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ORIGINAL PAPER

MANAGING INDUSTRY 4.0 INTEGRATION - THE INDUSTRY 4.0 KNOWLEDGE & TECHNOLOGY FRAMEWORK

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ABSTRACT. **Background:** This paper has the aim to address the key area of managing complex Industry 4.0 production systems to support a successful adoption and integration of Industry 4.0. This is achieved by approaching methodological research challenges of Industry 4.0 in the form of lacking reference models and the need to establish common definitions of fundamental concepts. The general underlying challenge this paper aims to contribute to solve can therefore be defined as how the technological advances, like CPS, IoT, Big Data or CC can be best linked with each other on different levels of perspective and how they can be used by decision-makers to generate economic value and to improve existing processes. This is achieved through the introduction of the Industry 4.0 Knowledge & Technology Framework (IKTF).

Methods: The Industry 4.0 Knowledge Framework (IKTF) is based on the concept of the micro-meso-macro analysis framework and consequently is representative for the approach of micro-meso-macro analysis in managerial practice. It proposes three categories of factors and places them in three basic levels layering them on top of each other. The macro-level includes the financial, political and sociocultural factors that influence Industry 4.0. The meso-level includes the technical and organizational factors. The micro-level refers to individual factors, particularly individual companies' intention to use Industry 4.0 in practical economic contexts.

Results: The Industry 4.0 Knowledge & Technology Framework (IKTF) provides guidance to corporate decision makers by providing a comprehensive, multi-level sequential integration framework for Industry 4.0 based on a sequential micro, meso and macro perspective analysis of the individual corporate context. The aim of the IKTF is to support an informed and successful managerial decision-making process and therefore enable the integration of Industry 4.0 in a corporate context.

Conclusion: As a first step, the structure, and contents of the IKTF are sequentially introduced and described. In a second and final step the functionality and applicability of the IKTF are demonstrated and discussed on a theoretical and practical level with the help of a case study.

Keywords: Industry 4.0, Smart Factory, exponential technological change, cyber-human systems, cyber-physical systems.

INTRODUCTION

Accelerating technological developments and the changes induced by the so-called exponential disruptive technologies lead to the necessity for companies to integrate new manufacturing methods in the form of Industry 4.0. This development is expected to allow companies to anticipate and utilize the potency of current and upcoming technological advancements in production technology and to leverage existing competitive advantages while unlocking new progress. The rising potency of technology in areas like general computer processing power, sensors, artificial intelligence, machine learning algorithms, robotics and automation technology breaks through the limits of the anticipated growth rates of traditional technologies and manifests in more radical visions for changes in industrial production systems [McAfee and Brynjolfsson, 2014, Fraunhofer IPT, 2019]. Underlying drivers for the possible exponential

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development of technology are the often mentioned “Moore´s Law” which shows that the number of transistors per microchip increased by the power of 10 in the last 40 years , “Metcalf´s Law” can also be mentioned which states that computing hardware becomes more powerful, small and more embedded over time and the vastly increased and ever increasing speed of technology adoption by users. “Butter´s Law of photonics” says that the amount of data one can transmit using optical fiber is doubling every nine months. “Rose´s Law”, which states that the number of qubits in quantum computers is growing exponentially and the concept of “Big Data” referring to the exponential growth of information generated by modern information systems. [McAfee and Brynjolfsson, 2014, Gimple, Röglinger, 2015]. In addition to the accelerating impact of disruptive exponential technologies, industrial production is driven by a hyper-competitive rivalry for market shares between formerly separated industries caused by a more global, digital and interconnected market environment [Turgay, Emeagwali, 2012]. Technology induced market disruption and the resulting volatile and complex market environments are expressed through constantly changing, more individualized customer requirements and shorter product lifecycles. These developments can be regarded as the determining factors for the successful development process of a market-oriented industrial production with a high-tech methodology that can fulfill the requirements of current and future market environments [Vaidya, Ambad, Bhosle, 2018 Lee, Bagheri, 2015]. These aspects are furthermore accelerated by the COVID-19 pandemic, a global “black swan” event which inflicts high and rising human and economic costs world-wide and as a result enforced a global partial or total lockdown of most facilities of production [Congressional Research Service, 2020, World Economic Outlook, 2020]. The vision of Industry 4.0 can be regarded as a potential answer to overcome the described current and future technological, social and economic challenges that disrupt the functionality of the traditional manufacturing paradigm of embedded production systems, computer systems that have a dedicated function within a larger technical system, as the primary systemic approach for industrial mass production in traditional market environments [Rojko, 2017, Pilloni, 2018]. The concept of Industry 4.0 requires a converging combination of digitized, intelligent systems of production through the means of emerging enabling technologies primarily in the form of cyber-physical systems (CPS), Internet of Things (IoT) and cloud computing (CC) [Rojko, 2017, Pilloni, 2018, Xu, Ling, 2018, Morrar, Arman, Moussa, 2017, Savastano, Amendola, Bellini, D`Ascenzo, 2019, Roblek, Mesko, Krapez, 2016]. The concept of Industry 4.0, therefore, represents, in theory, a transformative, evolutionary advancement from traditional embedded systems in manufacturing to smart industrial production systems defined by autonomous, interconnected CPS. This transformation is expected to allow the successful change from a more standardized mass-production system to a customizable, flexible, cost-efficient and demand responsive production that can efficiently fulfill the requirements of volatile market environments [Rojko, 2017, Pilloni, 2018, Savastano, Amendola, Bellini, D`Ascenzo, 2019, Roblek, Mesko and Krapez, 2016]. Even though the vision and the concept of Industry 4.0. are already well-described on a theoretical level, several unsolved challenges on the technological, integrative, and general level of understanding remain to be better understood and captivated [Savastano, Amendola, Bellini and D`Ascenzo, 2019, Roblek, Mesko, Krapez, 2016]. These challenges effectively inhibit a successful integration of the concept of Industry 4.0 in applied manufacturing systems and that until now, only a limited number of companies achieved performance increases through the integration of aspects of Industry 4.0. [Roblek, Mesko, Krapez, 2016]. It can therefore be concluded that the concept of Industry 4.0 while still not fully developed, is ambiguously connected to a variety of other meta-concepts or sub-concepts, like VUCA environments (Volatility, Uncertainty, Complexity and Ambiguity) [Gimpel, Röglinger, 2015]. This requires further academic investigation to explore possible trajectories of development and to enhance the overall understanding of the contained inherent characteristics of decision-making in a VUCA and Industry 4.0 context [Rojko, 2017, Pilloni, 2018, Savastano, Amendola, Bellini, D`Ascenzo, 2019, Roblek, Mesko, Krapez, 2016].

