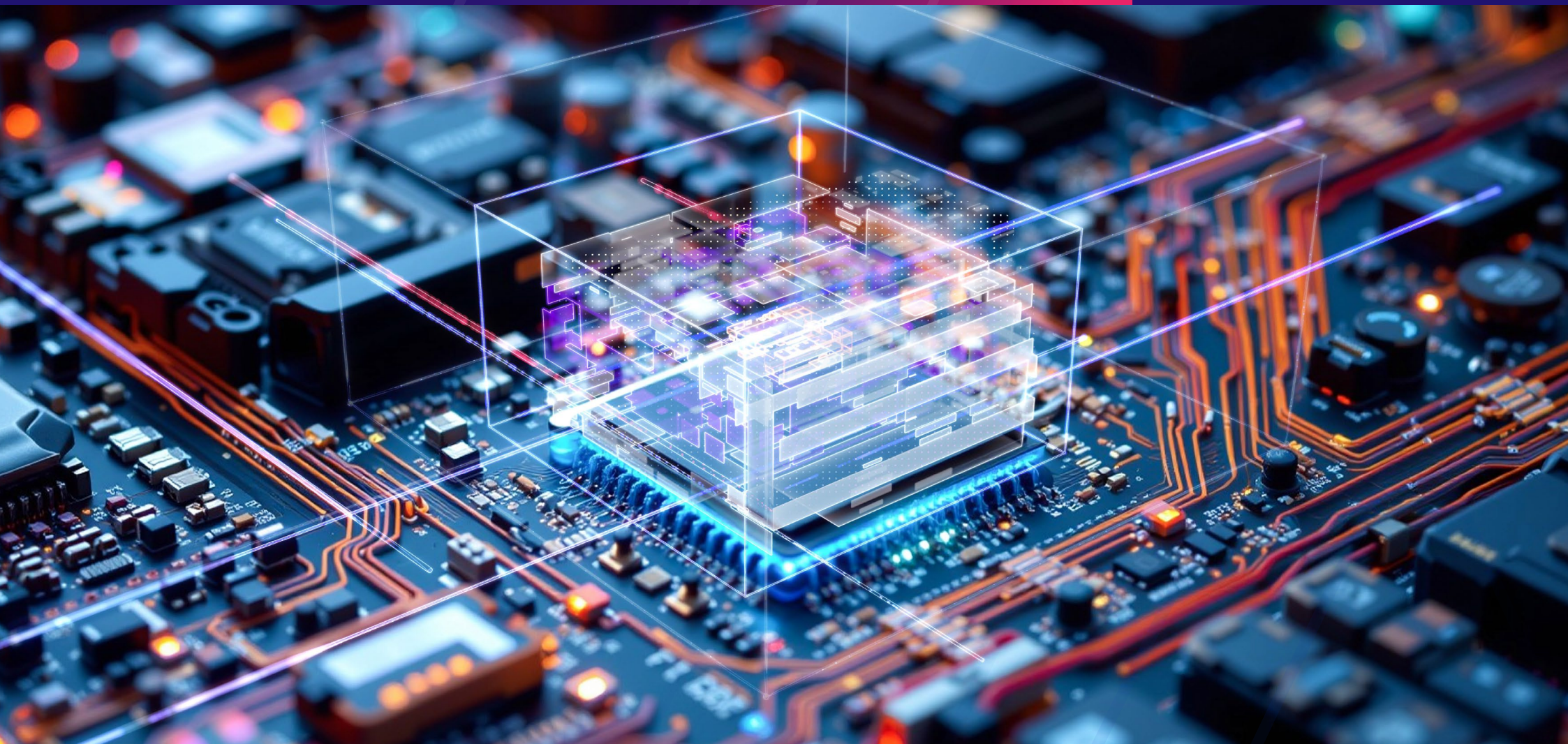
Paper

Competitive systems

Discover how digitalisation of manufacturing increases labour productivity

TNO Vector
Centre for Societal Innovation and Strategy



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This paper is part of a series of papers written for the 2025 TNO Vector Symposium: De kracht van samenwerkende systemen – Sturen naar een vitale, competitieve en veilige samenleving.

