Fraunhofer

Whitepaper

Turkish-German Digital Technology Exchange: R&D Cooperation in Manufacturing Engineering and Manufacturing-Related Information & Communication Technology

INTERNATIONAL INSTITUTE OF BUSINESS ENTERPRISES e.V.

ENOSAD 2004 INDUSTRIAL AUTOMATION MANUFACTURERS' ASSOCIATION

MEDİPOL UNV-İSTANBUL İSTANBUL MEDİPOL ÜNİVERSİTESİ

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Preface

Dear partners from industry, research and politics,

thanks to an initiative of IIB e.V. and Fraunhofer we are glad to present with this white paper our framework for Turkish-German collaboration in manufacturing and digital technologies. In a time of rapid industrial change, the Turkish manufacturing sector is actively seeking strategic cooperation with German research institutions to accelerate its digital transformation. The core driver is an urgent need to digitize production processes, optimize operations, and elevate competitiveness across value chains. By joining forces, Turkish industry aims to leverage German excellence in engineering, automation, and ICT, thereby turning challenges into durable, high-value opportunities.

Digitalization is not a luxury but a prerequisite for modern manufacturing. Turkish producers recognize that data-driven decision making, predictive maintenance, digital twins, and integrated supply chains are essential to reduce downtime, improve quality, and shorten time-to-market. German research institutions bring world-class capabilities in cutting-edge methodologies, standards, and actionable innovation ecosystems that can translate technology into scalable, real-world solutions. This partnership promises a win-win: Germany gains access to a vibrant market and a strategic hub in a dynamic region, while Turkey reinforces its industrial backbone through knowledge transfer, joint development projects, and access to advanced capabilities.

The benefits for Turkish industry are substantial. First, accelerated productivity gains and reduced operating costs through intelligent automation and asset optimization. Second, enhanced resilience and supply chain transparency through data spaces, standard interfaces, and secure data sharing. Third, accelerated innovation cycles via co-created competencies in AI, machine learning, digital twins, and Industry 4.0 concepts tailored to Turkish production contexts. Fourth, a stronger capability to meet international quality and environmental standards, supporting Turkey’s Green Deal alignment and circular economy objectives. Fifth, the creation of high-skilled employment and sustainable value creation through product-service ecosystems and new business models that leverage data as a strategic asset.

This collaboration aligns with Turkey’s ambition to become a regional hub for nearshoring, intelligent manufacturing, and advanced engineering. By combining Turkish manufacturing strengths with German research rigor, we can unlock scalable, sustainable growth, foster regional stability, and contribute to a thriving European knowledge economy. We invite researchers, industry partners, and policymakers to join this strategic dialogue and co-design a roadmap that converts shared knowledge into tangible, lasting impact for both nations.

Sincerely yours

Cem Şanlimeşhuu
ENOSAD Chairman

Contents

1. Management Summary

This study argues for a reinforced bilateral collaboration between Germany and Türkiye in Research & Development for manufacturing technologies and associated ICT. It highlights the strategic relevance of Türkiye as a nearshoring hub and Germany's leadership in advanced manufacturing. The objective is to strengthen supply chain resilience, accelerate digital transformation and enable new value-based business models, such as product-service-systems, underpinned by interoperable data ecosystems and standardized digital practices.

Key trends and drivers that we mention in this study: modern manufacturing is shaped by digitalization, AI and machine learning, data spaces (Gaia-X/Manufacturing-X/Catena-X), digital product passports and circular economy imperatives aligned with the EU Green Deal. The shift from product-centric to value-based offerings increases the importance of ICT-enabled services and data-driven decision-making.

Strategic potentials

- **For Türkiye:** Enhanced global competitiveness through AI diffusion, digital infrastructure upgrades and data spaces; reduced import dependence via technology transfer and EU-standardization; growth of innovation clusters and transfer centers; deeper integration into European supply chains through Green Deal compli-ance and circular economy practices.
- **For Germany:** Access to Türkiye as a high-tech production and R&D base; joint R&D accelerators (2+2 program); leverage Turkish innovation ecosystems, e.g. via MEXT, Teknopark Istanbul, Bilişim Vadisi, and EU funding channels; contribute to Green Deal objectives through circular economy initiatives; participate in cross-border data ecosystems to enable secure data sharing and new services.

Focus Areas and recommended Actions

- Bilateral R&D programs: Reinstate and expand 2+2-style calls; co-fund joint projects in manufacturing, digitalization, AI and logistics; utilize TÜBİTAK's international funding mechanisms and bilateral project supports.
- Standards and interoperability: Establish OPC UA presence in Türkiye; Catena-X representation; integrate with Manufacturing-X and data spaces to enable cross-border data exchange and compliance with digital product passports and lifecycle analytics.
- Innovation clusters and transfer centers: Develop Turkish clusters of excellence like Aachen, OWL or Karlsruhe; promote joint industry-research projects with Fraunhofer and German industry partners.
- Digital infrastructure and capabilities: Accelerate broadband rollout; advance AI competencies; deploy pretrained AI models; establish joint Master-/PhD-programs; clarify Data Governance.
- Sustainability and circular economy: Joint projects on digital product passports, lifecycle assessment, recycling/remanufacturing; align supply chains with EU standards.
- Resilience and supply chains: Co-create regionalized procurement strategies, dual-/cross-sourcing, and enhanced transparency via data-driven risk analytics.

A deeper Turkish-German collaboration in R&D, digitalization, Industry 4.0 and AI offers substantial mutual gains: Germany reinforces its global value chains and nearshoring access, Türkiye accelerates technological modernization, reduces import dependence and positions itself as a resilient regional hub. A concrete bilateral program, standardized data exchange, innovation clusters and infrastructure partnerships are essential for rapid, measurable results.

» Digitalization is not a luxury but a prerequisite for modern manufacturing, and we need end-to-end visibility from suppliers to final test. Stronger Turkish-German applied R&D cooperation will help us implement standard interfaces and secure data sharing, so we can reduce downtime, improve quality, and shorten time-to-market at scale.«

White goods / appliance manufacturer (Türkiye)

2. Introduction

Four major trends are profoundly changing the conditions and requirements for engineering and manufacturing. These current developments are: the Russian expansion policy in Europe, which is also affecting Turkiye, the restrictive U.S. policy almost leading to the United States' complete withdrawal from Europe, the flooding of the European market with both cheap and high-quality Chinese products and the unforeseeable refugee crisis affecting both Turkiye and Germany.

For the manufacturing industry this results in the following challenges [0].

- **Competitiveness:** The European and the German equipment industry can only maintain its position in international competition if it consistently focuses on innovation, for example in the development of new components, machines, and production lines that describe, configure and improve themselves, including associated digital services.

- **Sustainability and resource efficiency:** Validating the CO_2 footprint of a machine or component not only on type level but also on instance level as opposed to average values will become mandatory for machine builders and component manufacturers, as will the requirement for factory operators to provide evidence of how much energy and raw materials were consumed in the production process. Digital services will also be needed for this, for example to reduce energy consumption in production by optimizing the sequence of manufacturing orders.

- **Resiliency:** Mechanical and plant engineering, including its automation components and the commissioning, repair and maintenance of machines and lines, are particularly dependent on reliable international supply chains. Machine builders import supplied parts from China at approx. 15%, more than twice the average for all German industrial sectors. As a consequence, flexibility and adaptability in the value chains of the equipment industry must increase significantly if it is to remain able to deliver amid growing uncertainty. Digital services, for example, help to quickly detect disruptions in supply chains and select alternative suppliers while taking all necessary risks and quality requirements into account [13].

- **Circular economy:** Fraunhofer is working on developing circular strategies and technologies for various industry sectors, in particular the automotive industry, starting with product development for the main components of a vehicle (battery cells, car body, battery housing, electronics and electrical systems, tires, etc.) These activities are based on the 10 R-Strategies, e.g.
  - avoiding products or manufacturing them differently,
  - extending the life cycle of products, and
  - recycling materials.

Such strategies and data-based services must also be developed for the machine and factory equipment industry, based on existing approaches, e.g., overhaul of motor spindles for machine tools, condition monitoring, predictive provision of spare parts, etc. Digital Technologies just as the Digital Product Passport (DPP) support the circular economy.

Simply supplying highly productive and reliable machines, lines or components will no longer be sufficient as a distinguishing feature and basis for business success in the future. A paradigm shift is taking place, moving from a focus on products to value-based added benefits, known as product-service systems (PSS), which generate new added value and secure or create future-proof jobs for highly skilled employees. Complementary services related to machines, in combination with the possibilities offered by industrial digitalization, also enable the prospect of data-based subscription business models in the "as a-service" economy, which are considered less susceptible to sales fluctuations and investment cycles and which, at the same time, can massively strengthen customer loyalty and thus the sensitive customer interface. Furthermore, sustainability aspects of the circular economy are strengthened by providing new business models in repair, refurbishment and remanufacturing.
The key to product-related digital services and potential additional value creation is information and communication technologies (ICT) [38].

In the following sections, the authors show that these conditions apply to factory operators and machine builders from both Turkiye and Germany. As a conclusion, we describe some action areas as recommendations for a future collaboration between Turkiye and Germany for the benefit of both countries.

3. Current Status

3.1. KPIs for collaboration between Turkiye and Germany

Turkey has strong industrial cores which make it stable during economic crises. This is a good basis for improving economic prosperity through value-adding capabilities. However, Turkiye's economic competitiveness compared to its peer group still needs improvement (see **Figure 1** for examples). To foster the ongoing digitalization across all industrial sectors, especially manufacturing, assembly and logistics, Turkiye should improve its infrastructure, not only to support industry alone but also to strengthen the entire value-adding chain, from basic research to applied research, start-ups and companies. Digital services will increasingly complement traditional production of parts, products, machines.

