080/10408398.2022.2106472.

Hilty, L. M., and B. Aebischer. 2015. "ICT for Sustainability: An Emerging Research Field." *Advances in Intelligent Systems & Computing* 310:3–36. https://doi.org/10.1007/978-3-319-09228-7_1/FIGURES/9.

Hulshoff, H. E. 2001. *Family Business in the Dutch SME Sector : Definitions and Characteristics*. Zoetermeer: EIM/Business & Policy Research.

"Industry 4.0 and digital transformation: Where to go | European Economic and Social Committee." Accessed September 15, 2023. https://www.eesc.europa.eu/en/our-work/opinions-information-reports/opinions/industry-40-and-digital-transformation-where-go.

Juzgado, P. D. B. 2010. "A3 Architecture Overviews: A Tool for Effective Communication in Product Evolution." *Dec.* https://doi.org/10.3990/1.9789036531054.

Kagermann, H., W.-D. Lukas, and W. Wahlster, "Industrie 4.0: Mit dem Internet der Dinge auf dem Weg zur 4. industriellen Revolution," https://www.dfki.de/fileadmin/user_upload/DFKI/Medien/News_Media/Presse/Presse-Highlights/vdinach2011a13-ind4.0-Internet-Dinge.pdf. p. 2, 2011.

Kagermann, H., and W. Wahlster. 2022. "Ten Years of Industrie 4.0." *Science (80-)* 4 (3): 26. https://doi.org/10.3390/sci4030026.

Kapeller, A., H. Felzmann, E. F. Villaronga, K. Nizamis, and A. M. Hughes. 2021. "Implementing Ethical, Legal, and Societal Considerations in Wearable Robot Design." *Applied Sciences* 11 (15): 6705. https://doi.org/10.3390/app11156705.

Karnik, N., U. Bora, K. Bhadri, P. Kadambi, and P. Dhatrak. 2021. "A Comprehensive Study on Current and Future Trends Towards the Characteristics and Enablers of Industry 4.0." *Journal of Industrial Information Integration* 27 (May): 100294. https://doi.org/10.1016/J.JII.2021.100294.

Kenett, R., R. S. Swarz, and A. Zonnenshain, "Systems Engineering in the Fourth Industrial Revolution: Big Data, Novel Technologies, and Modern Systems Engineering," p. 622, Accessed November 21, 2022: https://www.wiley.com/en-us/Systems+Engineering+in+the+Fourth+Industrial+Revolution%3A+Big+Data%2C+Novel+Technologies%2C+and+Modern+Systems+Engineering-p-9781119513896.

Kozlovska, M., D. Klosova, and Z. Strukova. 2021. "Impact of Industry 4.0 Platform on the Formation of Construction 4.0 Concept: A Literature Review." *Sustainability (Switzerland)* 13 (5): 1–15. https://doi.org/10.3390/su13052683.

Kranz, M., "Building the Internet of Things Implement New Business Models, Disrupt Competitors, Transform Your Industry," p. 272, 2016, Accessed November 21, 2022. https://www.wiley.com/en-us/Building+the+Internet+of+Things%3A+Implement+New+Business+Models%2C+Disrupt+Competitors%2C+Transform+Your+Industry-p-9781119285663.

Leng, J., W. Sha, B. Wang, P. Zheng, C. Zhuang, Q. Liu, T. Wuest. et al. 2022. "Industry 5.0: Prospect and Retrospect." *Journal of*

