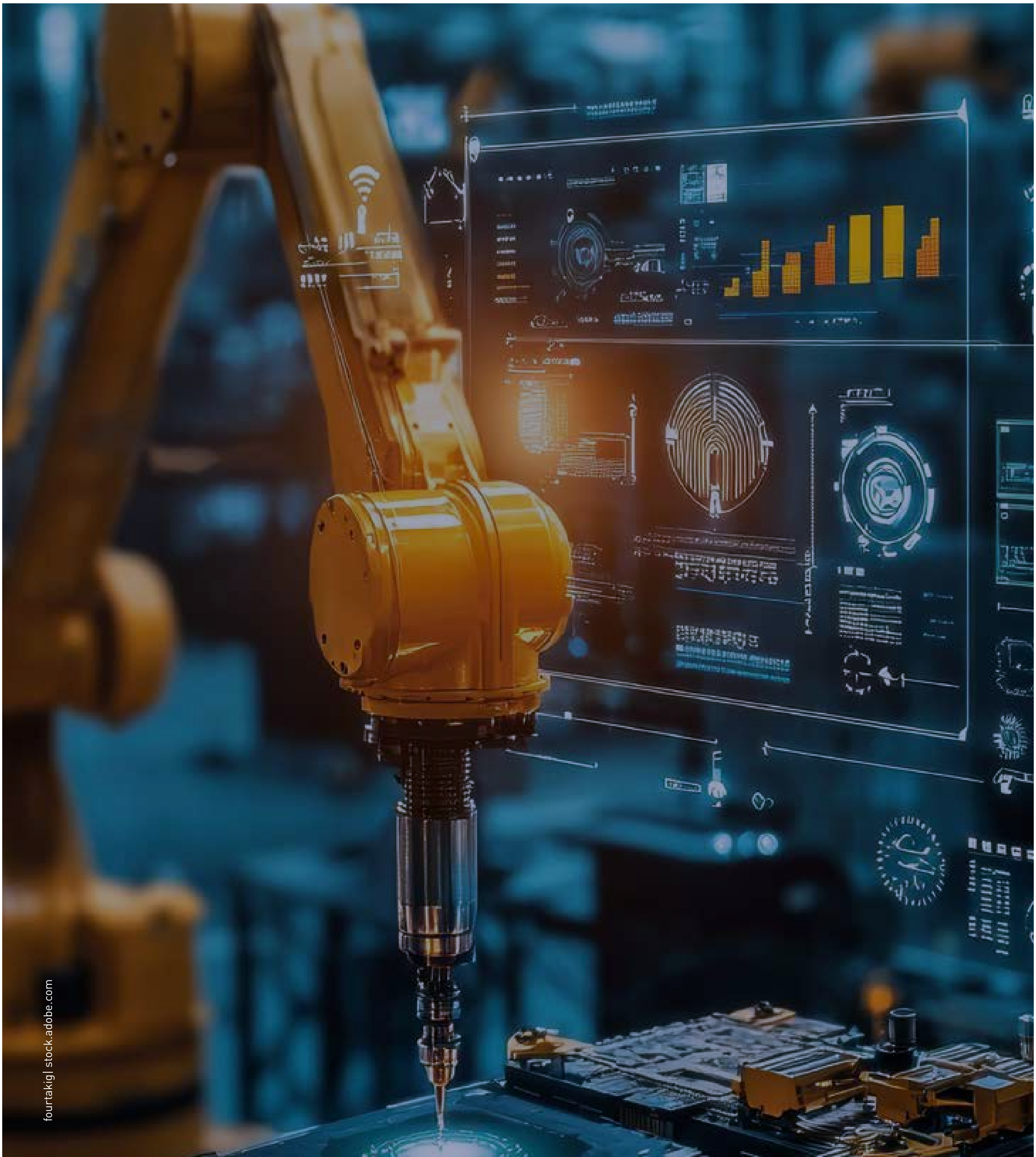

Digital transformation with confidence - A practical example of a trustworthy solution space for production