MOTIVATION

This paper has the aim to address the key area of managing complex Industry 4.0 production systems to support a successful adoption and integration of Industry 4.0. This is achieved by approaching methodological research challenges of Industry 4.0 in the form of lacking reference models and the need to establish common definitions of fundamental concepts. The general underlying challenge this paper aims to contribute to solve can therefore be defined as how the technological advances, like CPS, IoT, Big Data or CC can be best linked with each other on different levels of perspective and how they can be used by decision-makers to generate economic value and to improve existing processes [Thoben, Wiesner, Wuest, 2016].

The paper furthermore presents an improved version of the Industry 4.0 Knowledge & Technology Framework (IKTF) developed by Freund & Al-Majeed [Freund and Al-Majeed, 2020] and is build upon the research conducted by Freund & Al-Majeed and Millard in the area of complex systems management and cyber-physical systems [Freund and Al-Majeed, 2021, Freund, Al-Majeed & Millard].

The IKTF has the vision to guide decision makers to better understand the concept of Industry 4.0, its core concepts and how these concepts are related to each other in a coherent, sequential manner on three levels represented by a micro, meso and macro level of analysis. By achieving this the IKTF allows decision-makers to pinpoint their company's integration status and to support the overall proactive integration of Industry 4.0. One application example is the retrospective analysis of historical cases, as demonstrated in the final section of this paper. The aim of IKTF is to represent a coherent and logical analytical overview and support tool for the initial phases of Industry 4.0 integration thought process in a corporate context. In a next step, the core concepts and technological manifestations contained in IKTF are introduced and explained in further detail.

IKTF CORE CONCEPTS

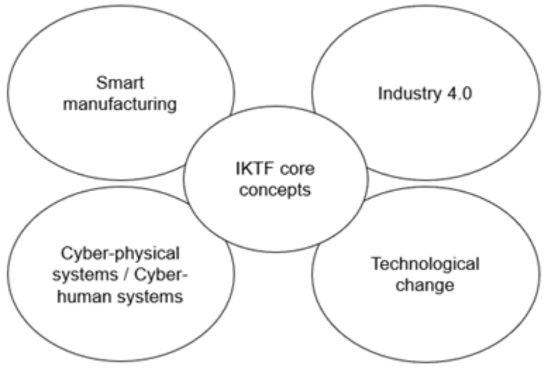


Fig. 1. IKTF core concepts

Figure 1 displays the underlying core-concepts of the IKTF. The core-concepts of IKTF, Industry 4.0, Smart Manufacturing and cyber-physical system architecture, cyber-physical systems, cyber-human system and technological change are now defined in more detail and provide a basis for the introduction of the IKTF in a later section of this paper.

INDUSTRY 4.0

Industry 4.0 is a manufacturing approach based on the integration of emerging technologies, like CC, CPS or IoT, in the business and manufacturing processes to achieve superior production capacities. The economic potential of Industry 4.0 is thus expected to be significant; for example, the German gross value is assumed to be increased by 267 billion euros by 2025 after the introduction of Industry 4.0. [Lee, Bagheri, 2015]. The technical aspects of the requirements of a successful integration are primarily addressed by the application of the concepts of Cyber-Physical Systems (CPS) [Rojko, 2017, Pilloni, 2018]. Any Industry 4.0 concept is therefore based on the connections of autonomous CPS building blocks. The CPS blocks are potentially heterogenous embedded systems equipped with intelligent, decentralized control and advanced connectivity. These blocks have the central ability to collect and exchange real-time information with the goal of monitoring and optimizing the production processes [Rojko, 2017, Pilloni, 2018, Savastano, Amendola, Bellini, D`Ascenzo, 2019, Roblek, Mesko, Krapez, 2016]. The technologies introduced by Industry 4.0 thus enable autonomous intelligent communication and cooperation among CPS, so that a higher level of intelligence, and therefore a higher level of flexibility and performance, can be achieved in industrial manufacturing processes. Industry 4.0 is thus assumed to enable three core aspects namely digitization of production, automatization of production and intelligent data interchange. As a logical consequence, the manifestation of Industry 4.0 is often exemplified through the concept of a smart factory. (SF) [Nagorny, Limo-Monteiro, Barata and Colombo, 2017].

SMART FACTORY

Smart manufacturing systems are largely autonomous, non-hierarchical physical and logical capsulated systems based on the Industry 4.0 concept that form a complex manufacturing ecosystem. These systems are often summarized under the term smart factory (SF). SF systems are heterogeneous, loosely coupled, cyber-physical systems that again accumulate in a cyber-physical system architecture, a cyber-physical system of systems, the smart factory. SF uses information to continuously maintain and improve performance and can be expected to be producing a high variety and volume of data due to the interconnected nature of the contained CPS [Mittal et.al., 2019, Freund, Al-Majeed, 2020]. Traditionally, manufacturing was defined as a sequence of processes through which raw materials were converted into finished goods for a fixed market. SF aims to integrate the properties of self-assembly to produce complex and customized products to exploit the new and existing markets [Gaham, Bouzouia, Achour, 2013].

CYBER-PHYSICAL SYSTEM ARCHITECTURE

A cyber-physical system architecture describes the overall integration approach of CPS to construct and achieve value creation in a manufacturing system.

CYBER-PHYSICAL SYSTEM

A CPS can be described as a new generation of systems that blend the knowledge of physical artifacts and engineered systems due to integrated computational and physical capabilities. CPS are established in order to produce a global intelligent behaviour featuring autonomy, self-control and self-optimization and are expected to be a decisive driving force for advances in different applicative domains including manufacturing control and for opening up new areas of innovation [Horvarth and Gerritsen, 2012, Schiliro, 2017]. CPS are characterized by advanced connectivity that ensures real-time data acquisition from the physical world and information feedback from the cyber space and intelligent data management, analytics and computational capability that constructs the cyber space. (Lee and Bagheri, 2015) CPS are also connected with high system complexity and contains an inherent trade-off relationship between the drawbacks of complexity and the performance increases gained [Freund and Al-Majeed, 2020].

CYBER-HUMAN SYSTEM

A CHS means that humans have an increasingly interconnected relationship with digitized and digital systems and represents an integral factor to establish a functioning CPS. This development is exemplified in the increasing human-machine interaction through new computer systems, the internet, mobile devices, improved sensor technology and possible future applications like brain-machine interfaces and leads to human lives and decision-making increasingly merging with technology [Gimpel and Röglinger, 2015, Horvarth and Gerritsen 2012].

Figure 2 now illustrates the concept of CPS and CHS [Freund & Al-Majeed, 2020].