	Agriculture	Industry	Services
Share of economic sements 2024 [% of GDP], (Source: Statista)	Ger 0,9% Tur 5,6%	Ger 21,1% (manufacturing), 5,4% (construction) Tur 25,9%	Ger 70,6% Tur 56,8%
Share of R&D expenses 2023 [% of GDP], (Source: World Bank)	Turkiye 1.46%	Germany 3,13%	OECD 2,72%
Ranking of Economic Performance, World Competitive Index 2025 (Source: IMD.org)	Turkiye 45th*	Germany 12th**	
Digital Future readiness score in Digital competitiveness landscape 2025***	Turkiye: overall 63th, Future readiness 59th	Germany: overall 18th, Future readiness 21st	

Figure 1: Comparison of KPIs Turkiye and Germany.

If we look at the trade numbers between Turkiye and Germany, the result is the following picture (**Figure 2**) of German exports to Turkiye and imports from Turkiye. According to Germany Trade and Invest (the economic development agency of Germany), Germany ranked third among the most important supplier countries, behind China (stable at 45 billion USD) and Russia (down 4% to 44 billion USD). The largest German export items were motor vehicles and motor vehicle parts, machinery, medical and pharmaceutical products, plastics, chemical products, and aircraft.

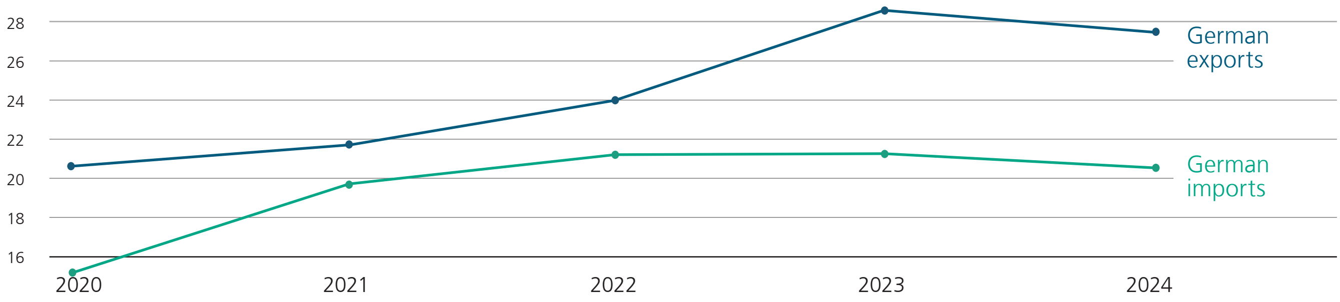

Figure 2: Bilateral trade: the German perspective (Source: TÜIK 2025).

* Source: https://www.imd.org/entity-profile/turkey-wcr/
** Source: https://www.imd.org/entity-profile/germany-wcr/
*** Source: https://imd.widen.net/content/xclarczvwr/pdf/WDCR_Report_2025.pdf

Modernization of the EU-Turkey customs union is required. Despite all well-known challenges and difficulties, Turkiye remains a key economic partner for Germany and the EU as the largest economy in Southeast Europe. In addition to being a bridge and hub for international trade, Turkiye is also an ideal location for nearshoring, joint value creation and the establishment of more resilient supply chains [4].

As shown by some aggregated trade numbers, the exchange of goods and services between EU27 and Turkiye have improved over the last 20 years, with this trend hopefully continuing in the years to come: The EU accounts for 41.3% of Turkiye's total exports and 31.5% of its total imports. On the other hand, Turkiye is an important trade partner of the European Union according to the foreign trade statistics of the EU, which indicates that in 2021, Turkiye ranked sixth in imports and exports of the EU with shares of 3.7% and 3.6% respectively [5]. This position improved in 2024: Turkiye ranked fifth in imports and exports of the EU with a share of approx. 4.2% [6].
Subsequent to Chancelor Merz's visit to Ankara on October 30, 2025, Germany started pursuing a strategic partnership with Turkiye. Due to the trends discussed in Section 4. below, this partnership is both necessary and important for both Turkiye and Germany. In Section 5.4., the authors of this white paper propose some measures to establish this strategic collaboration.

3.2. R&D cooperation

General information

At present, there are no official bilateral government programs supporting an R&D cooperation; however, small-scale collaborations already exist between Turkish universities or companies and German research and science institutions or private enterprises. One example that shows there is a real need for transformation in the Turkish industry is the MEXT initiative established by the partnership between the Turkish Employers' Association of Metal Industries (MESS) and McKinsey & Company. MEXT is a tech center that provides knowledge and tools regarding the digital and green transformation [7] (see Section 6.3 for details).
The European Union is currently funding the AI European Digital Innovation Hub in Turkiye, especially in the Istanbul region [8]. However, a bilateral forum for cooperation between Germany and Turkiye has still not been developed.

R&D landscape and innovation capacity in Turkiye

In 2024, Turkiye's innovation ecosystem demonstrated significant growth, with gross domestic expenditure on R&D totaling 651.8 billion TL. This represents an increase to 1.46% of the GDP, up from 1.39% in the previous year [1]. The private sector is the primary driver of this growth; financial and non-financial corporations funded 53.8% of these expenditures and carried out 64.8% of the total R&D activities [1]. Within the manufacturing industry, there is a strong focus on advanced technologies, with 46.9% of R&D expenditure directed towards high-technology activities and 40.2% targeting medium-high technology activities [1]. These figures indicate a strong industrial commitment to transformation, backed by a workforce of 310,473 full-time equivalent R&D personnel, 30.6% of whom hold a doctoral degree or equivalent [1].

Foreign trade and high-tech competitiveness

Despite strong R&D investments, foreign trade data from October 2025 reveals a structural need for technology transfer and collaboration. While the manufacturing industry accounts for 94.4% of Turkiye's total exports, the share of high-technology products within these exports remains at just 3.4% [2]. In sharp contrast, high-technology products comprise 12.7% of manufacturing imports, thus demonstrating a significant dependency on imported advanced technology [2].
Germany maintains its critical role as Turkiye's most important commercial partner, ranking first in exports with approximately 2 billion USD in October 2025 alone and ranking third in imports with 2.3 billion USD [2]. This volume underscores the potential for enhancing the strategic partnership in high-value-added production.

Digital maturity and AI adoption in Turkiye

The digital transformation of the industry is progressing but still faces structural barriers. As of 2025, the adoption rate of artificial intelligence (AI) among enterprises has risen to 7.5%, up from 2.7% in 2021 [3]. However, a sectoral divide is evident: While the information and communication sector leads with a 47.1% adoption rate, the manufacturing sector is significantly lower at 7.0% [3]. The primary barrier to AI adoption is the lack of relevant expertise, cited by 74.2% of enterprises, followed by high costs (67.4%) and legal uncertainties (62.4%) [3]. Regarding infrastructure, only 8.6% of enterprises have access to internet connection speeds of 1 Gbit/s or higher, a prerequisite for advanced data-driven services [9]. On a positive note, in terms of sustainability, 17.1% of enterprises are actively using ICT systems to monitor and reduce energy consumption, aligning with the green transition goals [9].

4. General Trends and Challenges for Factories

4.1. Dependency on foreign material sourcing

General information

Political or economic developments require regular adjustments to supply chains. Crisis events in particular cause profound changes, repeatedly necessitating the reorganization of supply chains. Reasons for this include:

- Suppliers of intermediate goods are unavailable due to crises or tariffs (e.g., the conflict in Ukraine).
- Transport routes are blocked, e.g., such as the case of the Suez Canal,
- (Raw) materials are suddenly no longer available in the required quantities, e.g., semiconductors – see the Nexperia example – or rare earths for permanent magnets.
- Demand for certain products rises sharply and unpredictably, e.g., vaccines.

These effects apply to both Turkiye and Germany. A sectoral study reveals, "that while the import dependency of exports was on a downward trend from early 2013 until September 2019, this trend reversed after this date and the import dependency of exports started to increase rapidly" [10]. "The highest import dependence of exports is observed in the manufacturing sector, including textiles, apparel and basic metals" [11].

Turkiye: structural dependencies in the manufacturing supply chain

The latest official statistics for October 2025 highlight a significant structural dependency on foreign inputs within the Turkish manufacturing ecosystem. While the manufacturing industry demonstrates robust capacity, accounting for 94.4% of total national exports [2], its operational continuity is heavily reliant on the importation of intermediate goods. In October 2025, "Intermediate Goods" constituted the largest category of total imports, with a share of 68.3% [2]. This high ratio indicates that a substantial portion of the production value chain depends on raw materials and semi-finished goods sourced from abroad, validating the risks associated with global supply chain disruptions.

High-technology gap and source dependency

This vulnerability is further exacerbated by the technology gap in trade. While the manufacturing sector's export volume is high, the share of high-technology products within these exports is limited to 3.4% [2]. Conversely, the share of high-technology products in manufacturing imports is nearly four times higher, at 12.7% [2], indicating a critical dependency on foreign technology providers for advanced machinery and components (**Figure 2**).

Geographically, this dependency is concentrated on specific partners: With a 12.6% share, China remains the largest source of imports, followed closely by the Russian Federation at 11.8% [2]. This concentration aligns with the strategic necessity for the supply chain diversification discussed in earlier sections.