Manufacturing Systems 65:279–295. Oct. https://doi.org/10.1016/j.jmsy.2022.09.017.
Li, L. 2022. "Reskilling and Upskilling the Future-Ready Workforce for Industry 4.0 and Beyond." *Information Systems Frontiers* 1 (Jul): 1–16. https://doi.org/10.1007/s10796-022-10308-y.
Li, D., Å. Fast-Berglund, D. Paulin, and P. Thorvald. 2022. "Exploration of Digitalized Presentation of Information for Operator 4.0: Five Industrial Cases." *Computers & Industrial Engineering* 168 (Jun): 108048. https://doi.org/10.1016/J.CIE.2022.108048.
Maddikunta, P. K. R., Q.-V. Pham, P. B, N. Deepa, K. Dev, T. R. Gadekallu, R. Ruby, and M. Liyanage. 2022. "Industry 5.0: A Survey on Enabling Technologies and Potential Applications." *Journal of Industrial Information Integration* 26:100257. https://doi.org/10.1016/j.jii.2021.100257.
Mandel, C., T. Stürmlinger, C. Yue, M. Behrendt, and A. Albers, "Model-Based Systems Engineering Approaches for the Integrated Development of Product and Production Systems in the Context of Industry 4.0," *SYSCON 2020 - 14th Annual IEEE International Systems Conference, Proceedings*, August. 2020. https://doi.org/10.1109/SYSCON47679.2020.9275902.
Martinetti, A., P. K. Chemweno, K. Nizamis, and E. Fosch-Villaronga. 2021. "Redefining Safety in Light of Human-Robot Interaction: A Critical Review of Current Standards and Regulations." *Frontiers in Chemical Engineering* 3 (Jul): 32. https://doi.org/10.3389/FCENG.2021.666237.
Muller, G. J. 2004. *CAFCR: A Multi-View Method for Embedded Systems Architecting; Balancing Genericity and Specificity*. Delft: TU Delft Repositories. https://repository.tudelft.nl/islandora/object/uuid:a6a63694-d0c6-4102-a06e-11b9ea563a8d?collection=research.
Müller, J. M., D. Kiel, and K. I. Voigt. 2018. "What Drives the Implementation of Industry 4.0? The Role of Opportunities and Challenges in the Context of Sustainability." *Sustainability* 10 (1): 247. https://doi.org/10.3390/SU10010247.
Nizamis, K., A. Athanasiou, S. Almpani, C. Dimitrousis, and A. Astaras. 2021. "Converging Robotic Technologies in Targeted Neural Rehabilitation: A Review of Emerging Solutions and Challenges." *Sensors* 21 (6): 2084. https://doi.org/10.3390/S21062084.
Phan Vo, C., T. Wolters, and P. Chi Vo, "Adoption of Industry 4.0 Technologies by SMEs Involving Their Innovation Networks," 2021. https://www.researchgate.net/publication/353212380.
Pulikottil, T., L. A. Estrada-Jimenez, H. U. Rehman, J. Barata, S. Nikghadam-Hojjati, and L. Zarzycki, "Multi-Agent Based Manufacturing: Current Trends and Challenges," *IEEE International Conference on Emerging Technologies and Factory Automation, ETFA*, vol. 2021 2021, https://doi.org/10.1109/ETFA45728.2021.9613555.
Qi, Q., F. Tao, T. Hu, N. Anwer, A. Liu, Y. Wei, L. Wang, et al. 2021. "Enabling technologies and tools for digital twin." *Journal of Manufacturing Systems* 58:3–21. https://doi.org/10.1016/J.JMSY.2019.10.001.
Rödger, J. M., J. Beier, M. Schönemann, C. Schulze, S. Thiede, N. Bey, C. Herrmann, et al. 2021. "Combining Life Cycle Assessment and Manufacturing System Simulation: Evaluating Dynamic Impacts from Renewable Energy Supply on Product-Specific Environmental Footprints." *International Journal of Precision Engineering and Manufacturing - Green Technology* 8 (3): 1007–1026. https://doi.org/10.1007/S40684-020-00229-Z/FIGURES/9.
Romero, D., J. Stahre, and M. Taisch. 2020. "The Operator 4.0: Towards Socially Sustainable Factories of the Future." *Computers & Industrial Engineering* 139:106128. https://doi.org/10.1016/J.CIE.2019.106128. Jan.