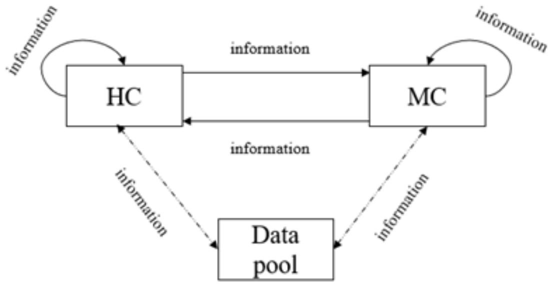


Fig. 2. CPS example

Figure 2 shows that an exemplary CPS architecture can be described as a closed loop heterogeneous system of a constellation of machine (MC) and human (HC) units with data interaction enabled through a reflexive and irreflexive multi-directional information flow with a shared data pool [Freund and Al-Majeed, 2020]. As a result, the illustrated structure of a CPS is characterized by highly interconnected constellation of heterogeneous agent types situated in reinforcing information diffusion and generation feedback loops.

TECHNOLOGICAL CHANGE

The term technological change is a positive transition of a system from a technological level (A) to a more advanced technological level (B) in a given transition time period (t). If the transition time periods between a series of technological levels Δ(t) decreases in an exponential manner exponential technological change can be identified. The transitioning from a technological level (A) to technological level (B) shall furthermore encompass the emergence of new and more potent technologies, like more productive and efficient tools, facilities or services (for example robotics or the internet) and the diminishment of less potent technologies. It also contains the habitual and institutional adjustments conducted by the society employing and interacting with the technologies. It shall therefore be assumed that technological change can be regarded for a company as a main impact factor of corporate structural change responding to external market incentives that drive competition and economic growth [Romer, 1990, Hochwallner and Ribeiro, 2018].

METHOD

The Industry 4.0 Knowledge Framework (IKTF) is based on the concept of the micro-meso-macro analysis framework and consequently is representative for the approach of micro-meso-macro analysis in managerial practice [Dopfer, Foster, Potts, 2004]. The micro–meso–macro analytical framework represents a proven method of analysis in the social sciences and economics and can greatly enhance the focus, clarity and strength of decision quality in many decision-making contexts [Serpa, Ferreira, 2019]. It proposes three categories of factors and places them in three basic levels layering them on top of each other. The macro-level includes the financial, political and sociocultural factors that influence Industry 4.0. The meso-level includes the technical and organizational factors. The micro-level refers to individual factors, particularly individual companies' intention to use Industry 4.0 in practical economic contexts. This framework is useful in that it affords insight into the various factors that influence the integration and usage of Industry 4.0. It is also suggested that there is interaction between, and interdependence of the different factors. It also proposes different points of high relevancy for decision makers and planners when developing Industry 4.0 integration initiatives. The applied micro-meso-macro framework is an adaption of the model presented by Ly et. al and is now illustrated in Figure 3 [Serpa, Ferreira, 2019].

Figure 3 shows, that change is the defining property of meso (i.e. the origination of new rules and the technological dynamics), and coordination occurs as micro and macro structures adapt and change according to the meso-level dynamics. This makes visible that the micro level refers to the individual carriers of rules and decision makers in the organization and the systems they organize, and the macro level consists of the aggregated effect of the system dynamics of the meso level. The micro level is thus positioned between the elements of the meso, and the macro level is positioned between meso elements [Dopfer, Foster, Potts, 2004].

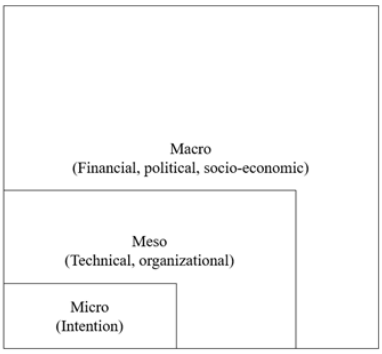


Fig. 3. Micro-Meso-Macro Analysis

THEORY SYNTHESIS

The definitions and concepts presented in this study are largely based on secondary sources and research, meaning a systematic foundational review of relevant literature. Information on the core research complexes “information”, “complexity” and “systems” is mostly available in (academic) books, professional journals, academic journals, reports or internet sources, mainly published in the research fields of philosophy, information technology, physics, engineering and business studies, as demonstrated by the following sections of this chapter. This paper quotes a wide range of sources in the form of basic theoretical considerations, expressed though the introduction and discussion of relevant definitions to allow a coherent pursuit of the previously mentioned aim of research through summarizing and synthesizing previous sources to develop a set of hypotheses out which directions for new future research may be derived. To allow the establishment of the IKTF core concepts in a coherent approach, a systematic review of relevant literature was conducted for this paper and in total 125 sources matching the scope of this article, in the form of academic journals and academic books of the mentioned academic fields, published between 2012 and 2021, were selected, individually read and reviewed by the authors and reduced by careful author selection to 29 key sources which served as the basis for theory synthesis of the presented framework. Theory synthesis has then be applied to define the in Figure 1 shown IKTF core concepts in more detail on the micro-meso and macro level.

After describing the applied methods for this paper, the Industry 4.0 Knowlegde & Technology Framework can now be presented in detail.

INDUSTRY 4.0 KNOWLEGDE & TECHNOLOGY FRAMEWORK

The Industry 4.0 Knowledge Roadmap (IKTF) can now be introduced and is based on the concept of the micro-meso-macro analysis framework presented in Figure 3 and consequently is representative for the approach of micro-meso-macro framework and its benefits for decision makers [Dopfer, Foster, Potts, 2004].

Figure 4 now illustrates the basic structure of the IKTF.

Figure 4 shows, that the basic structure of the IKTF follows an inverted Micro-Meso-Macro logic in which the macro-development level (M) is positioned at the bottom, followed by the meso level in the form of the framework level (F) and the micro level in the form of the integration level (I) at the top with transition indicators between each level. Each level follows the three-step (M1-M3, F1-F3, I1-I3) one-directional logic of displaying the most relevant Industry 4.0 concept for this level, followed by the resulting technological manifestations and the specific attributes in the form of socio-economic and technological impacts for the level. When the level internal logic chain ends a transition to the next level is implemented, as indicated by the arrows. It is also shown that the transition from (M) to (F) implicates a transition from the company external macro-environment to a company internal perspective, while (F) to (I) remain company internal. The external environment consists of an organization’s external factors that affect its business operations in an indirect manner. Thus, the organization has no or little control over these factors; that means, the external environment is generally assumed to be non-controllable and represented by (M). The internal environment describes forces or conditions or surroundings within the boundary of the organization represented by (F) and (I). The internal environment includes all assets contained within the boundaries of the organization. Some of these assets are tangible, such as the physical facilities, the plant capacity technology, proprietary technology, or know-how; some are intangible, such as information processing and communication capabilities. Consequently, decision makers can only use company internal assets in (F) and (I) as resources to make decisions in response to (M). In a next step, all IKTF levels are presented and described in more detail. The Macro Development Level (M) shall be defined as the larger and abstract level of understanding that stands above the other two levels of the framework. As already mentioned, (M) represents the company external world and the trends that impact Industry 4.0. (M) shall now be defined as the following level structure.

