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A new architecture model for smart manufacturing: A performance analysis and comparison with the RAMI 4.0 reference model

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ABSTRACT

In this paper we proposed a new architectural model of the smart factory to allow production experts to make easier and more exact planning of new, smart factories by using all the key technologies of Industry 4.0. The existing complex reference architectural model of Industry 4.0 (RAMI 4.0) offers a good overview of the smart-factory architecture, but it leads to some limitations and a lack of clarity for the users. To overcome these limitations, we have developed a simple model with the entire and very simple architecture of the smart factory, based on the concept of distributed systems with exact information and the data flows between them. The proposed architectural model enables more reliable and simple modelling of the smart factory than the existing RAMI 4.0 model. Our approach improves the existing methodology for planning the smart factory and makes all the necessary steps clearer. At the end of the paper a comparison of the proposed architectural model LASFA (LASIM Smart Factory) with the existing RAMI 4.0 model was made. The developed LASFA model was already successfully implemented in the laboratory environment for building the demo centre of a smart factory.

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1. Introduction

The introduction of Industry 4.0 and with it factories of the future has become an important focus of the world's industry over the past few years. The key technologies of Industry 4.0 can have a major impact on an increase in efficiency and the availability of production assets, raising the efficiency of equipment and production, and increasing the value per employee. At the same time, the goal of introducing smart factories is to reduce costs, lead times, delivery times, etc. The introduction of the technologies of Industry 4.0 into the factories of the future is essential if we want these factories to become flexible and agile. We found that the biggest challenge is how to start planning the factory of the future or how and where to start introducing the new technologies of Industry 4.0 into these factories.

The fourth industrial revolution combines various technologies, such as the digitalisation of production processes and systems (digital twins of production processes and systems), cloud computing in combination with new mathematical algorithms, artificial intelligence, digital agents, the Internet of Things (IoT), big data to create cyber-physical systems (CPS) and smart factories. Industry 4.0 also includes various automated systems that allow the automatic exchange of data [1].

We can assess Industry 4.0's integration into a company using different maturity models that show the maturity level of a company in terms of the integrated technology of Industry 4.0. Some models are web-based, self-assessment tools, others are published in scientific journals [2]. The group of web-based, self-assessment tools covers the maturity models of PwC (PricewaterhouseCoopers) [3], Impuls [4], IHK (Industrie- und Handelskammern) [5] and VDMA (Verband Deutscher Maschinen- und Anlagenbau) [6]. Each of these tools uses different approaches to understand Industry 4.0. We found a variety of models in scientific publications. A popular and frequently mentioned architectural model is *The Reference Architectural Model Industry 4.0* (subsequently referred to as RAMI 4.0) [7]. Other models include *The Industrial Internet Reference Architecture* (IIRA) [8], developed by the Industrial Internet Consortium, and *The Stuttgart IT-Architecture for Manufacturing* (SITAM) [2, 9], developed within several research projects at the Graduate School of Advanced Manufacturing Engineering. Smaller initiatives like *Virtual Fort Knox* and FIWARE also provide data-driven concepts [10, 11].

Many other researchers have looked at architectural models of smart factories and the connections between the systems they contain. Important contributions have been made by Monostori *et al*. [12, 13], Kemeny *et al*. [14, 15], Valckenaers *et al*. [16] Bagheri *et al*. [17], Leitao *et al*. [18], and others [19]. Hussain *et al*. [20] presented a framework for sustainable manufacturing with its associated architecture. Vieira *et al*. [21] presented a literature review of the areas of simulation. In [22], Zheng *et al*. were researching the conceptual framework, the scenarios, and the future perspectives of smart manufacturing systems for Industry 4.0. Zhang *et al*. [23] presented concepts to achieve real-time manufacturing, capturing and integrating three different layers. In Liu *et al*. [24] the authors discussed and compared the concepts of Industry 4.0 and cloud manufacturing.

The first part of this paper presents a detailed description of RAMI 4.0, which is taken as the basis and reference to perform a comparison with the newly proposed architectural model concept. The second section explains the proposed concept of the architectural model (LASIM Smart Factory, referred to as LASFA) in detail, showing all the key elements of a smart factory taken from different vertical layers of RAMI 4.0 and placing them into a two-dimensional platform. The acronym LASIM stands for the original name of the laboratory that proposed the new architectural model. The main difference between the newly proposed model and RAMI 4.0 is the graphical presentation of the elements in a two-dimensional platform. Subsequently, the new model shows the exact locations of the elements as well as the interconnections and the directions of the material/information flows between the elements. The last part includes a comparison of the LASFA model with the RAMI 4.0 architectural model and explains why our model is more useful and easy to understand. The paper concludes with a description of our findings. All the abbreviations used in the paper are explained in the Appendix A.