Whitepaper SF-3.6: 03/2025

smartFactory KL®

Abstract
In the current business landscape, industries are confronted with increasing pressure to adapt to market volatility, changing workforce demographics and evolving regulatory frameworks - challenges that traditional, siloed digitalization often fail to address. This paper introduces a holistic digital solution space, highlighting the strategic business benefits of seamlessly integrating assets, processes and contexts into cohesive digital models. By aligning technological innovation with core business objectives, organizations can enhance operational agility and streamline decision-making processes. Based on insights from the ***SmartFactory***KL Production Level 4 ecosystem, we demonstrate how modular yet comprehensive strategies - focused on trustworthiness - can be deployed across multiple domains in both brownfield and greenfield environments. The result is continuous in-service assessments and runtime risk management that promote greater resilience and competitiveness. The paper proposes a pragmatic approach for organizations seeking to modernize production environments without compromising regulatory compliance or organizational strategy.

Keywords
Trustworthiness, Safety, Cybersecurity, Resilience, Reliability, Privacy, Productivity, Integrity, Plausibility, Industry 4.0, Digital Twin, Multi-Agent System, Assessment at Runtime

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Content

1. Objective

At the time of writing this paper in early 2025 global economies are experiencing significant turbulence. Some major countries are increasingly protectionist, others are in recession. Market dynamics are evolving at an ever faster pace. Traditional industries such as the automotive sector face significant challenges. The demand for traditional internal combustion engines and their supply chains is declining. Furthermore, sustainability is becoming more important, while in some countries energy costs have increased drastically. To cope with all these challenges, it should be of major interest to manufacturing companies to be flexible and agile. One key enabler of adaptability is digitalization. However, the potential of digitalization is often missed because digitalization is not an answer in itself. The business, the business strategy and business goals have primacy. Nevertheless, data is key for more automation and better decision making. This paper describes at a high level what a digital solution space could look like and presents a concept implementation in the ***SmartFactory***KL ecosystem. The digital methods described here provide business benefits and decision-making support.

2. Challenges in the Current Situation

Businesses today face many challenges that are influenced by both external and internal factors. Externally, volatile markets, turbulence in supply chains and demographic changes are all affecting companies. At the same time there are internal barriers, structural, cultural and technical, that amplify the challenges.

External factors
Changing market conditions or turbulence in supply chains require companies to respond quickly and flexibly to changing external demands. This means that products and production setup must be constantly adapted to the specific current needs. Frequent changes during the product lifecycle are necessary to ensure security, interoperability and system integration.

Demographic change is leading to a growing shortage of skilled labor and a loss of expertise as ageing workforces retire and fewer young professionals follow. At the same time, regulatory requirements continue to increase and become more complex, presenting companies with administrative and organizational challenges. The implementation of sustainable and resilient production and operational processes is also becoming increasingly important in order to remain competitive in the long term. Companies are therefore increasingly forced to perform better with a smaller and less experienced workforce.

Internal factors
However, the evolution forced by the external factors described above is hampered by internal barriers. Silo thinking and the specialized languages used by different departments make collaboration difficult. As a result, a holistic view of the company is not available. In addition, there is often an unclear vision of the desired digital state, which prevents targeted implementation of measures. On a technical level, the interconnection of systems is also a challenge. Many companies use a variety of different systems and technologies from many suppliers. This makes integration difficult due to protocol and format incompatibilities. Another aspect is the often complex linkage of systems and data, including the required context or meaning, which is difficult to scale.

Problem statement
Digitalization as a solution to the challenges described previously often falls short of expectations and does not deliver the expected value. A key reason for this is the lack of a holistic approach. Instead of isolated measures, an overall strategic view is needed that integrates technological innovations and organizational adjustments to overcome internal barriers. In addition, analogue processes need to be fundamentally revised, as simply mapping them to digital processes will not unlock the full potential of digital capabilities.