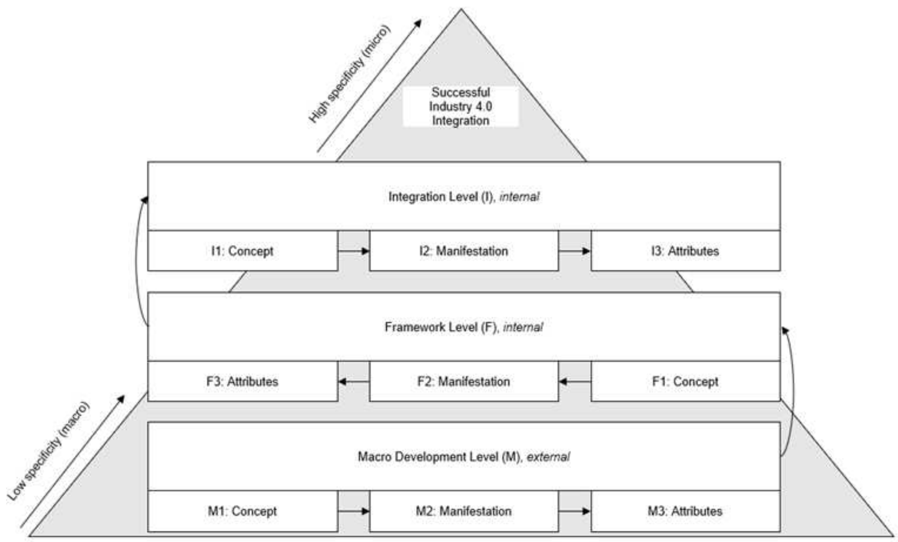


Fig. 4. IKTF basic structure

Figure 5 shows, that the core concept of (M) is defined as the already described core concept exponential technological change, which results in the manifestations as described in Table 1.

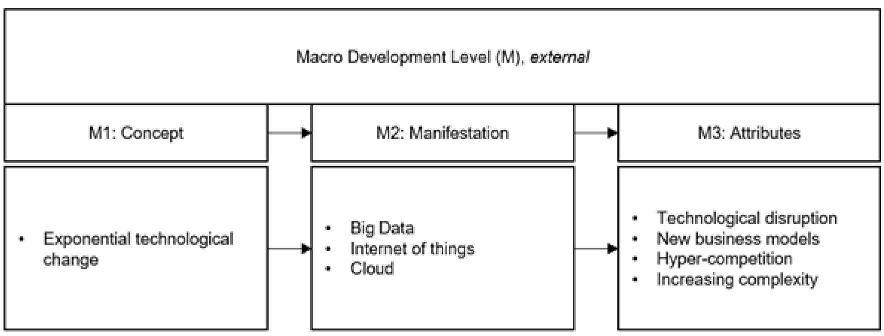


Fig. 5. IKTF basic structure

Table 1. Macro Level (M) Manifestations

Manifestation (M)	Description
M.2 Big Data	The increased usage of networked machines and sensors generates high-volume data. High-tech technology, like advanced machine learning, is necessary that can analyze and leverage large data sets including real-time data that are difficult to analyze by traditional methods. (Lee and Bagheri, 2015, Gaham, Bouzouia and Achour, 2013)
M.2 Internet of Things	The IoT enables the communication between physical and Internet-enabled devices through connecting physical objects through the virtual realm. (Mittal, Limo-Monteiro, Barata and Colombo, 2017)
M.2 Cloud	Cloud-based IT-platform serves as a technical backbone for the connection and communication of manifold elements of Industry 4.0. and IoT as they, for example, allow flexible and cost-efficient data storage upscaling. (Rojko, 2018)

Table 2. Macro Level (M) Attributes

Attributes (M)	Description
M.3 Technological disruption	The combination of technologies like IoT, cloud and Big Data in the Industry 4.0 is disruptive and leads to significant paradigm shifts in manufacturing. CPS for example derive from important technical advances on the internet, embedded systems, computer science and artificial intelligence. (Morrar, Arman and Moussa, 2017, Roblek, Mesko and Krapez, 2016)
M.3 New business models	Industry 4.0 and its embedded technology diffusion progress is expected to grow exponentially in terms of technical change and socioeconomic impact and allow for new types of business models, for example platform business. Benefiting of such a transformation requires a holistic approach of value creation that integrates innovative and sustainable business and technology solutions which modify or replace existing business models. (Morrar, Arman and Moussa, 2017, Roblek, Mesko and Krapez, 2016, Thoben, Wiesner and Wuest, 2016)
M.3 Hyper-competition	As explained in the introduction, industrial production is driven by a hyper-competitive rivalry for market shares between formerly separated industries generated caused by a more global, digital, and interconnected market environment. (Turgay and Emeagwali, 2012)
M.3 Increasing complexity	Cyber-physical system architectures are characterized by unprecedented scale and interconnectedness and are thus highly complex. Managing this complexity is a challenging task, as traditional analysis tools are unable to cope with the full complexity of CPS or adequately predict system behavior. One barrier to progress is the lack of appropriate science and technology to conceptualize and design the deep interdependencies among engineered systems of the Industry 4.0 concept and the changes manifesting in the company external environment. (Rojko, 2017, Pilloni, 2018, Thoben, Wiesner and Wuest, 2016)

These manifestations can now be attributed with the following properties as shown in Table 2.

After describing the macro-level manifestations and attributes, the framework level can now be defined in detail.

The Framework Level (F) represents the meso level that lies between the macro and micro level of the framework. the company internal reaction to (M). (F) shall now be defined as the following.

Figure 6 shows, that the concept of (F) is defined by the company internal concept Industry 4.0, which results in the already described manifestation Smart Factory and the attributes described in Table 3.