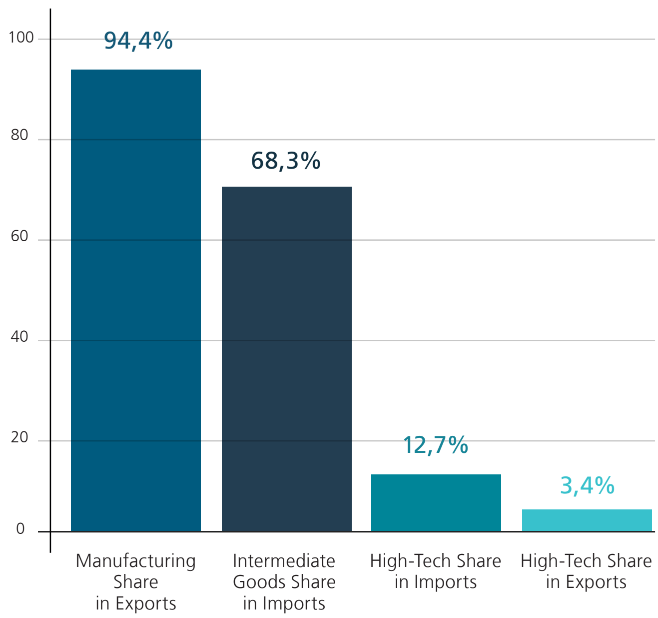

Figure 2: Structural Dependency Indicators in the Turkish industry.

4.2. Creating resilience

The dependence of factory operators and their equipment suppliers on foreign procurements is leading to a shortage of parts in manufacturing and assembly during the current crises, and the logistics of parts supply are taking on a new significance. Uncertainty about future geopolitical developments has motivated factory equipment suppliers to increasingly approach regional suppliers or select suppliers from politically friendly countries.

To mitigate the above mentioned supply chain risks, a digitalization transformation in logistics is imperative. However, current adoption rates suggest this is an area requiring immediate action. Among Turkiye's enterprises using artificial intelligence, only 13.6% utilize this technology for logistics activities [3]. Furthermore, for enterprises engaged in e-sales abroad, the "high cost of delivering or returning products" remains the single most significant challenge, as cited by 45.8% of companies [9]. This logistical friction points to a clear need for optimized, data-driven supply chain solutions.

Since 2018, further trade barriers have been erected, leading to the formation of "independent blocs". One example of this is the establishment of a separate supply chain for the Chinese market and another for the EU/U.S. with the aim of overcoming the hurdles created by tariffs and similar measures [12]. Due to possible geopolitical bloc formation, factory equipment suppliers are faced with the question of whether to continue sourcing materials and components globally or to establish regional networks.

Resiliency can be achieved in different ways [13], including through:

1. regionalization of the supply chain,
2. changing procurement strategies with dual and cross-sourcing,
3. building up storage capacity,
4. using recycling and other R-strategies to keep material circles small and
5. transparency for coordination and early risk analysis.

Supply chain resilience is a major topic for Europe's manufacturing industry, especially for parts and components that are sourced and delivered from Asia (**Figure 3**). Value creation is also a key success factor for Turkiye's own resiliency and fast recovery in the case of global or regional crisis. Turkiye can improve its position in the manufacturing industry by establishing itself as a major hub for assembly, storage and reliable on time delivery for European OEMs and their major suppliers. Digital solutions are crucial success factors for both topics: Data-driven services advance the resiliency and transparency of supply chains and also enable on-time delivery.

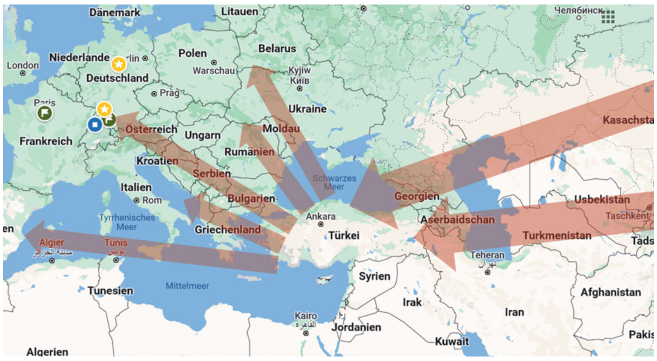

Figure 3: Turkiye's key position between Asia and Europe (Source: IIB).

To counter these risks at an early stage, new approaches and methods are needed to build adaptive supply chains. These enable rapid restructuring after a previously unforeseen risk has occurred. To this end, organizations must be as agile as possible and design the supply chain structures early on to facilitate quick decision making in the event of impending supply bottlenecks. A high degree of product modularization supports the adaptive structures of the supply chain and allows the product to be flexibly adapted to supply bottlenecks.
The high volatility of the markets also requires adaptive supply chains on the part of factory equipment suppliers. Although resiliency of supply chains has increased [14], there is still a long way to go.

According to [15], Turkish players see disruptions to global supply chains as an opportunity to shift European production chains to Turkiye (nearshoring).

4.3. Sustainability

Decarbonization and the demand to better utilize scarce resources through a circular economy are forcing companies to fundamentally rethink and redesign existing production processes up to product designs and their development. They must integrate innovative technologies and processes that use resources more efficiently, reduce waste and establish a closed-loop circular economy [16]. This requires not only investment in new machinery and equipment, but also in research and development to create sustainable materials and processes.
At the same time, manufacturing companies must ensure that they source raw materials sustainably, preferably from respon-

sible and renewable sources. To this aim, companies should closely cooperate with their suppliers to ensure that environmental standards are met and that the entire supply chain is transparent [13]. Data ecosystems and new standards as the Digital Product Passport can be used to help exchange the necessary data. In addition, companies must design their logistics in such a way that minimizes CO2 emissions, which often requires a realignment of existing transport routes and methods. Crises also give rise to profound changes and thus repeatedly lead to the adjustment of supply chains.

Instead of current linear economic systems where products are disposed at the end of their lifecycle, companies as well as national economies have started to follow circular economy approaches. "Close material flows throughout our society [..] are commonly known as Circular Economy. Although the idea of closed-loop material cycles has been around since the beginning of industrialization, it has gained momentum due to the current day discussions on climate change mitigation and sustainable development" [17]. The leading authors within the CIRP community [17] also elaborate on what sustainability is all about and how it can be defined.

In this whitepaper, we focus on technologies, innovations and sustainable solutions that are supported by Industry 4.0, which "describes a fundamental process of innovation and transformation in industrial production. This transformation is driven by new forms of economic activity and work in global digital ecosystems. Today's rigid and strictly defined value chains are being replaced by flexible, highly dynamic and globally connected value networks that emphasize new forms of cooperation" [18].

»

To move beyond isolated pilots, we need actionable ecosystems that translate technology into scalable, real-world solutions-especially for SMEs under cost pressure. Regional transfer centers and testbeds will let us validate AI-based quality control and predictive maintenance before industrial scaling, with measurable ROI and lower implementation risk.«

Plastics / packaging manufacturer

Turkiye's strategic alignment with the European Green Deal
According to a recent study by the German Institute for International and Security Affairs (SWP), Türkiye's industrial and supply chain policy is increasingly driven by geopolitical motivations that imply a close alignment with Germany and the EU [19].

The study highlights that Ankara aims to adapt its production and distribution networks to EU standards, specifically to comply with the European Green Deal. While the transition to a "green hightech economy" imposes short-term costs on Turkish competitiveness, it is strategically viewed as a long-term catalyst for comprehensive economic transformation and modernization [19]. This alignment is critical, as Türkiye positions itself as a central hub for nearshoring and resilient supply chains for European partners.

Turkiye's National Circular Economy Strategy and Action Plan
Complementing this external perspective, Türkiye has accelerated its domestic efforts through the "Green Deal Action Plan" coordinated by the Ministry of Trade. A key pillar of this plan is the transition to a circular economy, which includes the preparation of a "National Circular Economy Action Plan" and specific legislative alignments with the EU's Circular Economy Package [20]. Turkish business associations, including TÜSİAD, emphasize that this transformation is not merely about carbon reduction but rather a prerequisite for sustaining global competitiveness [21]. Key segments such as textiles, batteries, and construction materials are being prioritized for circularity to minimize the carbon footprint of exports to the EU market [21].

The increasing scarcity of resources, such as energy, raw materials, rare earths, etc., poses new challenges for manufacturing companies. However, the use of digital technologies can contribute significantly to overcoming these challenges and creating more sustainable and efficient value creation structures [22, 23].

4.4. Adaptivity

To manage the wide variety of product variants, R&D work has concentrated for some time on modular and adaptive manufacturing and assembly structures, including for series production that was previously organized according to the traditional line or flow principle. The core idea is to install universally usable machines and systems instead of specialized production facilities, some of which require their own infrastructure, such as overhead monorail or pallet conveyors. Universally usable production facilities are configured for a specific task and can be quickly reconfigured for new or modified tasks as needed. This requires adaptive "hardware," e.g., robots and manipulators, of course, but above all suitable control technology, software and communication technologies. An example of such innovative modular manufacturing concepts is shown in **Figure 4**.
This principle can be applied to individual lines and to entire production facilities. Such adaptive hardware with standardized interfaces between modules is already in use in practice.

