Journal of Machine Engineering, 2025, Vol. 25
ISSN 1895-7595 (Print) ISSN 2391-8071 (Online)

Received: *30 April 2025* / Accepted: *28 May 2025* / Published online: *05 June 2025*

systems integration,
empathetic technical systems,
resilient, human centered

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INTELLIGENT MANUFACTURING – A NEW UNDERSTANDING OF SYSTEMS INTEGRATION

The term "intelligent manufacturing" refers to the integration of technologies and systems to optimise the efficiency, flexibility or quality of processes in the context of industrial production. It describes a fully networked production environment in which machines, systems and humans communicate and cooperate. Traditional production methods are being transformed into data-driven, intelligent systems that are able to optimise themselves and react to changes such as disruptions in the production process. This paper analyses the relevance of a new understanding of system integration in the scope of "intelligent manufacturing" and derives the requirements for a target-oriented implementation in production. It also discusses the crucial role of interoperability between different systems and the need for a holistic approach to integration that includes not only technical aspects, but also corporate culture and employee skills. The concept of Empathetic Technical Systems is introduced, which are to be understood as a further development of cognitive systems and enable resilient production through empathetic cooperation. Finally, example scenarios are used to show how "intelligent manufacturing" can be realised with this new understanding of system integration.

1. INTRODUCTION

Disruptions due to unpredictable market and production conditions, such as order fluctuations and machine and personnel failures, have a negative impact on production efficiency. Efficient industrial production of goods requires the seamless interaction of different stakeholders. This requires humans, machines and processes to cooperate in an integrative manner by exchanging goods and information with each other via defined interfaces. System integration is a common approach to ensuring efficiency of production systems [1]. Horizontal integration in industrial production focuses on the end-to-end supply

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https://doi.org/10.36897/jme/205697

chain integration along the value chain. It aims to enable interoperability between processes, machines, and systems across different departments, companies, or sites. The scope of vertical integration is the integration of production levels from shop floor sensors to enterprise management within a single production site of a company [2]. System integration in the production industry is a necessary prerequisite and a key to improving competitiveness in high-wage countries and consolidating the market leadership that still exists there in some areas. Based on the understanding of classic system integration, it is essential to realise holistic system integration. This results in need for integrative networking of the ecosystems involved in product creation in the value chain. It is not enough for the human, machine and process stakeholders to communicate with each other. Rather, the production systems must be connected to the information technology and the production infrastructure in such a way that not only centrally planned processes in the value chain can be executed. It must also be possible to make decentralised decisions between purely technical systems such as machines and between humans and machines depending on the situation [3–6].

This leads to the need for rethinking the scope of system integration in production. The resulting requirements, which must go beyond cognition and digital networking, must be analysed and described in order to realise resilient production through cooperation. In the following, the history and transformation of system integration in the context of production is therefore explained in more detail. It is described which Industry 4.0 technologies are suitable for comprehensive system integration. In addition, the still open research questions that need to be scientifically investigated for the implementation of resilient production through system integration are highlighted. Finally, a conceptual perspective on cooperation using the research approach of Empathic Technical Systems is presented using an example.

2. SYSTEM INTEGRATION IN PRODUCTION SYSTEMS

With his statement “The whole is more than the sum of its parts”, the Greek universal scholar Aristotle created an early definition of a system that is still valid today and can be seen as the basis for the science of general systems theory [7]. There, a system is defined as “… a complex of interacting elements. Interaction means that elements, *p*, stand in relations, *R*, so that the behaviour of an element *p* in *R* is different from its behaviour in another relation, *R′*. If the behaviours in *R* and *R′* are not different, there is no interaction, and the elements behave independently with respect to the relations *R* and *R′*.” [8]. In general, systems can be divided into closed and open systems, whereby open systems interact with their environment while closed systems do not. In practice, most systems are open systems, as they interact with other systems and these interactions influence each other. Thinking in terms of more or less closed systems helps to reduce complexity and to model individual processes for the purpose of analysis.

A production system can be defined as a system that transforms inputs, e.g. raw materials or semi-finished products, into outputs, the actual products, with the help of well-organised interacting elements, e.g. humans, machines and processes. As effective and efficient production can only be achieved if there is a smooth interaction between humans and technology, a production system is also referred to as a socio-technical system [9].