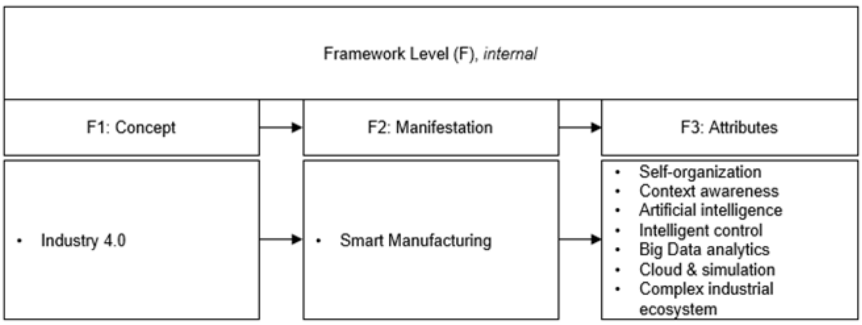


Fig. 6. Framework Level

Table 3. Framework Level (F) Attributes

Attributes (F)	**Description**
F.3 Self-organization	Manufacturing processes will be interconnected across corporate boundaries via CPS. These changes in supply and manufacturing chains require greater decentralization from existing traditional manufacturing systems. This results in a decomposition of the classic, centralized production hierarchy and a paradigm shift toward decentralized self-organization. (Lee and Bagher, 2015, Pilloni, 2018, Roblek, Mesko and Krapez, 2016)
F.3 Context awareness	Context awareness is an important intelligent characteristic of an SF and its underlying CPS and it is a combination of the following attributes: Awareness of identity, location, status, time. (Horvarth and Gerritsen, 2012)
F.3 Intelligent control, artificial intelligence	With the help of intelligent technology and context awareness, a CPS is expected to be able to change its actions based on its own experience and is thus self-learning and capable of evolutionary self-adapting to external changes. If it possesses intelligent control technology, it can make use of, for example, artificial intelligence techniques, like machine learning, to control its mechanisms via decision algorithms and is able to perform more reliable and accurate in a less stable environment. (Thoben, Wiesner and Wuest, 2016, Mittal, Khan, Romero and Wuest, 2019)
F.3 Big Data analytics	The collection and comprehensive evaluation of data from many different sources like production equipment and systems as well as enterprise and customer-management systems will become standard to support real-time decision making. (Pilloni, 2018, Morrar, Arman and Moussa, 2017)
F.3 Cloud & simulation	With Industry 4.0, organization needs increased data sharing across the sites and companies, achieving superior reaction times in milliseconds or even faster. This leads to the idea of having the connections of different devices to the same cloud to share information to one another. This can be extended to set of machines from a shop floor as well as the entire manufacturing system. Simulations will be used more extensively in plant operations to leverage real-time data to mirror the physical world in a virtual model via double representation. This includes machines, products, and humans, reducing machine setup times and increasing quality. Decision making quality can also be improved with the help of simulations, as possible system trajectories can be featured into the decision-making process. (Rojko, 2017, Pilloni, 2018, Xu and Ling, 2018)
F.3 Complex industrial ecosystem	Designing Industry 4.0 systems involves high complexity, which mainly originates from the high dimensionality and the internal complexity of components. As, for example, the IoT scales to billions of connected devices – with the capacity to sense, control, and otherwise interact with the human and the physical world – the requirements for dependability, security, safety, and privacy grow significantly and must be managed accurately. (Savastano, Amendola, Bellini and D´Ascenzo, 2019, Freund and Al-Majeed, 2020)

After describing the framework level manifestations and attributes, the integration level can now be defined in detail.

The Integration Level (I) represents micro level the company internal reaction to (F). (I) shall now be defined as the following.

Figure 7 shows, that the concept of (I) is defined by the already described company internal core concept cyber-physical system architecture, which results in the manifestations cyber-physical system and cyber-human system and the attributes shown in Table 4.

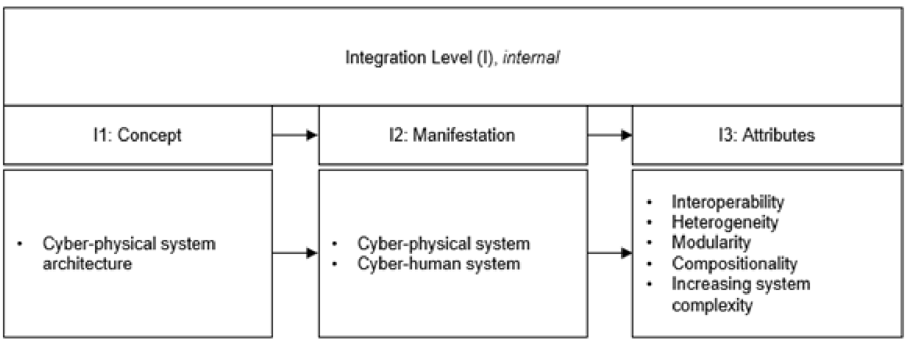


Fig. 7. Integration Level

Table 4. Integration Level (I) Attributes

Attributes (I)	Description
I.3 Interoperability	Interoperability is the characteristic due to which, system units are able to exchange and share information with each other. With the help of networkability, systems can collaborate in different process-related aspects, and for this collaboration, they have to allow each other to share and exchange information. Similarly, distributed systems allow the information and data of one system to be accessed by other systems in the network. (Nagorny, Limo-Moneteiro, Barata and Colombo, 2017, Gaham, Bouzouia and Achour, 2013)
I.3 Heterogeneity	Heterogeneity considers the diversity and dissimilarities in the units and components. (Thoben, Wiesner and Wuest, 2016, Gaham, Bouzouia and Achour, 2013)
I.3 Modularity	Modularity is the property of a system by which a unit can be decomposed into components that can be recombined to form different configurations. (Mittal, Khan, Romero and Wuest, 2019, Gaham, Bouzouia and Achour, 2013)
I.3 Compositionality	Compositionality is the property that deals with the understanding of the whole system based on the definition of its components and the combination of the constituents.(Mittal, Khan, Romero and Wuest, 2019, Gaham, Bouzouia and Achour, 2013)
I.3 Increasing complexity	CPS emerge through networking and integration of embedded systems, application systems, and infrastructure, enabled by human machine interaction. In comparison to conventional systems used for production such a system is expected to be increasingly more complex. (Thoben, Wiesner and Wuest, 2016, Camarinha-Matos, Fornasiero, and Asfarmanesh, 2017)

After presenting all levels of the IKTF in detail, it is now possible to present the complete IKTF framework..

COMPLETE FRAMEWORK

The complete IKTF framework results and is displayed in Figure 8.