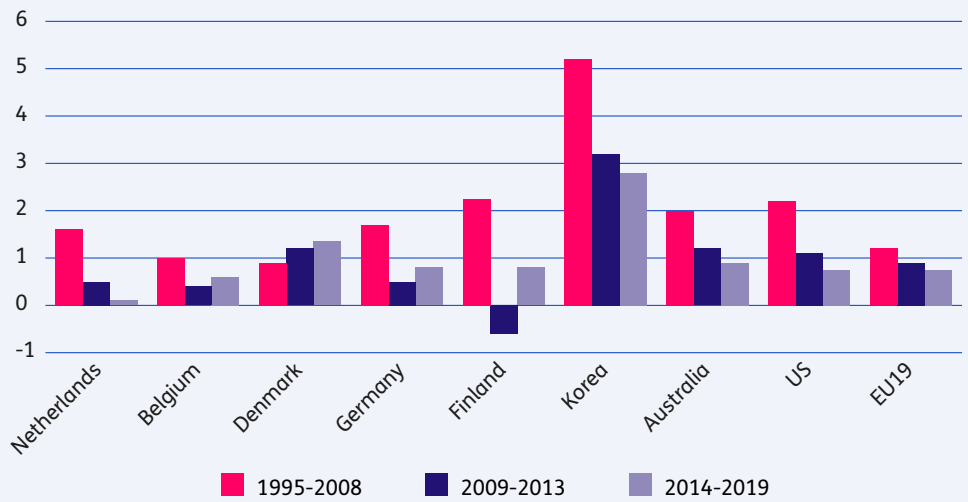
The goal of this paper is to provide additional insight to participants on the subject of discussion.

1. Introduction

Economies of the Netherlands and the EU face a confluence of pressing challenges. Emissions need to be reduced, and geo-political developments urge action to build more resilient and autonomous economic systems, while demanding consumers require higher output within shorter time-frames. These challenges require economies to be highly productive to stay competitive. Yet, the active labour population is shrinking (Draghi, 2024) and labour productivity growth continues to decrease (Figure 1),[1] posing a significant constraint on one of the most vital resources.

Competitiveness in this context is a systemic attribute, deeply rooted in the institutional, regulatory, and structural foundations of an economy to support long-term earning capacity in the Netherlands and EU. It goes beyond individual firm performance or cost efficiency, reflecting the capacity of a society as a whole to support productivity, innovation, and sustainable development over time. Draghi (2024) emphasized that enhancing competitiveness is more than reducing costs or improving market efficiency; it is fundamentally about strengthening the underlying systems that enable innovation, investment, and strategic autonomy.[2]

Figure 1: Average annual labor productivity growth per hour worked, TNO (2025b)



1 With decreasing fertility rates and increasing life expectancy, about 22% of the global population will be over 60 years old by 2050.
2 Draghi (2024) highlighted also a widening innovation gap, particularly in Europe. Factors include risk-averse mindsets, strict regulations, and a brain drain, with Europe lagging in GDP growth behind the US. The regulatory maze in the EU, for example in AI adoption, further hampers innovation, which risks economic stagnation and discourage investment.

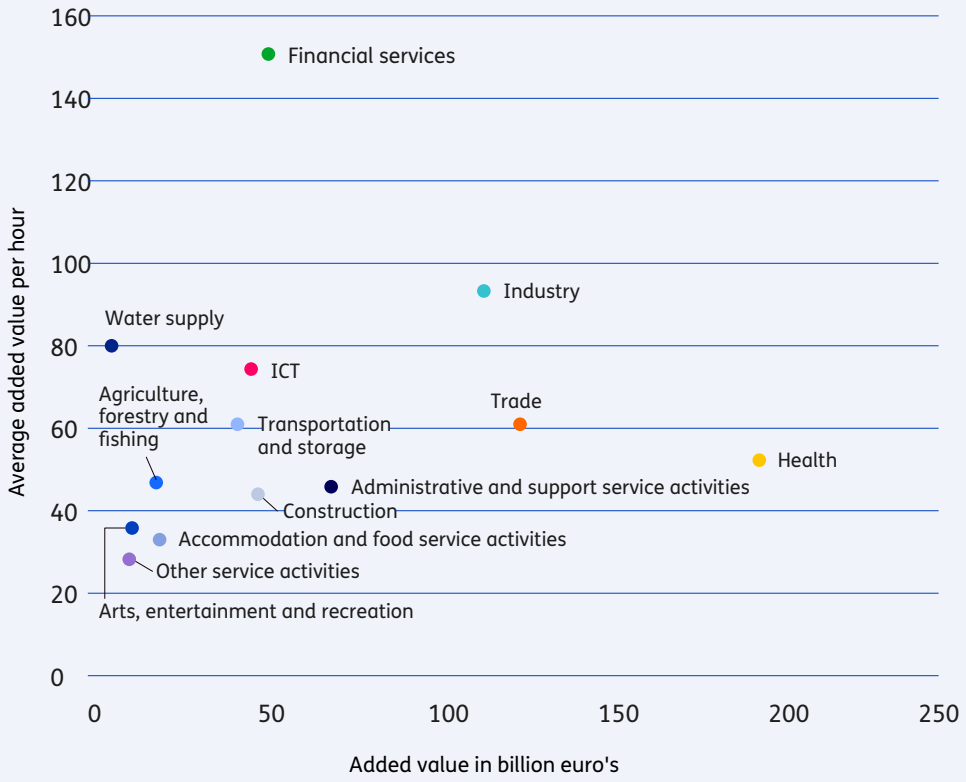
Manufacturing is an important domain in this conversation. It's not only a cornerstone of economic productivity and employment (Figure 2)[3] but also a critical lever for transformation. To stay competitive, manufacturing companies must balance resilience with agility, navigating fluctuating value chains and costs, demands for faster and more personalized production, innovative products, (increasing) costs such as labour, materials, energy and demands for consistently high quality.