The term system integration is closely related to information and communication technology and the desire of companies to make their business processes more efficient through automation. The essential exchange of data between different computer systems and software applications made it necessary to interconnect them. However, integration of systems has played an important role in industrial production at least since the introduction of Taylorism in the context of assembly line production. For the realisation of mass production, the systems for the individual work steps were linked mechanically together via a conveyor belt in such a way that a new system was created. This was a purely mechanical form of system integration in which the workstations of the successive work steps were rigidly connected to each other to ensure efficient production. This mechanical integration enabled the precise control and synchronisation of production steps, but also led to a strict, inflexible organisation of work. Production lines were designed to produce a high volume of identical products with minimal variation. This was an effective measure in stable environments but offered little flexibility for change. With the third industrial revolution, when information technology and automation were introduced, the picture of system integration changed. The use of Computerised Numerical Control (CNC) and Enterprise Resource Planning (ERP) systems led to further vertical and horizontal integration in production. With the concept of "Computer Integrated Manufacturing" (CIM), not only the computer systems in the offices were interconnected with each other in order to exchange administrative data, but the production systems were also included in this networking. This not only led to better planning of production processes, but also to a more efficient execution of these processes, as the production systems were now able to report their work progress back to the planning systems. However, the integration possibilities of the systems were also constrained by the fixed hierarchical structure of the automation pyramid, which limited flexibility. Furthermore, restricted technological possibilities for data acquisition and communication hindered a comprehensive system integration. [10]. With the introduction of Industry 4.0, the transformation of production systems to Cyber-Physical Production Systems (CPPS) was strongly accelerated. CPPS are characterised by their cognitive capabilities. They are able to use sensors to perceive their environment, process the collected data locally and communicate with other systems in the Industrial Internet of Things (IIoT) [4, 5, 11–13]. After research initially focused mainly on the investigation of Industry 4.0 technologies and their use to achieve self-organised production, the focus shifted to applications and humans as an indispensable element in production, often called Industry 5.0 [14]. Research aims to investigate how humans and CPPS can work together in an integrative manner in order to combine the unique capabilities of both sides as efficiently as possible [15–18]. The technologies of Industry 4.0 and the focus on application and human-centricity of Industry 5.0 are demonstrating new possibilities for system integration in intelligent production. These are largely based on the complete and flexible networking of all systems involved in the value chain to create seamless interoperability.

3. SYSTEM INTEGRATION WITH DIGITAL TWINS IN INDUSTRY 4.0

A digital twin is generally understood to be a virtual representation of a physical object or process, whereby data is continuously collected from the real object in order to gain insights into its condition and behaviour. This allows the real object to be monitored, simulated and controlled. The concept of the digital twin as it is generally accepted in the context of Industry 4.0 was created by Grieves and Vickers in 2001 and published in 2002 in the article "Conceptual Ideal for PLM" [19].

Digital twins are a prime example of system integration, as they enable industry to connect real objects and processes with digital models and exchange information for optimisation in the meaning of the Digital Factory. They enable the complete integration of all subsystems in a factory. This paves the way for the vision of self-organising production, in which the hierarchical order according to the classic automation pyramid and the concept of central planning and control are dissolved. CPPS form the information basis for digital twins, as they enable the transfer of data from the real physical object to its digital representation in the cloud and vice versa using the IIoT. For comprehensive system integration using Digital Twins the creation and establishment of commonly accepted standards that regulate not only the technologies used but also the content is necessary. Therefore, the IDTA was founded in Germany in March 2021 by a consortium of 23 industrial companies and associations such as the Mechanical Engineering Industry Association (VDMA) and the Association of the Electrical and Digital Industry (ZVEI). The aim of the constantly growing community is to establish the digital twin as a core technology of Industry 4.0 and to develop it to market maturity. This is to be achieved by creating a standard for digital twins through the definition of content for digital twins of production systems and the provision of partial model templates. The Asset Administration Shell (ASS), which can be seen as the technological implementation of the Digital Twin concept in Industry 4.0, plays a central role here. The ASS makes it possible to create standardised and manufacturer-independent interoperability for systems in industrial environments, which is a fundamental prerequisite for the integration of the various production systems in the digital factory [20].

This provides the prerequisites for holistic system integration in which all systems involved in value creation can interact with each other. However, since production systems, as already mentioned, are socio-technical ecosystems that are subject to internal and external influencing factors, new concepts must be developed that enable flexible and cooperative decision-making. One approach is the introduction of Empathetic Technical Systems.

4. EMPATHETIC TECHNICAL PRODUCTION SYSTEMS

The research approach of using cognitive systems in production goes beyond mere data acquisition and communication. It furthermore focuses on bringing intelligence into CPS by the integration of methods from the field of Artificial Intelligence. Such systems are able to perceive their own state and the state of their environment. From this information, they can device decisions and adjust their behaviour following a given goal. Nevertheless, their capabilities for efficient cooperative action are limited by the lack of knowledge about the objectives of the involved actors and the overarching corporate goals [21].