3. Digital Solution Space

To meet these challenges, we propose a holistic digital solution for production environments. This requires a unified system architecture and digitalization of almost all components, as well as specific digitalization requirements. The following sections address these issues. A key aspect is the availability of digital representations of assets, processes, context and metrics. This leads to a new asset category: software-defined assets. These assets are characterized by their functionality and performance being predominantly defined by software in the data space. This aspect is shown for the scope of this paper in Figure 1, where the hardware is surrounded by data spaces and the major functionality is provided in the industrial metaverse. For further information on such systems, chapter 2.2 in [1] is recommended. Given that all necessary aspects of the assets are available digitally, it is possible to establish behavior models of the assets. On the basis of this holistic digitalization, it is possible to set up continuous digital assessments and automated decision-support instances to assist experts. In future this will extend to autonomous decision-making instances. These will support the workforce and management to tackle the previously described challenges. Furthermore, the autonomous decision-making instances will evolve the whole system over time and adapt it to future challenges.

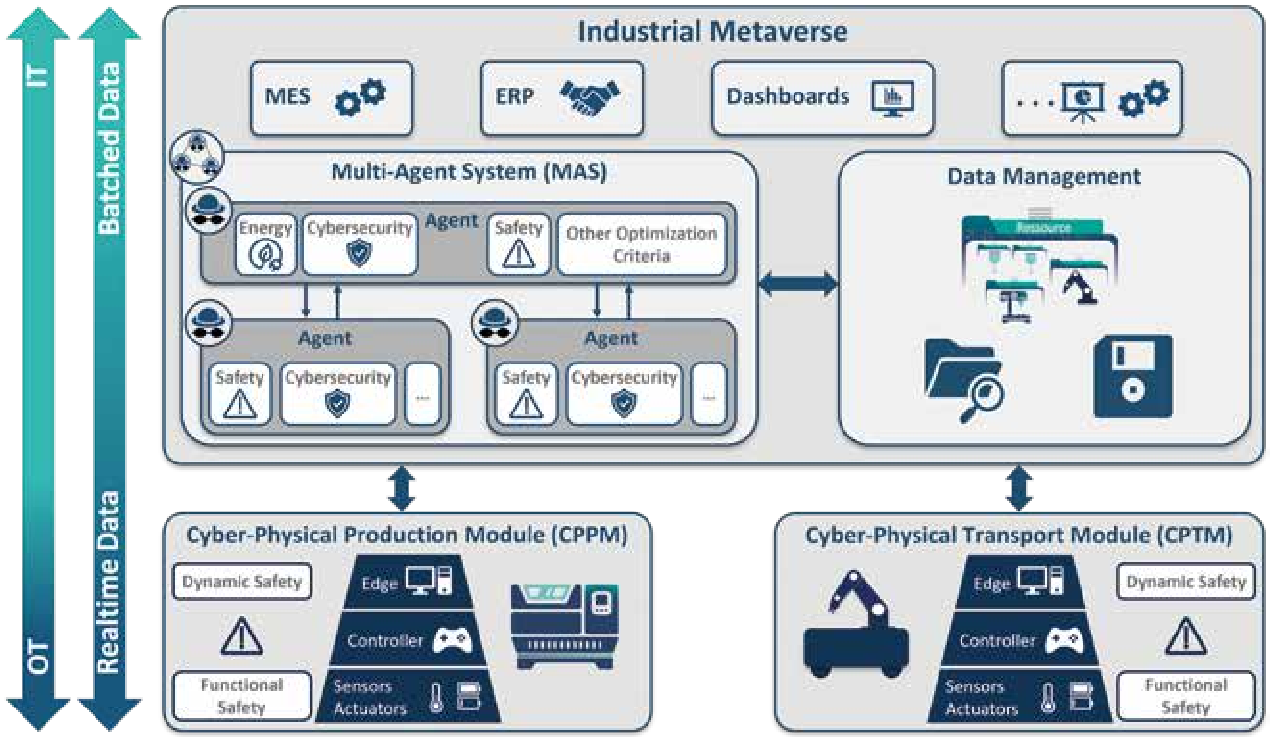


Figure 1 Sketch of the holistic digital solution space. Including hardware in dark blue and the surrounding data spaces as grey boxes

3.1 Building Blocks

Digital representations of assets
The digital representations of assets such as machines, products, materials, or workforce contain static information such as certain characteristics, manuals, or protocols, which need to be digitized in a machine-processable manner. In addition, online data, e.g. from sensors, must be included in order to obtain a comprehensive picture of the state of the system, which flows into the digital behavioral model including physical properties [2].