Adopting digital and automation technologies holds a key for securing long-term competitiveness for the manufacturing sector, transforming it into a digitalised manufacturing industry, also known as Smart Industry.[4] One of the main advantages of these technologies is their potential to augment or automate labour-intensive tasks, for example, by optimizing workflows, reducing human errors, and enabling real-time data-driven decisions. Consequently, employees can operate more efficiently and focus on more cognitively demanding tasks (Javaid et al., 2022), while tasks are performed smarter, faster, and with greater precision. These developments will contribute to the increase of labour productivity.

Therefore, the central question of this paper is:
How can the opportunities presented by the digitalisation of manufacturing be maximized and the associated challenges mitigated to enhance labour productivity and ensure competitiveness?

The rest of this paper is organized as follows. In Chapter 2 we discuss the opportunities and challenges of the digitalisation of manufacturing. In Chapter 3 specific examples and suggestions are made on how the opportunities of the digitalisation of manufacturing can be strengthened and the challenges mitigated to improve labour productivity. Chapter 4 ends with the concluding remarks and recommendations.

Figure 2: Size and added value per hour for the main sectors in the Dutch economy in 2023.[5] Data CBS, figure by TNO.



3 The manufacturing industry contributes to labor productivity as a rapidly growing high-productivity sector with an added value of 116 billion euro's in 2023 (TNO, 2024a).
4 This includes among others the use of automation of mainstream design, and robotics, Internet of Things (IoT), artificial intelligence (AI), big data analytics, and cyber-physical systems to improve efficiency, flexibility, and decision-making. See for example Smart Industry roadmap (2020) for more examples.
5 This figure excludes the sectors for raw materials, energy, trade in real estate, government services, education, and households.

2. Digitalisation of manufacturing: an opportunity and a challenge

Main opportunities

Labour productivity is defined as the amount of goods and services produced by each member of the labour force.[6] Digitalisation of manufacturing could improve labour productivity through increased efficiency on the shop floor, production of higher-quality products and services, generation of less waste, and reduced operational costs.[7] In turn, efficiencies created through digitalisation contribute to a more competitive position, making it worthwhile for companies to invest in digital technologies (Deepak Kumar et al., 2023, Matt et al., 2020).

Digital transformation of manufacturing can leverage interconnected systems to **enhance efficiency** on the shop floor through automating some or even all manual tasks (see for example, Ghobakhloo et al., 2022). When digital technologies are implemented in a factory system (and across value chains), various systems work together to enhance efficiency and thus productivity. Factory systems called digital factories typically integrate advanced machinery, automation, and data analytics within a single manufacturing facility.[8] These digital technologies focus on optimizing production processes, reducing downtime, and improving product quality through real-time monitoring and control – also called smart and flexible manufacturing.

On the other hand, digital technologies extend across value chains and through the entire network of suppliers, manufacturers, distributors, and customers – also called connected factories - which contribute to integrating material sourcing, logistics, production, and distribution. Digital twins and simulation tools allow for the testing of process changes without generating physical waste. Through predictive maintenance, optimized resource allocation, and decreased downtime, companies can significantly **reduce operational costs** over time.