To address this still open question, the transfer of empathy to technical systems can be helpful. This approach enables a novel system type with cooperative capabilities, referred to as Empathetic Technical Systems. Empathetic Technical Systems are understood as entities of a production system that can capture and understand the state and intentions of other actors through information technology, and can incorporate the insights gained into their own action planning. Systems of this kind form the basis for improving human-technology interaction and the cooperation of autonomous technical systems in the context of production. This approach differs from that of empathic systems. The research field of ‘empathic systems’, which has been known for many years, focuses on systems that can recognise and react to human emotions in order to enable a more intuitive interaction between humans and technology. These systems utilise sensors, AI and data analysis to interpret the user's emotional state and react accordingly. The term ‘Empathic Technical Systems’, as defined by the Fraunhofer project, emphasises the integration of empathic behaviour into technical systems. This is not about recognising human emotions such as sadness, anger or joy, but about recognising physical states such as declining performance due to, for example, fatigue in humans or wear and tear in production systems.

There are numerous definitions of empathy in the literature [22]. In general terms, empathy refers to the ability to put oneself in another person's situation. This enables humans to integrate other people's values into their own and take on new social roles. Empathy facilitates communication between humans, improves the ability to anticipate other people's behaviour and improves cooperation. Regarding technical systems, empathy can be seen as a higher level of cognition of technical systems, as it goes beyond pure data processing and enables a higher quality of cooperation. Empathy enables technical systems to perceive the perspective of other systems by having information about their goals, states and control variables and thus to flexibly adopt their roles and tasks. The concept of Empathetic Technical Systems, which is being researched in the Fraunhofer Gesellschaft's flagship project EMOTION, aims to transfer the bio-inspired idea of empathy to technical systems in industrial production as decision support in the event of conflicting goals in cooperative scenarios [23]. The information technology integration of humans as an essential part of the production system is also taken into account by the integration of digital assistance systems. To achieve this, it is necessary for all systems to be aware of the overarching company goals and, if necessary, to set aside local goals in order to achieve them. This is intended to create increased resilience to unexpected disruptions, e.g. due to the unavailability of production facilities, materials or employees. For a better understanding, the concept of Empathetic Technical Systems is described in more detail below and then made tangible using an exemplary scenario.

Through digital networking, system integration and cooperative decision-making mechanisms for multi-criteria problems, empathetic production aims to improve the ability to adapt, learn and react and thus increase resilience in production. Empathetic cooperation between AI agents is based on the use of the AAS, which enables the standardised provision of Digital Twins for humans, machines and processes. In this context, the agents represent an extension of these Digital Twins by integrating cognitive abilities with the ability to empathise. A central element here is the so-called EMOTION vector. It serves as a compression method for high-dimensional status information of the real objects in order to ensure efficient data processing and effective data exchange. As shown in Figure 1, in the platform for empathetic production systems, the integration layer connects the physical layer with the data management layer and the agent layer. Connectors for data acquisition are used to collect the data required for decision-making and to communicate it to the data management level via IoT protocols such as MQTT or OPC UA and the AAS of the respective physical object. There, the data is processed and compressed into information that enables the agents to make empathetic decisions. The decision is made on the basis of the status information and a balancing of the differing goals of the stakeholders against the overarching company goals as a compromise between selfish and altruistic behaviour in a cooperative way.