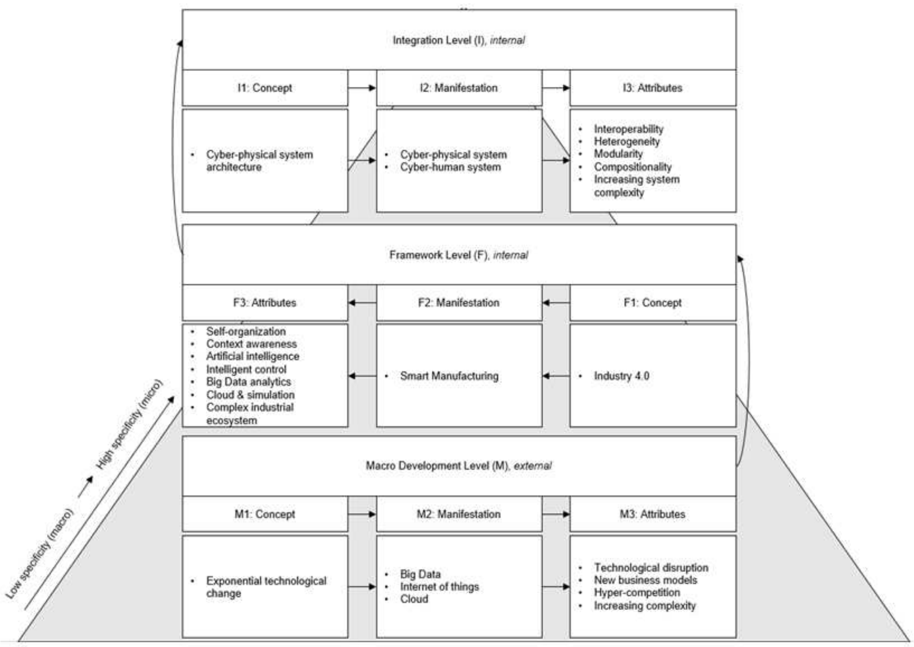


Fig. 8. IKTF - Complete Framework

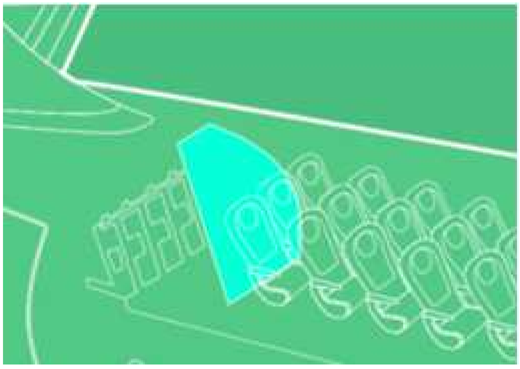
After presenting the complete IKTF framework, the resulting implications for decision-makers and the overall functionality can now be discussed on the basis of a case study.

IMPLICATIONS FOR DECISION-MAKERS

The IKTF shows, that decision makers must acquire sufficient knowledge in the macro-level, with low context specificity (M) about the concept, manifestations and attributes of exponential technological change and its disruptive effects on the financial, political, and socio-economic external environment of the company. This can be achieved through understanding analyzing the manifestations of Big Data, Internet of Things and Cloud and their attributes of technological disruption, new business models, hyper-competition and increasing complexity in the individual corporate context. A response through the utilization of company assets in the internal framework level (F) can then be formulated as a reaction by analyzing the applicability of the concept of Industry 4.0 with its manifestation smart factory and the attributes of self-organization, context awareness, intelligent control, artificial intelligence, Big Data analytics, cloud & simulation and the complexity of industrial ecosystems under the resource constraints and macro influence factors of the individual company. If this is achieved an integration approach can formulated by analyzing the applicability of cyber-physical system architectures, their manifestations cyber-physical systems and cyber-human systems with the attributes of interoperability, heterogeneity, modularity, compositionality and increasing complexity under the identified constraints on the framework level and macro level. This makes visible that a successful integration of Industry 4.0 is an extensive, difficult to achieve task which requires extensive knowledge, reflection and insights on all levels of specificity. According to the IKTF no level of the framework can be skipped or only partially understood. Only a comprehensive understanding of the framework levels and the successful application on the individual corporate context allow a successful integration of industry 4.0. This highlights the importance of informed and analytical decision making on all corporate areas in the context of Industry 4.0 integration. In the final step of this paper, the IKTF is applied to case study to further display the functionality and practical applicability of the line of argument and the framework.

CASE STUDY: AIRCRAFT PARTITION REDESIGN FOR AIRBUS 320

After presenting the theoretical foundation of the IKTF, the framework is now applied to a rudimentary case study to showcase its functionality. The case utilized is taken from [26,27]. European aircraft manufacturer Airbus collaborated with Autodesk to rethink the design of aircraft partitions of the Airbus A320 cabin, as part of creating a vision for future aircraft design. This vision includes the overarching goals of a more eco-friendly, lighter plane designs and a more customizable customer experience. The partitions used to separate the cabin crew's workstation from the rest of the cabin represents a major engineering conundrum, especially to the aircraft manufacturers, who want these partitions to be as small and light as humanly possible.



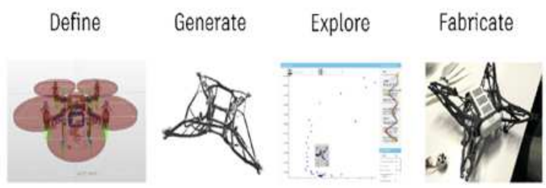
Source: Autodesk, 2021

Fig. 9. Aircraft partition

This new partition was planned to be:
- significantly lighter than the current partition, meeting the goal of reducing the weight of the plane,
- strong enough to anchor two jump seats for flight attendants during take-offs and landings
- have a cutout to pass wide items in and out of the cabin
- no more than an inch thick
- attached to the plane's airframe in just four places.

To meet the outlined requirements, it was decided to leave traditional manufacturing and design paradigms behind and to start working with the company Autodesk Research on the so-called "Bionic Partition", based on generative design, that mimics the evolutionary design approaches found in nature.

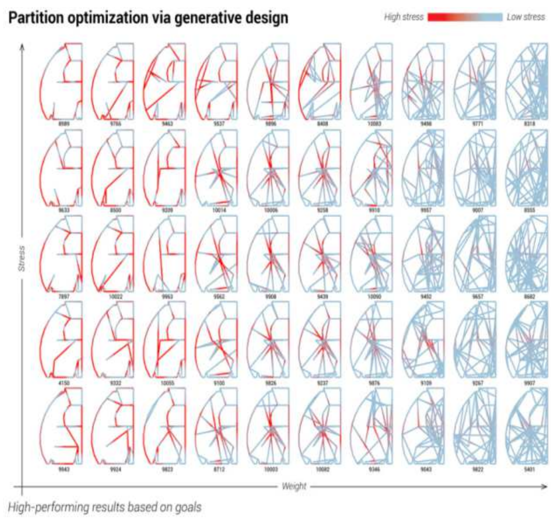
Engineering design software (Autodesk Dreamcatcher), machine learning techniques and additive manufacturing based on 3D Printing were used to generate a new partition based on bionic, generative design principles. To allow a better understanding of the case the rudimentary concept of Autodesk Dreamcatcher is now illustrated in Figure 10.



Source: Autodesk, 2021

Fig. 10. Autodesk Dreamcatcher

Figure 11 now illustrates a sample of the partition optimization in the generative design process based on the parameters stress and high-performing results based on system goals.



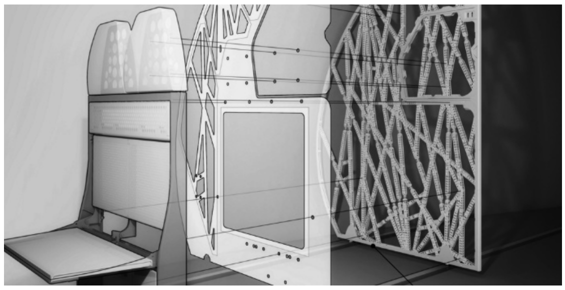
Source: Autodesk, 2021

Fig. 11. Partition optimization via generative design

The new partition was 3-D printed using new innovative, generative design algorithms based on bionics, represented by the interconnectivity found in slime-mold singular-celled organism and grid structures of mammal bone growth dynamics in biological systems. Over 10,000 design options were created by the software in the process and checked for applicability. More than 100 separate pieces were 3D printed and assembled in a process of additive manufacturing. Figure 12 now shows a final 3D printed piece of the partition, while Figure 13 shows the final product.