Digitalisation of manufacturing can facilitate precise control over material and energy inputs, contributing to leaner operations and minimizing environmental impact. Advanced monitoring systems and predictive analytics enable early detection of defects and process deviations, thus supporting more consistent **quality** assurance and reduced rework or recalls.

Additionally, digitalisation could be used to **make work accessible** to a larger group of workers with different backgrounds and different education levels (de Vries et al., 2025). Additionally the onboarding process can be streamlined, stimulating new employees to work independently quicker (de Vries et al., 2025). Streamlining the onboarding process and leveraging digitalisation to a larger share of the workforce contributes to an overall increase in production.

Main challenges

Firms that implement digital technologies not only are able to increase labour productivity on the shop floor but also achieve a sustainable competitive advantage: they are better equipped to respond to market dynamics, offer mass customization, and innovate more rapidly. Yet companies also face multitude adoption challenges (see for example: Ghobakhloo et al., 2022, Zabudkina et al., 2024, TNO, 2024a, Rani et al., 2025). They involve financial, technical, organizational, social and regulatory aspects, for which the main challenges (in particularly for small and medium-sized enterprises) are discussed below.

The cost of upgrading to digital technologies could be substantial before productivity gains are realized, which often goes hand in hand with limited available resources.[9] The longer companies postpone adopting digital solutions, the more difficult and costly the transition will become. The high initial investment costs, coupled with uncertain short- to medium-term returns on investment with limited to no quarantuee of a successful transformation are more easily covered by larger enterprises with more financial resources. In contrast, small and medium-sized enterprises (SMEs) often face difficulties in accessing external funding sources, including innovation grants, subsidies, or venture capital.

Moreover, the individuals best positioned to lead digital transformations—so-called change agents—are often the same people responsible for day-to-day operations, leaving them with limited time and capacity to drive change.

At the same time, any transformation requires non-monetary changes. Organizational culture and internal resistance to

6 Glossary:Labour productivity - Statistics Explained - Eurostat: when considered for the sector or whole economy the definition is that labour productivity is the amount of value added for the sector or whole economy per unit of labour.
7 In the Netherlands the developments in this regard are stimulated through Smart Industry program (Smart Industry Schaalsprong Agenda 2022-2026).
8 See for example Roadmap-Smart-Industry-2020.pdf.
9 According to Corrado et al. (2021), high industry output was driven historically by large physical capital stocks. Now, digital technologies enable new levels of scale for companies. Internationally this leads to an increasing divide within sectors between the most productive companies (which are those that have higher investments in intangible capital) and the rest of the companies in those sectors.

change as well as limited availability of knowledge, available resources and skills can pose significant costs as well. For a example, the difficulty of aligning new data-driven, automated workflows with existing organisational practices could slow down the pace of digital transformation. Transitioning to these advanced systems often clashes with established processes and entrenched mindsets. There are costs also associated with balancing opportunities with existing capacities: in practice, daily production demands all attention of SMEs.

Despite the potential of digitalisation, **integration of advanced technologies in existing production and across value chains** remains challenging. Digitalisation of manufacturing advancements are out of reach for companies with limited basic digitalisation, and there are many of these companies across the value chains in manufacturing. A considerable number of SMEs operate manually or use outdated or non-interoperable machinery and software systems, which are not easily compatible with newer digital technologies.[10] The replacement or retrofitting of such systems requires substantial investment and often entails operational disruptions. The lack of modularity and standardization in legacy systems further complicates integration efforts.

If a large amount of partner organisations is less digitalised, integrating new smart technologies with legacy systems can be complex and time-consuming. A key aspect of successful digital transformation is the integration of cooperating systems: seamless interaction between technologies and machines both within the factory and across the entire value chain. If it is achieved, all components across the cooperating systems work together harmoniously, maximizing efficiency and productivity. When only parts of the system are digitalized, the lack of integration can hinder the overall performance, reducing the potential gains from automation and digitalisation.

A shortage of employees with the necessary digital skills is yet another challenge (FME, 2022, TNO, 2024a). Many SMEs lack the internal human capital required to manage such technologies effectively. The implementation, continuous use, maintenance, customization, of digital technologies necessitate proficiency in advanced digital competencies, including data analytics, cybersecurity, and systems integration. Recruiting skilled personnel and reskilling or upskilling existing employees poses significant financial and organisational challenges.