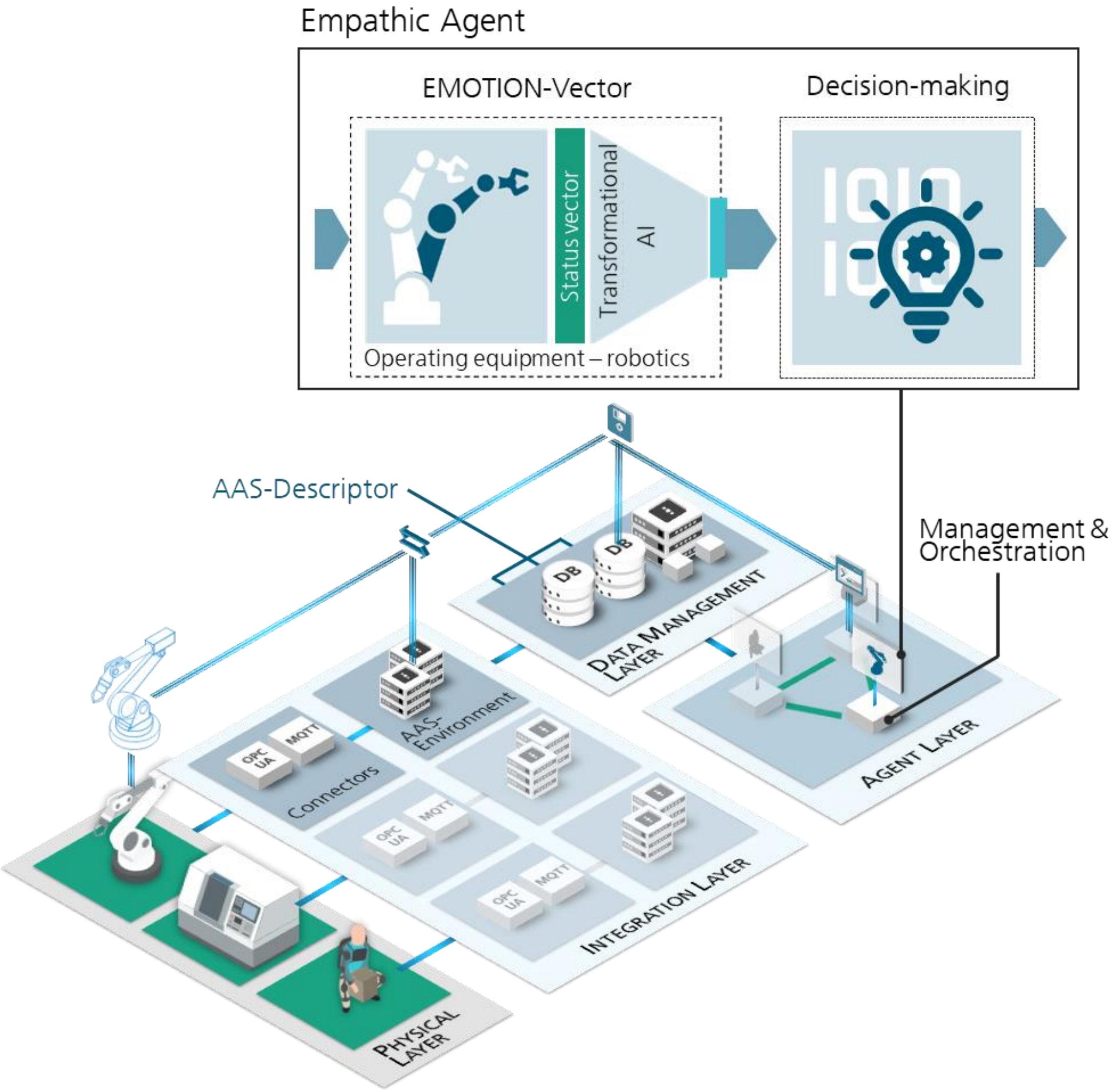

Fig. 1. Platform for Empathetic Production Systems

The example of the conflict of interest in work order processing by machine tools shows what an empathetic decision can look like in the event of an impending machine failure. In principle, the machine tools have the goal of processing the work order assigned to them on time, which corresponds to selfish behaviour. Cancelling their own work order in favour of processing an order assigned to another machine tool, on the other hand, corresponds to altruistic behaviour.

A machine tool equipped with a condition monitoring system is able to determine the deterioration of its health status. For example, if the machine tool detects that the current order cannot be completed in time due to an impending failure of the main spindle, it communicates its status to the other machine tools in the factory. These machines first check whether they are technologically capable of taking on the job. In this case, the next step is to check whether they themselves have an assigned order and how relevant the processing of their own order is for achieving the overarching company objectives. The machine then analyses whether the effects of cancelling its own order jeopardise the achievement of the company's overarching goals less than a breakdown-related failure to meet the delivery deadline of the essential order. Finally, the machine communicates the decision and takes over the essential order of the machine at risk of failure. The empathetic agents are then used for local replanning and the maintenance organisation unit is informed about the condition of the machine at risk of failure so that it can be restored to a functional condition as quickly as possible.

This cooperative decision-making process characterises Empathetic Technical Systems. It is only possible if the stakeholders involved are aware of their own goals as well as the goals and conditions of the other stakeholders in the factory. This allows them to assess the consequences of the decision for achieving the overarching corporate goals.

5. SUMMARY

The article points out the central importance of system integration in the context of intelligent manufacturing. The meaning of the term system integration is analysed in more detail and it is shown how system integration for Industry 4.0 can be implemented with the help of technologies such as the digital twin, the asset administration shell and multi-agent systems. In addition, the concept of empathetic technical systems is introduced and it is shown how these systems lead to a new perspective on the understanding of system integration and how they contribute to the vision of self-organised production.

ACKNOWLEDGEMENTS

This work was supported by the Fraunhofer flagship project EMOTION.

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