Digital representation of processes
Representations of processes are available digitally. These are machine-processable descriptions of the workflows of a company. This allows for automation and proper consideration in the digital system. The digital representations should cover the main value creation processes, such as manufacturing or work processes, which require specific functions or skills at certain locations and times. Auxiliary processes, like maintenance, should also be included to ensure holistic digitalization and ultimately this opportunity of a holistic risk and compliance assessment and decision support

Digital representation of context and environment
In order to achieve holistic digitalization it is necessary to digitally represent the context and the environment of the previously mentioned assets and processes. Without proper understanding of the context, automated systems will not be possible. This is a crucial topic, that is still often overlooked or handled by humans and which limits digital solutions today. The context in the digital industrial space is created automatically by mapping the asset interactions in the digital twins (DT) in the virtual workshop while considering the active production and auxiliary processes.

Digital behavioral models
Digital behavioral models describe how the assets will act under certain conditions and detail their skills and capabilities. The combination of the behavioral models will then enable insightful predictions of the performance and dynamics of the system. The models must be available in adequate granularity, such as appropriate temporal resolution: while production processes might need runtime simulations, maintenance requires degradation states over years.

Digital representation of evaluation criteria
Evaluation criteria must be digitally represented to ensure compliance and operational success. Regulatory requirements include health, safety, environmental, cybersecurity, insurance or other requirements. Operational requirements cover production goals with target functions (e.g. minimal resource usage), maintenance, warranty requirements from machine suppliers, and other business Key Performance Indicators (KPIs).

Digital assessment and decision-making instance
Digital assessment and decision-support or in future a decision-making instance should be established for automatically prepared or autonomous decisions, for instance by utilizing a multi-agent system (MAS) distributed across various levels. At the system level, strategic planning decisions are made, while at the asset level, operational decisions are handled, often in a time-critical manner. Each level should consider relevant aspects of its domain according to the evaluation criteria, with appropriate time horizons for decision-making.

3.2 Requirements on Digitalization Technology

For the technologies utilized the following operational and structural requirements apply:

- **Trustworthiness:** Security, privacy, safety, reliability and resilience of the entire cyber-physical production system (CPPS) [3] [4].
- **Interoperability:** For communication between systems and for breaking down data silos.
- **Adaptability:** Supports frequent functional and product changes, allowing systems to evolve.
- **Scalability:** Accommodates growing volumes of assets, data and user demands.
- **Modularity:** For a flexible and scalable system design.

Data quality
In order to draw valuable conclusions with confidence, it is strictly necessary to maintain a high quality and integrity of data. This means that data needs to be trustworthy, especially in terms of security, privacy and reliability, and the data must be contextualized by adding semantic information. This allows for validation and verification of the data and hence of the whole system. In general, the data needs to be manageable and to fulfill the availability requirements.

Governance considerations
Governance considerations contain operational as well as compliance aspects. For instance, compliance requires a formalized hazard and risk language. Risk assessments including rules and constraints must be tailored to the time horizon and the industry domain under consideration. Furthermore, the currentness of the respective evaluation criteria needs to be ensured. The entire system of digital representations, evaluation criteria as well as the assessment and decision-making instance must comply with cybersecurity and data protection regulations during both design and operation.

Quality assurance
Quality assurance involves rigorous verification and validation of data and models. Third-party monitoring systems may be necessary for liability or trust reasons. This goes hand in hand with a necessary traceability and verifiability of decisions to ensure all actions can be reviewed and justified. Measures taken must avoid retroactive effects that could compromise system integrity. The corresponding framework conditions include the availability of standardized digital tools as well as tested and certified procedures for release and compliance.