There is **a growing gap between the frontrunners and the rest** in leveraging digital applications to enhance productivity (TNO, 2024a). Late adopters are catching up slowly in industries characterized by more intensive use of digital technologies and digital skills, suggesting obstacles to the transfer technologies and knowledge (Berlingieri et al., 2020). The widening gap has several implications. Companies that fail to adopt digital technologies risk falling behind their competitors in terms of market share and profitability. They may also struggle to innovate, limiting their ability to respond to changing market demands. The disparity in digital adoption can contribute to broader economic inequality, as digitally advanced companies thrive while others lag behind.

In short, digitalisation of manufacturing offers clear advantages but there are a multitude of challenges associated with the transformation journey, ranging from technological hurdles to workforce adaptation. As companies embark on the Smart Industry transformation, it is essential to explore the strategies and (system) solutions that can effectively tackle these challenges. The next chapter will delve into practical suggestions to overcome these challenges and strengthen the aforementioned opportunities and thereby stay competitive. From leveraging advanced technologies to fostering a collaborative work environment, we will examine how these solutions can be implemented to drive progress and success.

10 The lack of interoperability standards and the fragmented nature of industrial supply chains exacerbate these difficulties.

3. Perspective on a competitive industrial system

Even though companies and organisations are aware of the potential benefits of digitalisation, they also foresee challenges and are wondering how to approach the process of implementing new technologies (see Textbox below).

Increasing labour productivity within manufacturing enterprises is a complex issue that requires **a systematic approach**. In this approach a strategy is necessary that considers the perspectives of the primary process, employees, the organization, technologies, and a position in a value chain at the same time. This means that various perspectives and elements must be integrated simultaneously to arrive at effective solutions. In this context, it is important to focus on the core activities of the company, as well as the employees, the organization, and the technologies used. Relations across the value chains, with partners and knowledge institutions are important and each one of these could play a role in stimulating the digitalisation of manufacturing.

The following steps outline key actions to support the exploration, development, and implementation of innovative solutions to maximise the opportunities and mitigate the challenges of the digitalisation of manufacturing, particularly for SMEs.

Many (small and medium sized) manufacturing companies are asking themselves the following questions on how and where to begin with digitalisation and robotisation:

- How do I ensure sufficient flexibility and adaptability in low volume and high mix production with digitalisation and robotisation? In other words, how can technological solutions in production be quickly or automatically adjusted to product variants and new products?
- How do these new technologies integrate with my existing IT/machine infrastructure?
- How do I ensure alignment in the supply chain: with customers and suppliers?
- How do I get my people from different departments on board with these changes?
- How do I ensure that technology is effectively adopted and can be used, maintained and updated on the shop floor?
- How do I ensure that the experienced employees' knowledge of production processes & machines is captured, preserved (in decision support systems) and transferred to (inexperienced) colleagues?

Start with Internal Engagement: Employees' involvement is crucial for the success of any change. Their feedback and active participation should be encouraged. Increasing labour productivity can be effectively addressed by initiating a project with an internal leader and a multidisciplinary team with knowledge regarding: work preparation, production, engineering, quality, IT. This ensures a broad range of insights and expertise, bringing together knowledge and perspectives from across the organization as well as creating a broad support base.

In the initial phase of the project, it is important to define a clear scope. For example, the short term objectives as well as a long-term vision can help to clarify which digital technologies and processes - including those dedicated to improving labour productivity are in scope. This differentiation allows the project team to achieve tangible results quickly while working towards structural innovations with a sustainable and productive character.

Various organizations and public private partnerships are already implementing smart digital technologies, which can provide inspiration. Public private partnerships include field labs[11], regional innovation hubs, and industry associations. This contextual exploration stimulates cross-pollination and promotes the adoption of best practices and emerging technologies.[12]

The introduction of new technologies in the work environment could require new skills and expertise, which might not be immediately available. Where specific knowledge or competencies are lacking within the organization, targeted external expertise can be engaged. This includes collaboration with knowledge institutions, industry experts, and technological integrators or solution providers. These strategic partnerships contribute to the quality and applicability of the developed solutions and increase the chances of successful implementation within the operational context.

Put humans and primary processes central: Effective technological innovation requires that both the primary production process and the employees are central to technological development and implementation (a human-centric approach, EC, 2021; Baltrusch et al., 2021). In particular, because the role of skilled employees remains essential in tasks such as assembly, inspection, maintenance, and trouble-shooting especially in high-mix, low-volume environments - where full automation is often not feasible.