For series production in which cycle time varies more due to the wide range of variants, these approaches mean modularizing entire conveyor systems and organizing the material flow, for example using automated guided vehicles (AGV) – enabling each workpiece to take an individual path through assembly modules, which in turn are supplied with pre-commissioned baskets of parts by AGVs in a timely manner. This scenario requires continuous localization and online tracking of workpieces, AGVs, add-on parts and their means of transport. Conveyor technology on multiple floors, such as in today's automotive plants, is then no longer necessary; trackbound vehicles are also largely eliminated from the factory. Today's (mostly outsourced) logistics with external supplier warehouses, supermarkets, milk-run trains for conveyor supply and Kanban carriers on the conveyor are being replaced the picking parts sets for specific assembly scopes. However, this pushes the usually applied control concept to its limits. Control is evolving from a more centralized system to a decentralized one, to hierarchical swarms whose participants work together collaboratively and (partly) autonomously: Adaptability requires appropriate software applications and services. Instead of programming, the software uses auto-configuration mechanisms enabled by the embedded and machine-readable configuration descriptions of the hardware [24]. Machine-to-machine communication and communication between field devices and manufacturing execution functions during production runtime allows manufacturers to keep devices and operators informed about the status of the modules at all times. Shared information models (such as digital twins) form the semantic basis for data access and exchange. A comprehensive study released by Fraunhofer summarizes the potential and the required technologies for cyber-physical matrix-production systems [25].

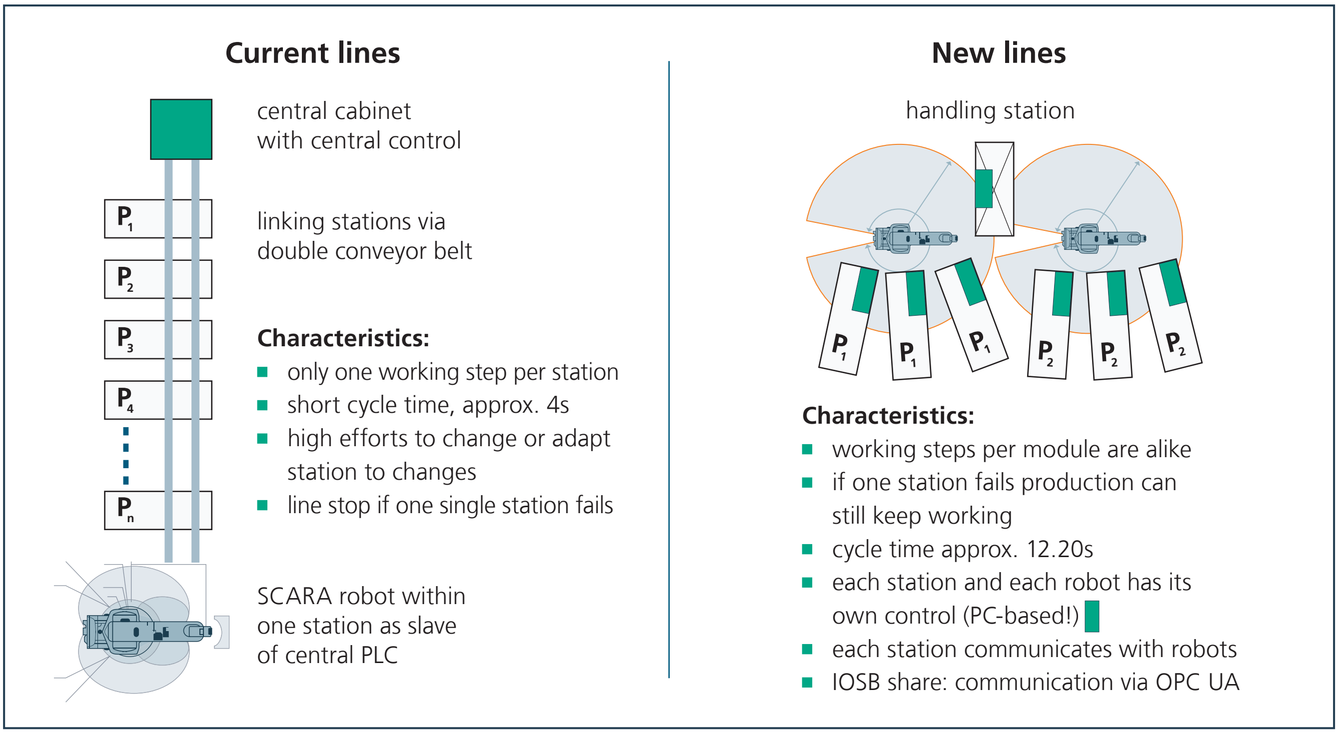

Figure 4: Modular machines with decentral controls, enabling digitized changeover (Source: Fraunhofer IOSB).

4.5. Automation requirements due to lack of skilled and qualified personnel

Automated production systems are particularly advantageous for the manufacturing industry, especially in high-wage countries, because they not only deliver reproducible product quality but also counteract the shortage of skilled workers.
Flexible automation has been relevant in research and practice since the 1980s, as automation (production factor: "capital") replaces the production factor "labor." The trade-off between fixed costs associated with automation and the more variable costs of manual labor must be considered. The degree of automation is determined during the factory planning process, based on the location-related factor costs and the expected utilization of the installed production capacity.
Small and medium-sized enterprises (SMEs) in particular, which produce only small quantities with a wide variety of parts, face enormous challenges when they want to automate their production processes [26]. Two obstacles can be identified [27]:

- **Wide variety:** This requires automation components that are specially adapted to individual products or production steps, such as different gripping systems, which increases complexity and costs [27].

- **Cost pressure:** High acquisition and commissioning costs must be spread over the small number of units, making it difficult to achieve economic efficiency [27].

However, the latest developments in modern manufacturing technologies offer solutions to these challenges. The trend toward more flexible machines and systems, in conjunction with software-based configuration, enables the implementation of adaptive manufacturing systems [28]. This facilitates the profitable automation of even small series down to batch size one. The following key technologies are crucial for achieving these goals:

- **Collaborative robot systems (cobots):** Their versatility and ease of programming allow them to be used flexibly for different tasks [29], reducing the need for product-specific hardware and thus lowering the cost per variant.

- **High-resolution camera systems:** Enable robots to perceive workpieces and their surroundings, allowing automatic adaptation to different part geometries and positions without costly mechanical retooling, thus making variant diversity manageable.

- **Simulation software:** Allows new automation configurations to be tested and evaluated virtually, reduces the hardware costs for commissioning and optimization, and speeds up adaptation to new products and product variants [30].

4.6. AI and ML

According to [31], AI and ML (machine learning) are both "must technologies" for machine builders and components suppliers: "Despite AI's transformative power, many companies in machinery and equipment manufacturing are still in the early stages of adoption. However, the rapid pace of AI development leaves no room for hesitation. Companies that fail to act risk falling behind, as competitors can now close gaps faster than ever, leveraging AI to gain a prominent edge. This urgency is particularly pronounced in Europe, where regulations such as the EU AI Act impose stricter requirements on local companies."
The increasing use of sensors and network integration of machines and material flow equipment allows the continuous recording and integration of status and operating data that is highly critical for the effective use of AI (**Figure 5**). The analysis of machine data using ML and AI based on these enables the ability to

1. identify and even predict unplanned equipment downtime for individual pieces of equipment at an early stage, thereby ensuring that the right spare parts are available just-in-time (predictive maintenance), so that the availability of machines and systems remains high,
2. identify quality problems and (automatically) adjust process parameters so that the required quality is maintained,
3. make reliable predictions about the timing of processes (sequences of operations, cycle times, etc.),
4. respond to malfunctions or short-term changes in requirements as automatically as possible,
5. detect hidden anomalies in complex processes and
6. ensure energy-efficient operations by balancing the availability and price of energy types, e.g., by scheduling production orders or working steps in such a way that peak loads and thus high energy costs are avoided.

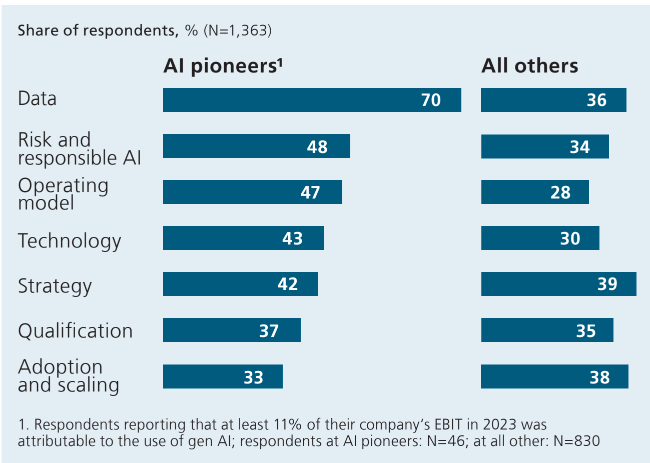

Figure 5: Challenges of creating value with AI (Source: [31]).

» SMEs in Türkiye want digitalization, but the real bottleneck is skills and implementation know-how on the shopfloor. A regional transfer and training center model – supported by German-Turkish cooperation – would let us pilot solutions, train technicians, and adopt proven reference architectures without taking unacceptable project risk.«

SME manufacturer (metal / textiles / general manufacturing)

With AI and ML, entire process sections, right through to the supply chain, can also be analyzed and optimized. The following steps are required to create an ML model: The relevant data from machines and components must be identified, connected, recorded, and annotated. An algorithm suitable for the application must be selected, parameterized, and trained with the data. This process is time-consuming, ties up resources, and requires expert knowledge of automation technology and data science. To successfully use ML models in production and reap the benefits, the process of creating the models must be simplified (automated) to such an extent that it can be carried out with as few resources as possible. Pre-trained models for monitoring plants and components can help here, i.e., the steps for identifying and annotating the data as well as selecting, parameterizing, and training algorithms no longer have to be carried out by the plant/factory operator. Pre-trained models can add significant value, especially for identifying rare malfunctions and failures and their transferability to new plants. In addition, it must be ensured that the models created can be transferred to new sensors or new equipment performing the same process (transfer learning) and continuously compared with operational data (relearning).