4. Digital Transformation Strategy

From a management perspective, the focus is on how to achieve the business objectives arising from current industrial challenges by exploiting the technological vision described in the previous chapter. Therefore, the following section focuses specifically on the management perspective of digitalization and demonstrates the business value of holistic digitalization. It also details the key requirements that must be met to ensure the effectiveness and sustainability of the digital transformation process.

4.1 Paths to and through Digitalization

A possible digital transition strategy should cover these topics:

- **Business objectives:** The individual goals, more specifically the value creation, that digitalization should achieve.
- **Evaluation of the current state:** Determine what is already available at the company.
- **Digitalization strategy:** A step-by-step approach.
- **Employee training:** Build-up awareness of system capabilities.

The first step is to analyze the current state of digitalization. Particular attention should be paid to evaluating the main processes, i.e. the way in which the company makes money. In particular, it is important to set clear objectives for how value creation should occur in a digitalized world. Thus, this step defines the goals of digitalization, which can be measured against the current state, resulting in a gap analysis.

The transformation towards holistic digitalization cannot take place in a single step but should be implemented gradually as part of an investment and product cost plan. Moving asset design and development to virtual and simulative environments is key. In addition, a complete description of the asset, its use and environmental conditions, as well as the mapping of regulatory requirements in the digital representation are essential. Synchronizing the digital representation as part of the asset management system enables efficient management and monitoring of asset usage.

Finally, it is important to involve the workforce in the digitalization process. Employees are experts on how value is created in the organization. Therefore, they need tools to support their daily work. In the future, there will be digital tools that require awareness and training to use effectively.

For a short-term implementation, the company internal architecture does not need to be eliminated or replaced. Instead, the digital environment is coupled with it to allow reduced effort data exchange. In the long term, the traditional and digital systems will increasingly merge. Step by step, this will lead to a holistic digitalization of the company, which will address the current challenges.

4.2 Assessment of the Transformation Progress

The progress of the transformation can be measured quantitatively by monitoring defined Key Performance Indicators. These KPIs enable early identification of deviations and corrective actions. The continuous evaluation of KPIs not only ensures precise control of the transformation process, but also supports an agile response to changing conditions in the production environment. As digital transformation continues, it becomes increasingly important to continuously and systematically assess the maturity of the implementation.

Field monitoring of assets is a key indicator, as it provides direct insight into the status and performance of the physical interfaces. In particular, the establishment of a synchronization loops that allows digital and physical assets to be operated in parallel and coordinated is essential. Also, the digital representation of assets plays a key role here: it not only serves as a test object for simulations and type tests, but also enables continuous validation and optimization of the operational status. Similarly, the digital representation of products provides a basis for verifying lifecycle compliance and makes a significant contribution to the transparency of production processes.

5. Technologies and Advanced Methods

This chapter presents technologies and advanced methods that can be used to compose the building blocks described in Chapter 3 "Digital Solution Space" and fulfill the posed requirements, e.g. trustworthiness. The implementation of these technologies, in conjunction with others, facilitates the establishment of a future-proof manufacturing system within a production environment.

5.1 Data Acquisition and Processing

Secure and structured data management is fundamental to ensuring trust in today's production environments. Efficient data acquisition, encryption and integrity management enable a seamless flow of information between physical assets, digital representations and decision-making systems - ensuring interoperability and security across the entire production network. Data acquisition includes real-time data collection from sensors, machines, and modules, as well as batch data processing. To achieve end-to-end security, data must be protected both in transit and at rest using encryption techniques and secure communication protocols. Integrity checking and redundancy mechanisms help prevent the tampering, loss or corruption of critical data, ensuring reliable and tamper-proof information. A centralized data management approach supports structured access control, using metadata to efficiently organize information while maintaining availability - even during network outages. Scalability and flexibility are also critical, enabling dynamic adaptation to increasing data volumes and supporting modular processing architectures. By integrating secure and efficient data management principles, industrial systems achieve high resilience against cyber threats, improved operational visibility and optimized decision making based on reliable, contextualized data.