11 Also examples of successful implementation could be found here in TNO (2024d).
12 See for example, https://smartindustry.nl/personeel-meenemen-in-innovatieve-ontwikkelingen#ondernemersverhalen; https://metaalunie.nl/Teqnow/Productiviteit.

The knowledge and practical experience of these employees are a crucial source for designing, evaluating, and implementing smart technologies, like robotics and digital solutions. Only by systematically utilizing their insights can technologies be developed that align with real work processes, which improves adoption in a later stadium. Asking questions such as "which steps are currently performed manually?", "what challenges do you as an operator face?", and "what information or support is missing?" helps identify meaningful technological interventions.

Although many technologies are already available on the market, successful implementation within a factory typically requires customization. This necessitates collaboration between internal teams and external partners, such as technology integrators or machine builders, to develop solutions tailored to the specific context of the company. For example, consider implementation of digital work instruction systems, which are readily available and used in various companies, but require customization to integrate in existing solutions (TNO, 2024c).

Connect to the existing infrastructure within the factories and across the value chains to ensure effective information provision that can be used in the shop floor: To benefit from the full potential of digitalisation in manufacturing, it is essential to connect to the existing IT and machine infrastructure, both within the factory but also externally in the value chain. An effective strategy starts with leveraging readily available data generated by existing machines and systems. Initiatives such as Strengthening the Dutch Industrial SMEs demonstrate that valuable process improvements can be achieved with limited resources. Concrete applications include linking digital work instructions to ERP systems or integrating operator with digital product passports.

In practice, however, many existing and recently developed systems are not inherently interoperable, leading to the need for technical and financially intensive customization. To address this, it is advisable to align with existing data standards for chain information exchange, such as those developed within initiatives like the Smart Connected Supplier Network. These standards promote compatibility and scalability of digital solutions.

Best practices and current examples of successful integration and digitization projects can be found on platforms like Smart Industry Netherlands. These provide valuable insights for companies looking to develop their digital infrastructure step by step and future-proof.

Leverage on smart solutions with and around AI to support the workers: Developments in generative artificial intelligence (GenAI) are progressing rapidly and offer new opportunities for industrial digitization. One application area involves accelerating the creation and maintenance of digital work instruction systems. While digitizing instructions adds value, the practical execution such as creating and updating content often proves labour-intensive for work preparation and engineering (TNO, 2024c).

With the use of AI-driven tools, work instructions can be automatically generated based on video footage of actions on the shop floor. This lowers the barrier for creating instructions and enables operators to independently and quickly create digital content (e.g., via tools like Instant Instructions - Tech Transfer).

Additionally, the integration of GenAI with 3D data unlocks the potential for autonomous machine control such as Flexible manufacturing automated workflow generation and Autonomous workflow 3D printing. This advances towards more adaptive control of production processes, especially in complex or highly varied production environments. These applications illustrate the potential of GenAI not only to optimize existing processes but also to enable new forms of interaction between humans, data and machines.

Although technological innovations in production environments promise to contribute to higher labour productivity, **the actual impact often remains insufficiently understood**. Evaluations so far typically focus on individual technologies or company-level assessments and are often snapshots. There are some practical examples available. For instance, the Inther research (also highlighted in Stroosma, 2022) and other experiments have measured the impact of digitization and automation on lead times, error reduction, and efficiency. Initiatives like Strengthening the Dutch industrial SMEs also demonstrate at the company level how technological interventions lead to concrete improvements.

However, the long-term effects of these technological solutions on labour productivity are still under-researched. More studies are needed that follow companies over extended periods. Only then can it be determined whether initial productivity gains are sustainable and to what extent these effects can be scaled up to sectoral or macroeconomic levels. Future research should therefore focus on quantifying structural effects and developing methods to systematically measure productivity impact within various technological and organizational contexts.[13]

13 See for example FRAIM for more information.

4. Concluding remarks & recommendations

To remain competitive, companies need to work more efficiently and produce more with fewer resources to increase labour productivity. Innovation of production processes based on digitalisation and automation is essential to achieve this productivity increase. The manufacturing industry, which is at the heart of this discussion, is under pressure also due to labour market shortages and changing customer demands. Companies in the manufacturing industry are increasingly focusing on and interested in digitalisation. The involved technologies offer numerous benefits, such as increased efficiency, cost savings, and improved quality. These technologies can increase output by optimizing workflows, reducing human errors, and enabling real-time data-driven decisions. They also empower employees to operate more efficiently and focus on higher-value tasks. Altogether they have the potential to improve the overall competitiveness of the firms.