Samaras, G., "Human-Centered Systems Engineering." Accessed November 21, 2022. https://www.iise.org/SHS/Details.aspx?id=24058.
Scheffer, S., A. Martinetti, R. Damgrave, S. Thiede, and L. van Dongen. 2021. "How to Make Augmented Reality a Tool for Railway Maintenance Operations: Operator 4.0 Perspective." *Applied Sciences* 11 (6): 2656. https://doi.org/10.3390/APP11062656.
Schroeder, A., A. Ziaee Bigdeli, C. Galera Zarco, and T. Baines. 2019. "Capturing the Benefits of Industry 4.0: A Business Network Perspective." *Production Planning & Control* 30 (16): 1305–1321. https://doi.org/10.1080/09537287.2019.1612111.
"SEBoK." Accessed November 21, 2022. https://www.sebokwiki.org/wiki/Guide_to_the_Systems_Engineering_Body_of_Knowledge_(SEBoK).
Singh, M., E. Fuenmayor, E. P. Hinchy, Y. Qiao, N. Murray, and D. Devine. 2021. "Digital Twin: Origin to Future." *Applied System Innovation* 4 (2): 36. https://doi.org/10.3390/ASI4020036.
"Smart Industry Implementatieagenda 2018-2021 DUTCH INDUSTRY FIT FOR THE FUTURE", 2022. https://smartindustry.nl/en/roadmaps/smart-industry-implementatieagenda-2018-2021.
Steinert, M., L. J. Leifer, and L. Leifer, "Scrutinizing Gartner's hype cycle approach," 2010. https://www.researchgate.net/publication/224182916.
Tao, F., B. Xiao, Q. Qi, J. Cheng, and P. Ji. 2022. "Digital Twin Modeling." *Journal of Manufacturing Systems* 64:372–389. https://doi.org/10.1016/J.JMSY.2022.06.015. Jul.
Tedaldi, G., and G. Miragliotta. 2022. "The Role of Engineering-To-Order Machinery Manufacturers in Future Cloud Manufacturing Supply Chains: A Business Case and a Strategic Perspective." *Production Planning & Control* 33 (9–10): 1011–1023. https://doi.org/10.1080/09537287.2020.1837942.
Thiede, S. 2021. "Digital Technologies, Methods and Tools Towards Sustainable Manufacturing: Does Industry 4.0 Support to Reach Environmental Targets?" *Procedia CIRP* 601–606. https://doi.org/10.1016/j.procir.2021.02.001.
Thiede, S., R. Damgrave, and E. Lutters. 2022. "Mixed Reality Towards Environmentally Sustainable Manufacturing - Overview, Barriers and Design Recommendations." *Procedia CIRP*, 308–313. https://doi.org/10.1016/j.procir.2022.02.051.
Tsaramirsis, G., A. Kantaros, I. Al-Darraji, D. Piromalis, C. Apostolopoulos, A. Pavlopoulou, M. Alrammal, et al. 2022. "A Modern Approach Towards an Industry 4.0 Model: From Driving Technologies to Management." *Journal of Sensors* 2022:1–18. https://doi.org/10.1155/2022/5023011.
Vaidya, S., P. Ambad, and S. Bhosle. 2018. "Industry 4.0 - A Glimpse."*Procedia Manufacturing*, 233–238. https://doi.org/10.1016/j.promfg.2018.02.034.
van Dongen, L. A. M. 2015. "Through-Life Engineering Services: The NedTrain Case." 29–51. https://doi.org/10.1007/978-3-319-12111-6_3.
Vodenko, K. V., M. A. Komissarova, and M. M. Kulikov. 2019. "Modernization of the Standards of Education and Personnel Training Due to Development of Industry 4.0 in the Conditions of Knowledge economy's Formation." *Studies in Systems, Decision and Control* 169:183–192. https://doi.org/10.1007/978-3-319-94310-7_18.
Wasserstein, Ronald L., Allen L. Schirm, and Nicole A. Lazar. 2019. "Moving to a World Beyond "$p < 0.05$"." *The American Statistician* 73 (sup 1): 1–19. https://doi.org/10.1080/00031305.2019.1583913
Xu, L. D., E. L. D. Xu, and L. Li. 2018. "Industry 4.0: State of the Art and Future Trends." *International Journal of Production Research* 56 (8): 2941–2962. https://doi.org/10.1080/00207543.2018.1444806.