Ultimately, the use of AI methods and tools, especially in industrial manufacturing, must be systematized in a way that ensures reliable engineering while meeting the requirements for functional safety, IT security and robustness – an approach called "AI systems engineering." AI systems engineering focuses on systematically developing and operating AI-based solutions – integral part of systems that perform complex tasks. In this respect, AI systems engineering complements fundamental research on AI and ML and bridges the gap to engineering sciences. The goal is to make AI and ML methods applicable to typical engineering questions and procedures and transfer them into suitable system architectures using computer science methods, for example, with regard to availability, resilience and expandability [32]. Machine learning, large language models, federated learning and other approaches will play a major role in the future for both manufacturers and their equipment suppliers.

AI adoption and barriers in Turkish manufacturing

The challenges of implementing AI systems – specifically the need for expert knowledge and high-quality data – are acutely prominent in the Turkish industrial sector. According to 2025 data, while 47.1% of enterprises in the information and communication sector have adopted AI technologies, the adoption rate in the manufacturing industry remains significantly lower at 7.0% [3]. This disparity underscores the difficulty of transferring AI capabilities from IT-centric sectors to operational factory floors.

The argument that creating ML models requires expert knowledge and ties up resources is validated by local statistics. The primary barrier to AI adoption in Türkiye is the "lack of relevant expertise in the enterprise," cited by 74.2% of companies [3]. Furthermore, "difficulties regarding the availability or quality of required data" are reported as a major hindrance by 54.7% of enterprises [3]. These figures confirm that the complexity of identifying, connecting, and annotating machine data creates a bottleneck for Turkish manufacturers, highlighting the urgent need for the pre-trained models and automated model creation approaches discussed in the previous section.

Despite these barriers, early adopters are focusing on core value creation areas. Among the enterprises using AI, 41.1% utilize it specifically for "production or service processes," and 13.6% for "logistics" [3]. However, to scale this up and bridge the gap to AI systems engineering, the industry must overcome the high implementation costs, which 67.4% of enterprises currently view as a prohibitive factor [3].

4.7. Digital twins, data spaces and data ecosystems

The concept of the digital twin (DT), a virtual representation of the properties of physical goods, dates back to 2002. It was originally defined for the product lifecycle management (PLM) field, which was initially used mainly for design and simulation tasks in the aerospace industry [33, 34]. Today, the term "digital twin" refers to a concept in which products, machines, and their components are modeled using digital tools – including all geometric, kinematic and logical data. A digital twin is therefore a representation of the physical asset in the real factory and allows it to be simulated, controlled and improved.

A digital twin is not a monolithic data model but rather comprises various aspects of digital representations, functionalities, models and interfaces. It is crucial that these aspects of the digital twin are modeled in a way that ensures semantic interoperability between the sub-models [35].
Digital twins are essential for Industry 4.0, data spaces and data exchange between companies and the further digital transformation in manufacturing. Their content is created in the various lifecycle phases of a product or factory, using different tools on a range

of platforms. Practical examples show that digital twins are very application-specific and must be defined in a way that is tailored to each company.
Especially in the machine building sector, simply supplying or operating highly productive and reliable machines, systems or components will no longer be sufficient as a distinguishing feature and basis for future business success. A paradigm shift is taking place from productcentric sales to benefit-oriented sales, called product-service systems (PSS), which generate new added value and secure or create future-proof jobs for highly qualified employees. In addition to traditional hardware-related skills, factory operators and equipment suppliers must quickly learn and master a comprehensive set of capabilities in order to be able to implement and effectively use new methods and tools such as Gaia-X, platforms and data ecosystems, data security and sovereignty, etc. None of this will be successful on its own: The actual knowledge gap can only be closed in cooperation with like-minded partners. The secure exchange of data fosters cooperation and innovation within the ecosystem, enabling the implementation of new business models that were previously unprofitable. The basis of such a data ecosystem is secure, open and transparent access to data for all ecosystem participants who are authenticated.

The basic assumption underlying industrial data ecosystems is that sharing data across companies offers greater potential for joint usage than internal improvements to individual processes. In addition to this ICT technology-centered argument, it can be observed that factory equipment suppliers and operators are certainly willing to take a digitalization approach, but that the necessary investments are often not justified by the benefits they provide. Data ecosystems therefore also focus on improving the better scalability of digital technologies and offerings.

Additionally, technological sovereignty is one of Europe's strategic goals and, for example, is firmly anchored in the German federal government's current hightech agenda.
"It is (...) crucial for the security, defense and competitiveness of Germany and Europe" [36]. Data spaces are an important tool for achieving data sovereignty because they enable participants in a data ecosystem to share data without it being stored centrally. Data spaces therefore help to reduce dependence on extraterritorial platform providers, primarily Microsoft, Google, and AWS.

The basic architecture of data spaces consists of shared services, connectors and business applications, which ecosystem partners combine to implement use cases. **Figure 6** summarizes this relationship. In the current Manufacturing-X projects, in which Fraunhofer is also involved, the partners are jointly developing shared services. The MX-Port is to be implemented in three configurations [37], which are emerging as interoperability standards for data exchange in the manufacturing industry: Eclipse Dataspace Components (EDC) using the Dataspace Protocol (DSP), Asset Administration Shell (AAS), and OPC UA (Open Platform Communications Unified Architecture). By applying these standard services, digital twins can be shared between companies to get more out of their data and improve competitiveness, resiliency and sustainability. Legislative requirements such as digital product passports or product carbon footprint calculations can be more easily fulfilled.

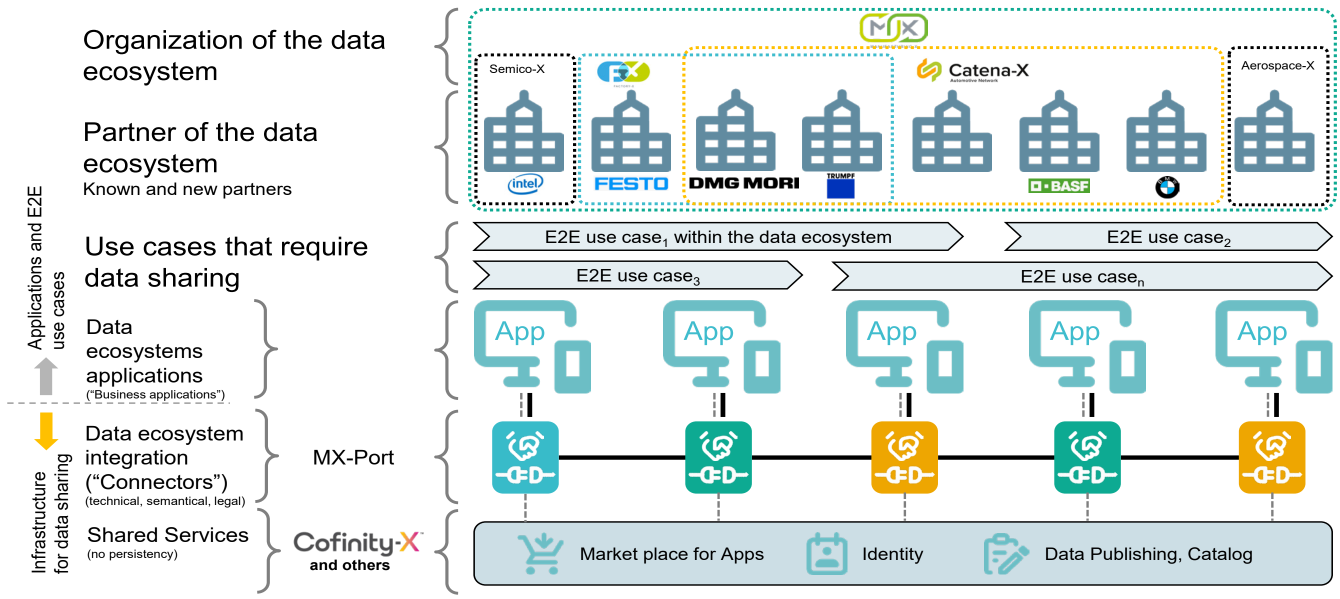

Figure 6: Levels of data space infrastructure and applications (source: Kube, G., Factory-X).

4.8. Special challenges to SMEs

Before Industry 4.0, life in the manufacturing world was still easy: production and IT were two separate domains. The automation pyramid reflected this common sense: At the field level – with manufacturing, assembly and material flow processes, sensors, actuators, controllers and their real-time communication, operations were largely independent of higher-level IT systems, including the internet, of course. At the ERP (enterprise resource planning) and MES (manufacturing execution system) levels, there were independent systems with distinct functionalities. With the advent of cyberphysical systems, the Internet of Things, end-to-end networking "from sensor to cloud," and collaborative approaches to data exchange, the architecture, interaction and responsibilities of IT and OT have completely changed. IT is increasingly penetrating field devices and machines. Access to data from field devices and machines within factories is now standard across all levels of the former automation pyramid. The level model has evolved into a network, with devices intrinsically connected to the internet. Many companies use data from machines and systems to continuously improve their key performance indicators. Although the buzzwords and trends have changed over the years, the tasks remain similar: collecting, communicating and processing heterogeneous signals and data from industrial processes, and using modern software development tools to prepare, evaluate and interpret them in complex IT components and systems.

In the future, additional potential can be leveraged, especially through exchanges with other companies, such as suppliers, customers and equipment manufacturers.

- In engineering, enables companies to test and validate production facilities and even entire factories and their digital twins, quickly put them into operation and continuously update them
- Along the supply chain, for example, to enable complete traceability or compare production requirements and available capacities during runtime
- To improve production processes, for example by quickly adjusting process parameters based on various conditions or measured values.

The possibilities of Industry 4.0 are far from exhausted: It is important to view the digitalization of products, production processes and their equipment, as well as the associated IT systems and infrastructures, as integral components.