5.2 Digital Twins

Digital twins are essential technologies in the digital solution space. They act as digital representations of physical or logical systems, enabling the capture, processing, and utilization of real-world data for optimization, decision-making, and analysis. In addition to mirroring production processes, they offer a wide range of practical applications:

- **Real-Time Monitoring:** Continuous tracking of machine and process states to enable quick responses to deviations or malfunctions.
- **Simulation:** Virtual testing and optimization of production systems or processes before physical implementation. Likewise, real-time synchronized digital twins can integrate predictive analytics to detect potential issues at an early stage.
- **Optimization:** Detailed analysis of production data to continuously improve processes, resource utilization, and particularly energy efficiency.
- **Safety and Risk Management:** Representation of safety guidelines and risk assessments within the digital twin, reducing extensive worst-case assumptions and allowing for context-specific adaptation of safety measures.

The Asset Administration Shell (AAS) is a key technology for the implementation of digital twins. It serves as a standardized interface and structured information management unit that provides metadata, status information, lifecycle data and security rules for an asset. The AAS is based on standards such as DIN SPEC 91345 (RAMI 4.0) [5] and IEC 62832 (Digital Factory Framework) [6] and its structure supports both interoperability between different systems and scenarios such as plug-and-produce.

5.3 Advanced Contextual Semantic Information

In today's manufacturing environments, traditional data models are increasingly unable to handle the growing complexity and variety of information. A more advanced representation is required to efficiently link and interpret heterogeneous data sources such as machine status, production parameters and safety guidelines. This semantic integration enables deeper insight into manufacturing processes and therefore more informed decision making. A key element in achieving such advanced representation is the use of ontologies and semantic models, which provide a formal structure for capturing knowledge from multiple sources and defining the relationships between data entities. To store and retrieve these often-complex relationships, graph-based databases are particularly valuable because they can model intricate relationships between data points in a highly flexible way. Building on these principles, knowledge graphs represent a promising approach that allows data points to be semantically linked and complex dependencies - such as those between production parameters and safety rules - to be transparently mapped. By visualizing these links, knowledge graphs enable early detection of inconsistencies or errors through automated plausibility checks, while effectively integrating safety and hazard rules along with their various interdependencies [7] [8]. In this way, a knowledge graph-based approach not only manages the complexity of modern production systems, but also supports dynamic, evidence-based decision-making.

5.4 Risk Number

Manufacturers and operators must carry out a risk assessment to identify and mitigate the risks associated with machinery and systems. This legal requirement places the onus on the manufacturer to evaluate all phases of the lifecycle and on the operator to consider factors such as the relevant operating conditions and the environment. For the manufacturer, risk assessment is part of the technical documentation and is usually completed after delivery and commissioning. For the operator, however, it is an ongoing process to identify risks and hazards throughout the lifetime of the machine.

Challenges of risk assessment:

- **Manual effort:** ISO 12100 [9] provides valuable help, but the process is often lengthy, laborious and dependent on experts. This is at odds with the current desire for flexible and fast production.
- **Normative static processes:** For operators, risk assessment is a continuous process that must be flexible due to dynamic production conditions.
- **Worst-case scenarios:** Without real data, assessments are often made based on worst-case assumptions, which increases costs.
- **Dynamic adjustments:** Rapid production changes can lead to risks being overlooked, incorrectly assessed or losing track of hundreds of pages of documentation.
- **Conformity:** In the event that the operator company makes substantial modifications to a machine then the operator effectively takes on the role of the manufacturer and assumes a manufacturer's responsibility for the conformity of the altered system.

A promising way to operate a compliant system is to perform an automated risk assessment at runtime using a digital twin. The digital twin simulates any necessary change and evaluates the safety of the system, eliminating the need to manually create or modify the risk assessment. Assisted or automated risk assessments lead to an increase in efficiency and a reduction of effort for the safety approval process. This can be achieved through the automatic calculation of a risk source.

$$\text{risk number}_{safety} = (\text{severity or impact}) * (\text{exposure and duration}) * (\text{occurrence of hazardous event}) * (\text{avoidance or limitation option})$$

While the extent of the damage can still be determined relatively well from the performance parameters, the probability of occurrence is the great unknown and therefore often leads to worst-case assumptions. This reduces the risk but increases the cost more than necessary by oversizing the measure.