Source: Autodesk, 2021

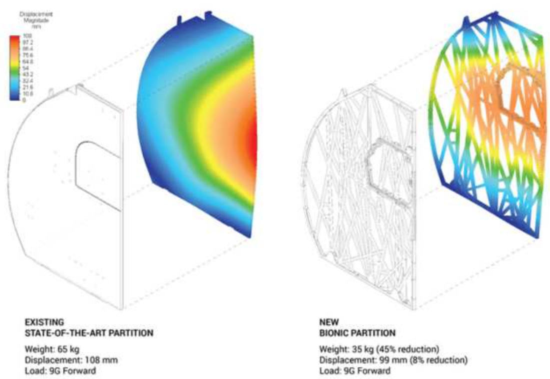
Fig. 12. Final printed piece– part of a bionic aircraft partition by Airbus



Source: Autodesk, 2021

Fig. 13. Bionic aircraft partition by Airbus

Figure 14 now illustrates a comparison between the bionic partition and the standard partition.



Source: Autodesk, 2021

Fig. 14. Bionic aircraft partition by Airbus compared to standard partition

The new partition weighs in at 35 kg, significantly lighter than Airbus's original partitions that weighed 65 kg apiece, which represents a 45% weight reduction. This results in (if all four partitions in an Airbus 320 were replaced) 500kg overall weight reduction of the aircraft, reduced fuel consumption, reduction of CO_2 emissions. Due to the usage of 3D printing and additive manufacturing material consumption is reduced by 95% in comparison to traditional manufacturing processes [Autodesk, 2021]. Moreover, because the designs created by the generative design software are so complex, classical manufacturing techniques were out of the question when it came to building the part [Skillton, Hoysepian, 2018].

After describing the case, the IKTF can now be applied for further analysis.

CASE STUDY: IKTF APPLICATION

The IKTF is now applied to the presented case as shown in Figure 15.

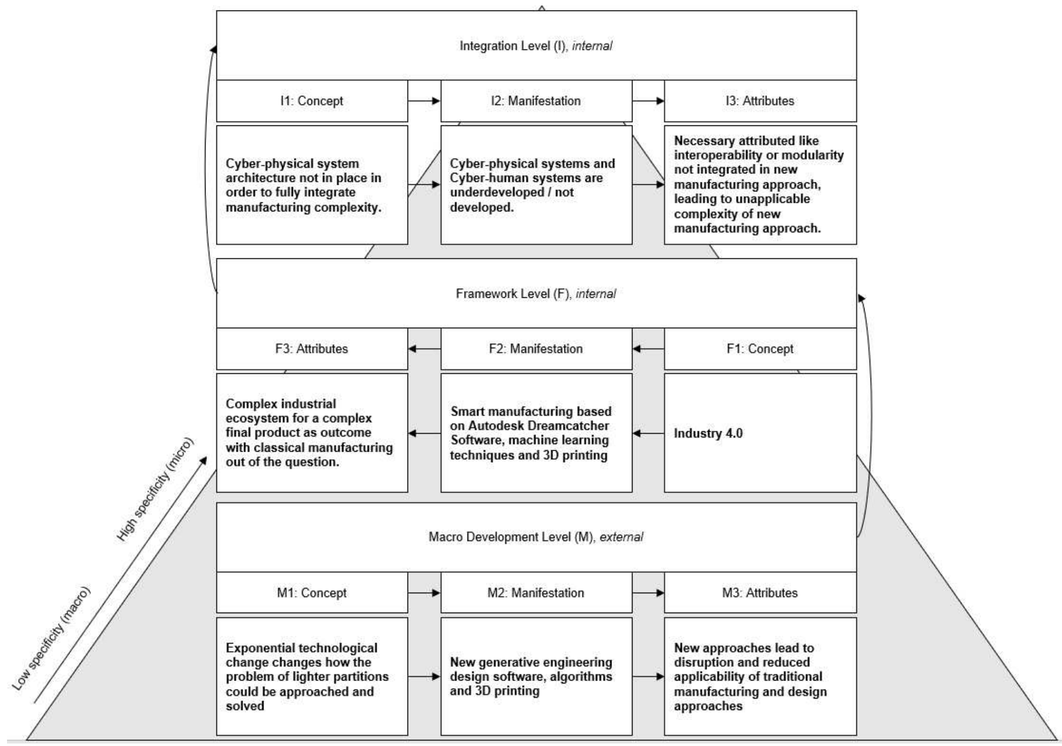


Fig. 15. IKTF – Case study application

After integrating the case in the IKTF the different levels of the framework can now be described in Tables 5, 6 and 7.

Table 5. Macro Level (M) Application

Macro Level (M)	Case Application
M1	Exponential technological change changes how the problem of lighter partitions could be approached and solved in general on the technological level.
M2	Big Data, Internet of things, Cloud can be applied as enablers in the form of new generative engineering design software, algorithms, and 3D printing.
M3	Technological disruption, increasing complexity manifest themselves in new approaches that lead to disruption and reduced applicability of traditional manufacturing and design approaches.

After describing (M) for the case in Table 5 a transition to the framework level is now possible.

After describing (F) in Table 6 for the case a transition to the integration level is now possible.

Table 6. Framework Level (F) Application

Framework Level (F)	Case Application
F1	Industry 4.0 can be described as the necessary framework concept to capitalize of the macro level developments.
F2	Industry 4.0 manifests in the concept of smart manufacturing which itself is based on the 3D printing, the generative design software Autodesk Dreamcatcher software and machine learning techniques.
F3	The attributes artificial intelligence, self-organization, cloud and simulation, context awareness and Big Data analytics can now be identified in F3 for F2 and already indicate the necessity of a complex industrial ecosystem to allow the production of the new product.

Table 7. Integration Level (I) Application

Integration Level (I)	Case Application
I1	Appropriate cyber-physical system architecture proportional to final product complexity is not in place, while classical manufacturing approaches are no option for production.
I2	Cyber-physical and cyber-human systems are necessary, but not in place, to manifest to fully capitalize on the benefit of the new, highly complex product
I3	The attributes of interoperability, heterogeneity, modularity, compositionality, and an overall production system of higher complexity should be integrated in a potential production approach for the new product.

After describing (M) in Table 5, (F) in Table 6 and (I) in Table 7 it is now possible to interpret the results of the IKTF in the next chapter..

INTERPRETATION

Figure 16 now shows the interpretation of the presented case in the IKTF format.