The use of data-driven AI and ML processes in industrial applications is becoming a strategic advantage over competitors.

SMEs, in particular, will not be able to keep step with these new technologies if they stay on their own: They have to collaborate, an approach which is currently not in the DNA of small enterprises. Regarding digital transformation, they need a clear roadmap for their company, otherwise they will be "lost in space" between all existing and upcoming digital technologies. Such a digitalization roadmap consists of building blocks such as PLCs (and other controllers) and a semantic model for machines and their components, production-related IT systems (such as MES and their integration with ERP systems), technologies to support workers in manufacturing, (e.g., vision technology for quality control), AR glasses to support after-sales service, open standards that the company uses for data exchange and the integration of digital twins, use cases for the application of ML and AI, etc. The roadmap is always individual for each company and has to be updated from time to time.

In Turkiye, the digital transformation landscape is characterized by a sharp dual structure. While large enterprises (250+ employees) act as early adopters comparable to their European peers, small and medium-sized enterprises (SMEs) face a significant digital divide. Recent statistics from 2025 reveal that the gap exists not only with respect to advanced technologies but also in basic digital visibility.
For instance, while 92.5% of large enterprises have a corporate website, this percentage drops to 52.4% for small enterprises (10-49 employees) [9]. Similarly, regarding AI adoption, large enterprises are nearly four times more active (24.1%) compared to small enterprises (6.6%) [3]. This indicates that the majority of the industrial base is still at the early stages of the digitalization curve.

The reluctance of Turkish SMEs to integrate into hightech ecosystems is driven by a complex set of barriers rather than mere inertia. According to 2025 data, the lack of relevant expertise is the primary bottleneck, cited by 74.2% of enterprises [3]. However, financial pressure is equally critical; 67.4% of companies report high costs as a prohibitive factor [3], a challenge exacerbated by the inflationary environment which restricts capital expenditure for non-core activities. Beyond resources, structural uncertainties play a major role: 62.4% of enterprises cite legal uncertainties and 54.7% point to data quality issues as reasons for avoiding the adoption of AI [3]. This suggests that SMEs do not just need funding; they need legal guidance and data governance frameworks.

Infrastructure and market access challenges
Infrastructure limitations further hinder the ability of SMEs to participate in data-intensive manufacturing networks (data spaces). As of 2025, only 8.6% of enterprises have access to internet speeds of 1 Gbit/s or higher, while the majority (54.8%) operate with speeds below 100 Mbit/s [9]. This bandwidth constraint limits the efficacy of cloud computing and realtime data exchange. Furthermore, e-commerce integration remains low, with only 13.6% of enterprises engaging in e-sales [9]. For those attempting to export via digital channels, logistics remains a critical pain point; 45.8% identify the high cost of product delivery or return as the main obstacle to international e-sales [9].

Conclusion: A guided roadmap is essential
Given these structural, financial, and infrastructural constraints, Turkish SMEs cannot be expected to navigate the transition to Industry 4.0 independently. The digitalization roadmap must therefore be collaborative, providing SMEs with access to shared highspeed infrastructure, pretrained AI models to bypass the expertise gap, and legal frameworks to reduce uncertainty.

4.9. Summary and conclusions

Innovation is an indispensable foundation for longterm success in the manufacturing industry and in the mechanical and plant engineering sectors [31]. However, challenging economic circumstances, have led manufacturing companies to decrease their costs, while at the same time, technological requirements have significantly increased due to digital technologies, AI, robotics and other are that are not in the core competencies of traditional manufacturers and their equipment providers [39]. Although Germany is strongly capable of generating knowledge and developing new technologies in laboratories, it's lagging behind in its ability to create marketable innovations and industrialize new technologies **(Figure 7)**. The authors are convinced that in this situation, cooperation and collaboration between Turkiye and Germany can create win-win-situations for both partners.

»Scaling Industry 4.0 across multiple factories requires common standards, not one-off integrations. We strongly support steps like broader OPC UA adoption and participation in Catena-X / Manufacturing-X to enable data spaces with data sovereignty – so Turkish sites can collaborate across borders while keeping control of their data.«

Multi-site manufacturing group

INNOVATION CAPABILITY: RANKING AND INDEX VALUES OF THE ECONOMIES

RANK	ECONOMY		
1	SWITZERLAND	71	→ 0
2	SINGAPORE	64	→ 0
3	DENMARK	59	→ 0
4	SWEDEN	56	→ 0
5	FINLAND	56	↗ 1
6	IRELAND	54	↘ -1
7	BELGIUM	48	→ 0
8	NETHERLANDS	48	↗ 1
9	AUSTRIA	48	↗ 1
10	UNITED KINGDOM	46	↗ 3
11	SOUTH KOREA	43	→ 0
12	GERMANY	42	→ 0
13	AUSTRALIA	39	↘ -5
14	CANADA	38	↗ 3
15	USA	38	↗ 3
16	NORWAY	38	→ 0
17	ISRAEL	37	↘ -3
18	FRANCE	34	↗ 3
19	TAIWAN	33	↘ -4
20	GREECE	31	↘ -1
21	PORTUGAL	31	↗ 2
22	SPAIN	31	↘ -2
23	RUSSIA	30	↗ 11
24	HUNGARY	29	↗ 3
25	CZECHIA	29	↘ -1
26	MEXICO	25	↗ 3
27	POLAND	25	↘ -5
28	JAPAN	25	→ 0
29	ITALY	25	↘ -3
30	CHINA	24	↘ -5
31	INDIA	22	→ 0
32	SOUTH AFRICA	18	↗ 1
33	BRAZIL	17	↘ -1
34	TURKEY	17	↘ -4
35	INDONESIA	11	→ 0

Figure 7: Innovation capability: ranking and index values of the economies (Source: [39], changes in ranking positions vs. 2024 are shown on the right).

5. Measures for Turkish-German R&D Cooperation

5.1. Existing R&D Program Tübitak

Bilateral calls for proposals for joint collaborative projects involving science and industry (2+2 project approach) have been published in the past. A similar bilateral call for proposals with Turkiye should be prepared, especially for topics in manufacturing, addressing the challenges outlined in Section 2. In the following, we will briefly describe the current possibilities for R&D cooperation between Turkiye and Germany; the authors see many ways to improve them.
TÜBİTAK's International Support Framework facilitates bilateral R&D cooperation primarily through its "1071 – Support Programme for Increasing Capacity to Benefit from International Research Funds," which serves as the national funding mechanism for international joint projects. This program is particularly relevant for the "2+2" collaboration model (involving academic and industrial partners from both Germany and Turkiye), offering substantial financial incentives to mitigate the risks of crossborder innovation.

Funding rates and budget limits
According to the official program regulations, TÜBİTAK provides funding to Turkish partners under the following terms:

- **Support rates:** Higher education institutions and public bodies receive **100%** grant support. For the private sector, the support rate is **75% for SMEs** and **60% for large enterprises** [40].
- **Budget caps:** The program offers a funding upper limit of up to **200,000 Euro** per project (excluding overheads and incentives), with a maximum duration of **36 months** [40].
- **Eligible costs:** The funding covers personnel costs, equipment, travel, consultancy services, and consumables required for the R&D activities.

Bilateral cooperation mechanisms
In addition to the general 1071 framework, TÜBİTAK maintains specific bilateral cooperation agreements (including with German institutions such as DFG and DAAD) to support researcher mobility and joint academic projects. These initiatives are managed under the "Bilateral Project Support" schemes, which are periodically opened for calls to address specific thematic areas such as manufacturing technologies and digitalization [41].

5.2. Regional R&D and transfer centers

One measure to improve R&D capabilities and the exchange of R&D results with the industry is the implementation of R&D and transfer centers **(Figure 8)**.
Such innovation centers for innovative regions, technology parks and shared campuses for both research and industry should be established in Turkiye to accelerate knowledge generation and permanent innovation.

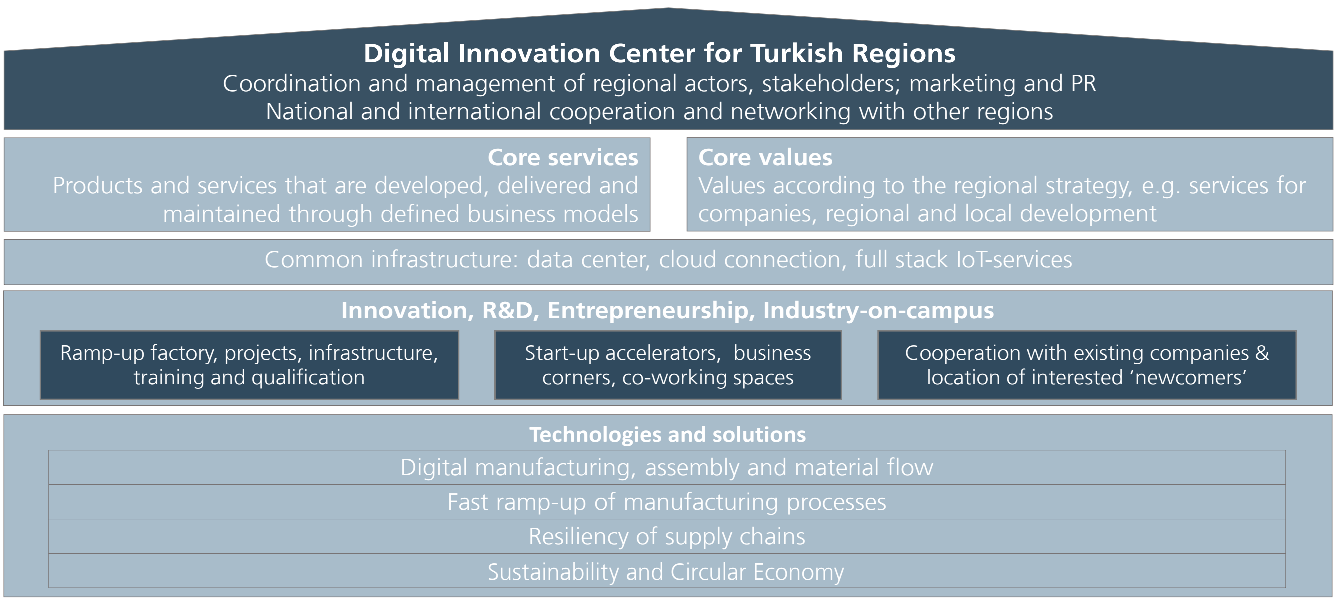

Figure 8: Building blocks for innovation centers (Source: IIB).