Citation from ISO 45001:2023 [10]:

"Uncertainty is the state, even partial, of deficiency of information related to, understanding or knowledge of, an event, its consequence, or likelihood."

Uncertainty can be reduced through available data and the digital twin:

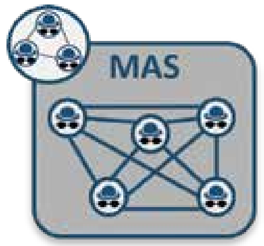
- **Automated risk assessment:** Enables risk assessment in the form of a risk score by quantifying the risk.
- **Expert support:** Supplements expert judgement with real operational data.
- **Objective assessment:** Converts subjective assessments into objective, automated risk metrics.
- **Requirements:** Requires machine-processable safety knowledge and trusted data.
- **Data base:** Uses live data, historical data and expert judgement.
- **Increased efficiency:** Reduces worst-case assumptions and enables situation-aware safety measures.
- **Regulatory compliance:** Facilitates compliance with standards and regulations.

Risk number calculation originates from the area of physical safety. In a cyber-physical system cyber security threats must also be considered. As described in [4] there is often greater latency in evaluating and responding to security events than is acceptable for time-critical safety-related events. Real-time safety must therefore continue to respond independently of the security state. The safety status and the security status must, however, be considered together to make risk assessments of the possible future trustworthiness of the system. This predictive trustworthiness in turn drives decisions on how to continue the production process.

$$\text{risk number}_{security} = \text{impact x occurrence (likelihood)}$$

Similarly to the risk number safety, it is also possible to derive a risk number in security since the risk here is also a product of the factors impact and occurrence. A precise definition of the parameters and their weighting will be part of future developments in this area.

5.5 Multi-Agent System



Multi-Agent systems (MAS) are modern approaches to controlling complex, dynamic production systems. They allow decentralized, automated decision-making and flexible adaptation to changing requirements. Instead of centralized control, individual units (agents) act autonomously, but work together cooperatively to achieve global system goals. This decentralization increases resilience by enabling decisions to be made locally and reducing the risk of single points of failure. It goes hand in hand with the principles of autonomy and cooperation: agents operate independently but dynamically allocate tasks among themselves to maximize efficiency. In addition, MAS are inherently modular, allowing individual components to be replaced or expanded with minimal disruption to the overall system. Another key advantage is their adaptability. They can respond flexibly to changes in the production environment, such as new requirements, varying workloads, or unexpected disturbances, without requiring a full-scale redesign. Equally important is the aspect of trustworthiness: each agent's actions and decisions can be traced, verified, and validated to maintain confidence in technology. This is especially crucial in industrial settings, where transparency and reliability are essential. It provides the basis for flexible, robust and adaptable production environ ments. A MAS structure for security integration has already been proposed in [8].

5.6 Verification and Validation

In a dynamic trustworthy architecture that integrates both safety and security aspects, mechanisms for verification and validation play a decisive role. They ensure that technical components and data not only function correctly (verification) but are also used reliably and contextually (validation). Validation means checking whether systems meet the defined requirements and work as expected in their intended environment. Verification, on the other hand, serves as proof that all implementations comply with the defined specifications. A central aspect is the context dependency of data. Information must be interpreted correctly depending on the application scenario, as it can have varying meanings in different environments. For example, the speed of an asset may be critical in one scenario and insignificant in another. Simulations, automated testing and contextual evaluation are used to implement these mechanisms. These methods help to identify potential errors or risks at an early stage and enable continuous monitoring of system reliability. Automated test procedures not only ensure data consistency and integrity but also provide the basis for automated certification. By continuously validating safety-critical parameters, conformance tests can be designed more efficiently, and regulatory requirements can be checked at run-time. This contributes significantly to the safety and efficiency of software-defined production systems.