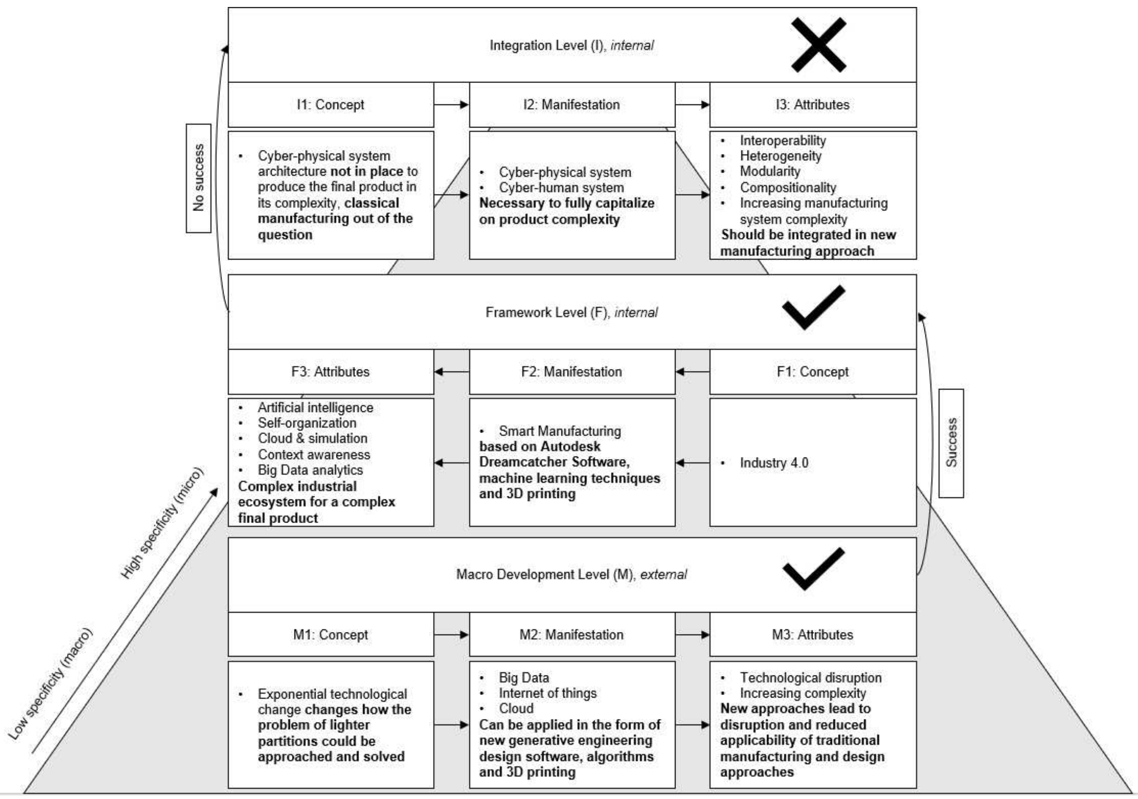


Fig. 16. IKTF – Case study interpretation

Figure 16 shows, that the Airbus project can be described to capitalize of the external level (M) can achieve a successful transition of from (M) to the internal framework level (F). (F) can be completed, but no transition to the integration level (I) is in place and whether a sufficient understanding of the required concept, manifestations and attributes is in place to allow full capitalization of a successful completion of (M) and (F).

The final IKTF of the described case allows to conclude that the newly developed bionic aircraft partition cannot be a successful product unless the integration level is completed. The IKTF thus recommends that it is necessary to translate the requirements of an complex industrial ecosystem for a product of high complexity into an adequate cyber-physical system architecture for production which is itself characterized by a combination of interoperable, heterogenous, modular cyber-physical and cyber-human systems which itself represent a highly complex system with compositionality. These recommendations, even though not specific, allow to question the economic viability of the new product designed and its applicability for mass production overall. This conclusion to the IKTF is in line with the presented case, which can be regarded as a lighthouse project of Airbus to explore technological not economic feasibility and presents a first proof of concept for the framework.

DISCUSSION OF RESULTS

The IKTF shows that the successful integration of Industry 4.0 is dependent from many layers of understanding which are sequentially connected on the micro-meso-macro levels of analysis. The IKTF furthermore proposes that decision makers follow the shown bottom-up approach when aiming for integration and identify how every concept applies for the individual corporate context and project they want to implement. As already mentioned in the introduction, the integration of Industry 4.0 is accompanied by a large variety of research and development issues, for example the management of system complexity in a VUCA environment and the development of universally applicable reference models and foundational definitions of fundamental concepts for Industry 4.0. As shown by the provided case study, the IKTF can serve decision makers in the context of management of system complexity, definitions and reference models by providing three functions:

- Obtain a multi-level understanding of Industry 4.0
- Definition of the corporate context in the framework of Industry 4.0
- Pinpoint the position and integration status of a given project in IKTF relative to the framework levels
- Show potential “weak zones” in the integration process
- Provide first implications for the scalability and economic validity of a given Industry 4.0 integration project

As argued by Camarinha-Matos, Fornasiero and Asfarmanesh the concept of Industry 4.0 has turned into a buzzword and an “everything fits” catalyzer for various technologies and manufacturing approaches. The “everything fits” mentality, making the concept difficult to understand, is additionally supported by companies and their respective managers utilizing their own descriptions and concepts, leading to a decreased diffusion of best practice methodologies [Camarinha-Matos, Fornasiero and Asfarmanesh, 2017]. The IKTF can contribute to avoid such a mindset and helps to replace it with a consistent and coherent analytical approach, as illustrated by the provided case study. Nevertheless, the IKTF is to be regarded as a foundational managerial decision-making tool that predominantly focusses on providing insight for decision-makers in the context of their respective company and on overcoming the challenge of developing Industry 4.0 reference and application models for integration processes and is thus limited in applicative value when applied out of this scope.

CONCLUSION

The IKTF analyzes Industry 4.0 on several levels of abstraction in a micro-meso-macro framework and introduces the different positions of different core concepts in a coherent and logically consistent framework that represents relevant Industry 4.0 core concepts, manifestations and attributes on three interdependent levels. These levels can then be applied to a given managerial decision-making problem, for example the integration of a new technology, in an analytical way. While doing this, the levels of the IKTF and their respective internal logical chains cannot be seen isolated from each other since every level and builds on the concept, manifestation, and attributes of the previous level. Hence, the practical integration of Industry 4.0 requires decision makers to have insights into company external and internal interconnected knowledge and technology fields on different levels of abstraction to be successful, as shown by the provided case study. The IKTF, therefore, proposes a well-structured solution to the complex nature of Industry 4.0 and shows a path to informed managerial decision making.

OUTLOOK

To advance the applicability and theoretical foundation of the proposed framework, future work focuses on verifying, expanding, modifying, and applying the ITKF via extensive case study research in European companies.

CONFLICT OF INTEREST

The authors of this study have no conflict of interest to declare.

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