Some results from European initiatives are innovation clusters in Hamburg (aerospace), Aachen (manufacturing), Lemgo (automation), Karlsruhe (AI for manufacturing), Eindhoven (ASML community) and Sheffield [42]; in Germany, these clusters were established through a national competition for excellence clusters. To illustrate the results, four examples from the these clusters will be described in the following.

Aachen

Aachen, located right at the Dutch and Belgian border, has become a major cluster for innovation and cross-border cooperation **(Figure 9)**: "Covering an area of around 800,000 square meters, it will be one of the largest technology-oriented research landscapes in Europe, with 16 research clusters and 10,000 direct and indirect jobs. The basic idea is that RWTH Aachen University will provide its expertise and unique research infrastructure. In return, national and international companies will contribute their own research and development resources to the campus. This not only gives industry partners highly sought-after access to qualified young talent, but also helpful access to special training and continuing education programs. Six clusters have already been established on the first of the two development areas [...]: biomedical engineering, sustainable energy, photonics, production engineering, heavy-duty drives and smart logistics. Around 360 companies are already involved in these clusters" [43].

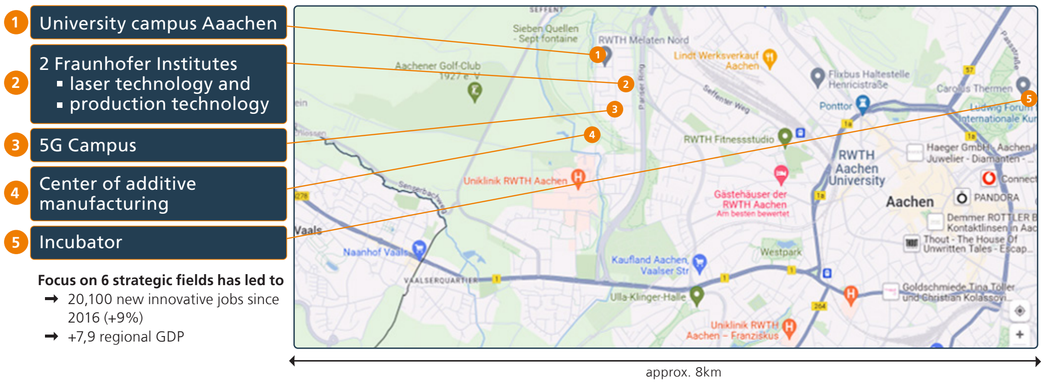

Figure 9: Overview of the Aachen innovation hub (Source: IIB).

Hamburg

The Hamburg Aviation cluster is a major part of Hamburg's innovation strategy; it has established itself as the leading aviation cluster in Germany **(Figure 10)**. "Hamburg is Germany's largest center for the civil aviation industry and, alongside Toulouse, the most important in Europe. In addition to the global players in the aviation industry, more than 300 predominantly small and medium-sized companies, research institutions, universities and training and further education facilities belong to the Hamburg Aviation Competence Network. [...] Hamburg is home to Airbus' headquarters in Germany, which employs around 14,000 people. The site plays a key role in the development and production of all Airbus programs. It is also home to the program management for the A320 aircraft family. Structural parts for the A319, A320, and A321 are manufactured and final assembly takes place here. In the aviation industry, research, development and implementation of new technologies are financially supported. In this context, the transformation to green flying requires investments in infrastructure as well as in climate-friendly technologies" [44].

Figure 10: Overview of the Hamburg innovation hub (Source: IIB).

IT'S OWL

The OWL (OstWestfalenLippe) region used to be a rural area in the "middle of nowhere". With innovation and cooperation between academia and industry, the region has been developed into a major industrial hub over the last 10 years, focused on automation and digitalization **(Figure 11)**. "In the leading-edge cluster it's OWL – Intelligent Technical Systems OstWestfalenLippe – more than 220 companies, research institutions, and organizations are developing solutions for intelligent products and processes so that companies can produce and work more sustainably. For over ten years, "it's OWL" has been developing solutions and applications in around 500 projects on topics such as artificial intelligence and intelligent product development, thereby supporting companies in their digitalization efforts.

The regional universities and research institutions are renowned for their interdisciplinary cutting-edge research in artificial intelligence, industrial automation, Work 4.0 and systems engineering. More than 1,000 scientists are working on solutions for tomorrow in four collaborative research centers, 18 research institutes, and three Fraunhofer facilities.
By the year 2023, the network will have launched projects worth 200 million EUR to tap into the potential of AI for production, among other things" [45].

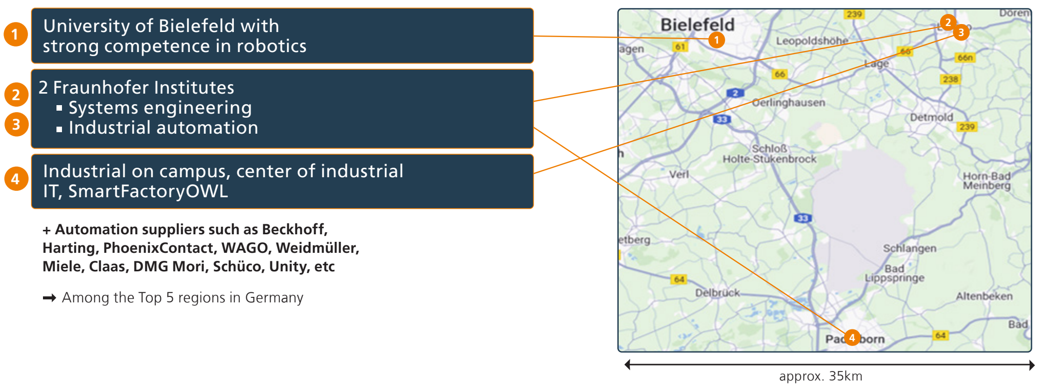

Figure 11: Overview of the OWL innovation hub (Source: IIB).

Karlsruhe

Karlsruhe, including its "TechnologyRegion" ecosystem, is among the three leading innovation regions in Germany, focusing on manufacturing, energy and information technology **(Figure 12)**. Due to its location on the Rhine River, it is also closely linked to and part of the "Eurodistrict Pamina" which includes the border regions of Southern Palatinate, Middle Upper Rhine and Northern Alsace. "Nestled in the TechnologyRegion, which covers an area of approximately 6,000 km² and has a total population of around 1.7 million, Karlsruhe is the regional center of one of Europe's most successful economic, scientific and research regions. A study by the EU Commission ranks Karlsruhe as the fourth-best ICT location out of over 1,000 regions in Europe, just behind Munich, Paris, and London. More than 1 million people work in the Karlsruhe TechnologyRegion (including the Bas-Rhin department), more than 182,000 of them in Karlsruhe itself" [46]. The Karlsruhe ecosystem is also linked to the Stuttgart region and through the AI Alliance Baden-Württemberg to the Heilbronn ecosystem, with the IPAI CAMPUS at its core (see next section).

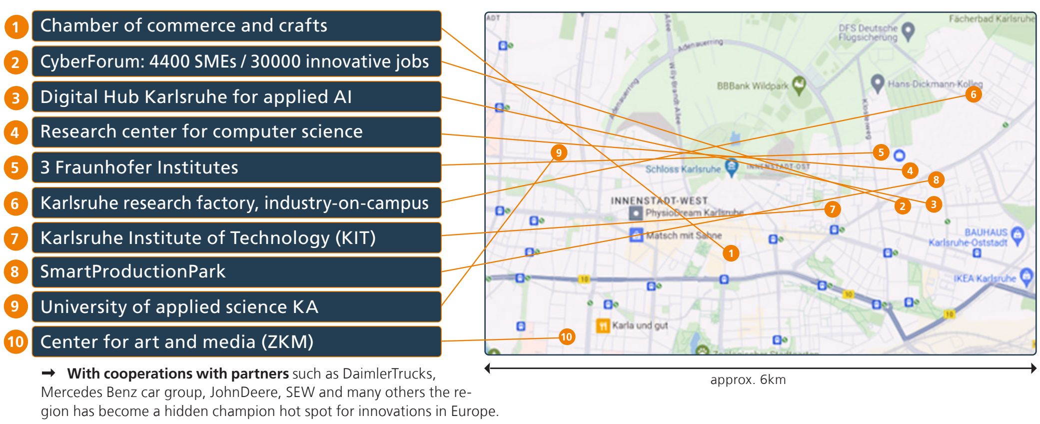

Figure 12: Overview of the Karlsruhe innovation hub (Source: IIB).

As these four examples clearly show, successful cities and regions run viable and lively ecosystems that bring together industry, research, science, start-ups and public organizations. They create value through ongoing networking and the active exchange of innovations, which also has a positive impact on the surrounding areas of the cities. The ecosystems succeed in creating new jobs for highly qualified staff, not only in established companies, but especially in new businesses.