6. SmartFactory KL Ecosystem

In the Production Level 4 ecosystem of ***SmartFactory*** KL [11], part of the production is controlled by a hierarchical MAS, as described in [12]. The hierarchical MAS is a central research object within our facility, where new concepts are developed, integrated into our demonstrator ecosystem and systematically evaluated. Besides the advantages of MAS described in section 5.5, the MAS is used as an active part of the digital twin and is combined with other digital twins technologies e.g. for data representation. The existing base architecture will be specifically extended with the concepts from [13] to realize an even more dynamic and resilient production environment. The individual handling of dangerous goods has already been successfully demonstrated in the previous ***SmartFactory*** KL white paper [9]. In addition, the system has been further developed in the area of autonomous mobile robots [14] in order to integrate enhanced safety mechanisms and optimized navigation strategies. The new components and their integration into the existing ecosystem are described in detail below.

To meet the increasing demands for modern, secure and trustworthy production systems, SFKL integrates two specific entities, Safety and Security, into the hierarchical SFKL MAS structure. These extensions enable dynamic, contextual evaluation and control of safety-critical processes, as well as ensuring data protection and integrity.

Safety Component

The safety component has the clear objective of proactively identifying hazardous situations and quickly initiating appropriate countermeasures without affecting the productive operation of a system more than necessary. It analyses relevant data, puts it into context and supports coherent decision making. Both historical information and live sensor data are considered, and DT technologies are used to realistically assess potential risks in advance. In modular production settings, changes in process steps or reconfigurations require rapid re-validation of safety parameters, for which the system can trigger runtime recertifications. By continuously monitoring context and asset states, these recertifications are achieved without extensive downtime or manual intervention. The result is efficient, end-to-end safety monitoring by distributed agents that protects the entire production process and enables flexible adjustments.

Security Component

All aspects of data processing in the industrial metaverse fall under cybersecurity best practices and applicable regulations for IT. The following considerations apply specifically to the level of agents and networked production equipment on the shop floor. The security component has the overarching goal of protecting data and communications across all agents without compromising ongoing processes. By continuously monitoring IT and OT communication flows, it detects and analyses potential threats at an early stage and reacts automatically to new threat situations. At the same time, critical information is encrypted both in transit and at rest to ensure integrity and confidentiality. Machine learning processes enable adaptive adjustment to new attack vectors, while a unified security strategy ensures that consistent policies are enforced at all levels of the system. The result is a context-adaptive security architecture that responds to potential threats and ensures long term compliance with current standards. This allows systems to be used to their full potential, as security and productivity requirements are continually balanced.

7. Conclusion and Outlook

This whitepaper outlines a digital solution space for a holistically digitalized and future-proof manufacturing system, emphasizing key technologies such as digital twins, automated risk analysis, and Multi-Agent Systems. It highlights the importance of integrating these technologies into existing plants, so that brownfield sites can seamlessly benefit from advanced methods such as run-time assessment and analysis. We show that the technologies needed to meet the challenges of the future are available today. The approach demonstrated by the ***SmartFactory***KL ecosystem offers benefits from bringing together expertise that drives innovation and adaptation in industries facing evolving challenges. Looking ahead, the development of digitalized production systems will increasingly rely on further advances in automation, the integration of smarter digital twins and improved real-time risk management. As market conditions and regulatory requirements evolve, systems designed today must be flexible and scalable. Cross-disciplinary collaboration, particularly through platforms, will be critical to creating and iterating on the necessary solutions. The future will prioritize the continuous exchange between experts, enabling the continuous testing and refinement of strategies and shaping industry standards.

SmartFactoryKL serves as an essential collaborative hub, providing real-world testing of the concepts outlined in this white paper. By providing a platform for experts to come together, it is driving the practical application of modular, interoperable systems in manufacturing. Through pilot projects and real-world experimentation, it bridges the gap between theoretical models and industry needs. Our role is central to driving technological innovation and enabling the seamless integration of modular, interoperable systems, making it a key enabler of flexible, adaptable, and future-proof manufacturing.

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