Unfortunately, many companies, especially SMEs, still struggle with implementing Smart Industry solutions due to high costs for upgrading and implementing the digitalisation of manufacturing and shortage of employees with the necessary digital skills. This leads to hindered value chain integration and hindered cooperation when partner organizations do not apply digital and automation technologies yet. This hindered cooperation is also intensified when there is a gap in digitalisation between frontrunners and followers.

Therefore, efforts should begin with the most innovative sectors and companies to maximise the impact of digitalisation — those operating at the forefront of technological development. These frontrunners, often concentrated in strategic industrial clusters and high-tech ecosystems, act as engines for emerging markets and innovation-driven growth across both the Netherlands and the EU. By adopting digital solutions early, these companies establish industry benchmarks, enable shared learning, and reduce uncertainty for others. Their progress can accelerate digital transformation across broader sectors. A pertinent example is the NXTGEN Hightech initiative, which encompasses high-tech manufacturing and plays a critical role in advancing technological capabilities and driving sustainable economic growth.

Recommendations

The digitalisation of manufacturing is not happening on its own. To maximise the opportunities that it offers for increased productivity and to mitigate the challenges we provide the following recommendations next to the aforementioned four step approach for SMEs:

- Employees and the primary processes have to be put central for a successful technology development and integration. So, digitalisation needs to be based on a **human centric approach**. This way technological solutions are not only tailored to the primary process, the tasks, but especially to the needs of the employees, leading to practical and effective usage.
- Labour-saving technologies such as robotics and artificial intelligence (AI) have to be adopted within **a broad range of organizations, especially for SMEs**. By integrating these advanced technologies, SMEs can streamline operations, reduce manual labour, and improve efficiency. This not only helps in addressing labour shortages but also enables businesses to focus on innovation and growth. The implementation of robotics and AI can lead to significant cost savings, improved accuracy, and faster turnaround times, making SMEs more agile and responsive to market demands. Embracing these technologies is essential for SMEs to thrive in a rapidly evolving economic landscape.
- Adoption of digitalization is heavily dependent on the knowledge and skill a company has at its disposal. Therefore, it is crucial to continuously provide education and training to **equip people with the skills** needed to adapt to new technologies. This involves not only technical skills but also fostering a culture that embraces change and innovation. User-centric design principles should be employed to create technologies that are accessible and easy to use, ensuring that everyone can benefit from digital transformation.

Ecosystem partners also play a role in stimulation digitalisation of manufacturing and mitigation of challenges associated with it. Specifically, various partners could stimulate the adoption of digitalisation in the following way:

- **Knowledge institutes and RTOs** such as universities and TNO could fulfil the role of independent advisor, developer or orchestrator in the development of technologies that can help increase labour productivity crucial for our productivity and prosperity. RTOs can help with the development of such technologies and work already on that (see for example Instant Instructions - Tech Transfer EN, Flexible manufacturing automated workflow generation | TNO).
- **Policymakers** play a crucial role with their policy instruments in fostering an innovation ecosystem that supports small and medium-sized enterprises (SMEs) in the digitalisation of manufacturing. By stimulating public-private partnerships, policymakers can create an environment where SMEs have access to the resources and collaboration opportunities necessary for research and development and innovation.

Recently, the Ministry of EZ launched for instance the policy experiment: shaping the future of work in SMEs. This involves cooperation between FRAIM (TuDelft, RoboHouse), TNO, Metaalunie, FME , Bouwend NL, Technniek NL. Human-centred innovation and systematic approaches from different perspectives are topics of this experiment. The approach and experiences will be evaluated and hopefully scaled up in the coming years. To complement public initiatives, targeted policy incentives are needed to stimulate private investment in digital infrastructure and technologies. These may include tax credits, co-investment schemes, loan guarantees, and innovation vouchers that lower the financial barriers to entry, especially for SMEs. By de-risking investments, governments can unlock significant private capital and accelerate widespread adoption of digital solutions.

Fostering digital transformation necessitates a systemic approach. A **systemic approach requires a collaborative effort** from all the participants across the ecosystem involved in the digitalisation of manufacturing. This way the digital transformation could be turned into a long-term competitive advantage.

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