5.3. Next-level AI clusters

Along with the above-mentioned top-level clusters, there are currently ongoing initiatives that aim to leverage the results from these clusters by providing the data center and AI infrastructure needed for future requirements. Examples of this include the following two initiatives.

Heilbronn and the IPAI
"From the end of 2025, the IPAI CAMPUS will be built in Heilbronn – an international location for over 5,000 people working on the development and application of artificial intelligence (AI). A forward-looking district bringing together business, science, and society is being created around 30 hectares. The campus is the heart of the Innovation Park Artificial Intelligence (IPAI)" [47]. Its mission is to transfer results from groundbreaking research to practical applications in everyday life and in industry [48]. The initiative and its investment are supported by the "Dieter Schwarz Foundation, […] which, through targeted investments in education, research, and entrepreneurship, promotes a dynamic environment that brings together companies, scientists, and students in Heilbronn" [49].

uptownBasel
"On the former [factory] site of Stamm Bau AG, the Schorenareal in Arlesheim, uptownBasel AG is developing and realizing a modern campus in the immediate vicinity of the economic center of Basel. The aim is to establish a leading Swiss location for Industry 4.0 on the new campus" [50]. The first building is now finished and in use **(Figure 13)**, including by a high-performance data center, cloud providers and other AI-related service providers that offer their services to in-dustrial corporations in the neighborhood, such as Roche, Novartis and others – of course, in close cooperation with start-ups and research organizations.

Similar activities are evident in Turkiye:
MEXT (MESS Technology Centre)
Established by the Turkish Employers' Association of Metal Industries (MESS), MEXT [7] serves as a premier industrial competence center in Istanbul. Spanning 10,000 square meters, it functions as a comprehensive **digital factory**, providing a tangible environment for the manufacturing sector to pilot digital and green transformation strategies. The center showcases over 170 real-world Industry 4.0 use cases, ranging from predictive maintenance and AI-based quality control to digital twins. While MEXT has successfully built an ecosystem of over 50 technology partners and launched an industry-focused AI Master's Program with Istanbul Technical University (ITU), it represents an ideal **implementation site** for international applied research. It offers the physical infrastructure necessary for testing innovative concepts before industrial scaling, making it a prime candidate for joint projects with German research institutes.

Bilişim Vadisi (Informatics Valley)
Positioned as Turkiye's "Mega Technology Corridor," Bilişim Vadisi operates campuses in Gebze, Istanbul, and Izmir, hosting over 4,000 personnel. It functions as a scalable ecosystem that bridges the gap between startups, large corporations, and venture capital, similar to the IPAI model in Heilbronn but with a specific focus on nationalizing critical technologies. A key component of its strategy is the **B-Stars AI Acceleration Programs**, supported by global tech giants, which aims to scale Turkish AI start-ups. Furthermore, as the R&D base for Türkiye's national electric car project (TOGG), it specializes in mobility, connectivity, and smart cities. This focus on the automotive and mobility sectors creates a natural synergy for collaboration with German engineering, offering a vast testbed for joint mobility solutions and deep-tech commercialization.

Teknopark Istanbul
Located adjacent to Sabiha Gökçen International Airport, Teknopark Istanbul has established itself as a specialized hub for **deep-tech innovation**, with a strong concentration in the defense, aerospace, and maritime sectors. Through its Cube Incubation center, it supports entrepreneurs tackling complex engineering challenges. Having facilitated over 100 million USD in technology exports, the park demonstrates strong commercial viability. However, its focus on deep-tech hardware and software integration presents a significant opportunity for collaboration on advanced R&D methodologies, where Fraunhofer's expertise in bridging basic research and industrial application could significantly accelerate value creation.Teknopark Istanbul launches deep-tech incubation center [51]. This video showcases Teknopark Istanbul, a key Turkish innovation hub mentioned in the response and highlights its focus on deep-tech entrepreneurship similar to the international examples provided.

Figure 13: Rendering of the "Kompetenzzentrum Industrie 4.0" building in Arlesheim (Source: [50]).

6. Recommendations and call for action

The institutional bilateral cooperation between Turkiye and Germany in the above-mentioned fields of R&D, digitalization, automation, Industry 4.0, innovative manufacturing technologies and AI/machine learning for manufacturing and logistics requires a revival and reactivation. Currently the stack of measures is empty **(Figure 14)**. The authors therefore strongly encourage policy decision-makers in both countries to breathe life into the strategic partnership with Turkiye sought by the German Chancellor (see Section 3.1).

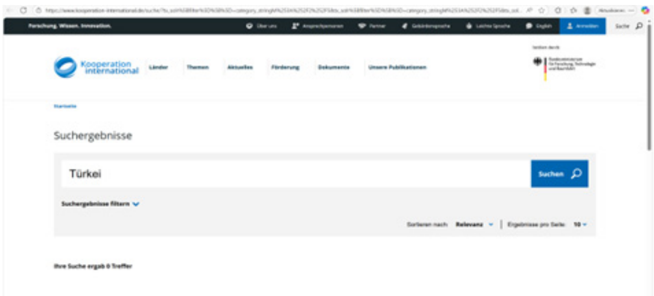

Figure 14: Empty query result field for the search for R&D cooperation.

To stimulate Turkish-German R&D-cooperation on the fields, that this white paper addresses, the authors recommend the following steps:

1. **Reboot and scale bilateral R&D funding and calls (2+2 model)**
   The 2+2 project method applied in the past should be used to revitalize the collaboration: These projects – originally initiated in 2014 – can be conducted in the research and development sector and involve at least one German and one Turkish research institution or university as well as both a German and a Turkish company. The approved funding was intended to lay the foundations for long-term R&D innovation partnerships. In addition, a permanent Bilateral Project Support platform with thematically focused calls on Manufacturing 4.0, AI, Logistics and Sustainable Production should be established.

   Expected outcomes: more joint projects, faster mobility of researchers and stronger industry uptake of outcomes.

2. **Build regional innovation clusters and on-campus collaboration**
   The authors suggest, to create Turkish regional transfer/innovation centers modeled on Aachen, OWL, Karlsruhe and others linking industry, universities and Fraunhofer-like partners. In addition, Turkish hubs such as MEXT, Teknopark Istanbul, Bilişim Vadisi and others should be linked with German clusters like IT'S OWL, KIT/Fraunhofer, for joint pilot projects. Along with these, on-campus cooperation programs between Turkish universities/institutes and Fraunhofer institutes to accelerate practical R&D-transfer should be established.

   Expected outcomes: stronger local ecosystems, more pilots and clearer path from research to industrial adoption.

3. **Accelerate digital infrastructure, AI capability building and talent programs**
   In both countries broadband deployment should be speeded up in manufacturing zones and address SME bandwidth gaps. A funding of joint programs (Master's/PhD) and facilitation of researcher/student mobility is required, along with the promotion of visa/clearance pathways to support exchanges. Accelerated use of AI needs the support for pretrained AI-models and automated ML-toolchains to reduce the barrier for Turkish firms, especially SMEs, to adopt AI in manufacturing, assembly and logistics.

   Expected outcomes: a capable workforce, faster AI uptake and more scalable AI-enabled manufacturing.

4. **Anchor interoperable data standards and cross-border data exchange**
   An official OPC presence in Turkey to enable machine-to-machine and MES integration should be established. OPC UA is an international standard for Machine-to-Machine-communication as well as for Machine-to-MES-communication. It also provides a large array of information models ("companion specifications") that define the meaning of data communicated both inside companies and between them. The use of companion specs makes it much easier to link machines from different vendors to IT-systems, allowing utilization of data for AI or machine learning, for example. Furthermore, to promote Catena-X a representation should be installed in Turkiye and aligned with Manufacturing-X. Catena-X is an international initiative

designed to enable the exchange of data between different tier levels, without central storage of the data that is provided and consumed. Catena-X is a collaborative data ecosystem for the automotive industry, comprising international members from Europe, North America and Asia. Catena-X is part of an even broader initiative called Manufacturing-X. Therefore, formal Turkish representations of Catena-X and Manufacturing-X should be created, to align bilateral projects with data-space standards such as MX-Port, Asset Administration Shell, OPC UA and others. Turkiye should join the International Manufacturing-X Council (IMXC). Manufacturing-X is an initiative aimed at creating data spaces for various vertical industry branches. The IMXC "is a partnership for the exchange of experiences, information, projects, standards and regulations. It considers manufacturing-related information between participants, including across international borders, considering the laws, regulations, standards and norms in each country [52]."

These measures support the implementation of bilateral Data Governance guidelines and Digital Product Passport concepts to ensure secure, compliant data sharing across borders.

Expected outcomes: Scalable, trust-based data exchange; easier AI and analytics deployment across value chains.

5. **Align with sustainability, resilience and circular economy goals**
   Both countries should co-design joint projects on Digital Product Passports, lifecycle analytics, remanufacturing and recycling aligned with EU Green Deal and circular economy standards. Such projects can work on developing resilient, data-driven supply chains with regional diversification, dual-/cross-sourcing and transparent risk analytics. Therefore, bilateral R&D should be linked to EU funding channels, e.g. Horizon Europe, and nearshoring objectives to strengthen European value chains.

   Expected outcomes: greener manufacturing, compliant supply chains, and reduced dependency on single sources.

»Resilience and sustainability have become operational requirements, not side projects. Joint programs with German partners can accelerate plant-wide use of AI, condition monitoring, and energy-focused optimization – helping us meet Green Deal alignment and circular economy expectations while staying globally competitive.«

Steel / metals processing

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