2. Reference Architectural Model Industry 4.0 (RAMI 4.0)

2.1 Brief overview

The organisations BITKOM, VDMA and ZWEI decided to develop a new architecture model for the needs of Industry 4.0. For this, they took the Smart Grid Architecture Model as a basis [25, 26]. RAMI 4.0 is a three-dimensional model that describes Industry 4.0's space. On the horizontal axis, the layers include different views, such as assets, functional descriptions, data maps, etc. This corresponds with the IT approach of grouping complex projects into subsystems. The other key criteria are the lifecycle (type) and service life (instance) of the products and production systems with the value stream they contain. The vertical axis represents the third type of key aspect, i.e., the allocation of functions and responsibilities within the factories or plants. The combination of a lifecycle and a value stream with a hierarchically structured approach for the definition of Industry 4.0 components is a special feature of RAMI 4.0. The model allows for the logical grouping of functions and the mapping of interfaces and standards [27].

The RAMI 4.0 model is based on the established standards for automation, such as IEC 62890, IEC 62264, IEC 61512/ISA95, as shown in Fig. 1. It combines the key elements and technologies of

Industry 4.0, integrated into a 3D layered model. In this way, a complex system with internal connections can be divided into smaller and, for a better understanding, simpler subsystems [2, 9].

On the right horizontal axis there are the Hierarchy Layers, which are listed in the international standard IEC 62264. This axis represents the various functionalities in companies and factories. In order to present Industry 4.0, the axis has been divided into smaller subsets [2, 9]. The left horizontal axis represents a sustainable cycle of production and product, based on IEC 62890. This axis is further divided into types and instances. The type passes into the instance when the development and the prototype are completed, and the product is in production. The six layers into which the vertical axis is divided serve to describe the splitting of the device, layer by layer [2, 7, 9].

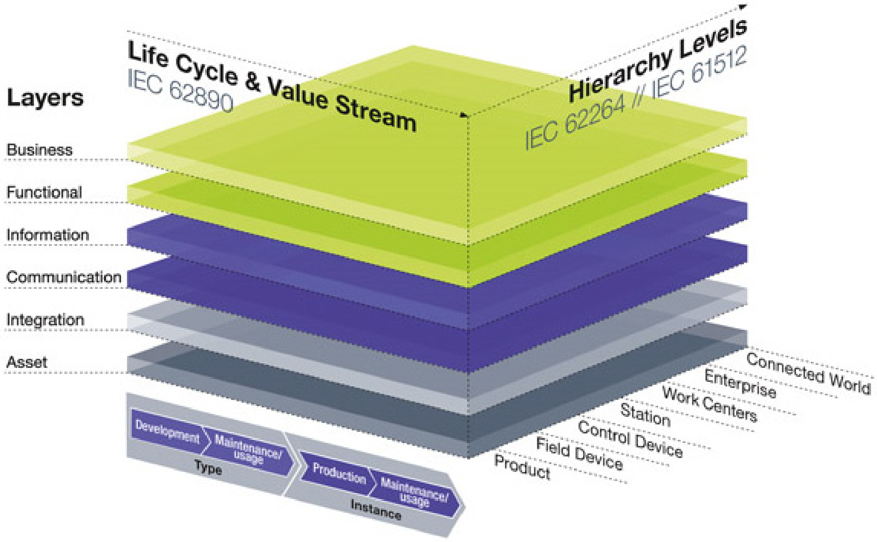


Fig. 1 Reference Architectural Model Industry 4.0 (RAMI 4.0) [2]

2.2 RAMI 4.0 in more detail

The RAMI 4.0 model has six layers on the vertical axis and two on the horizontal axis. Beginning with the vertical axis, the first layer is the 'Asset layer', which shows the physical objects, such as metal parts, documents, archives, diagrams, humans, etc. One layer higher is the 'Integration Layer', where transformations and connections of the physical objects into a digital world takes place. The components of the 'Asset layer' are connected with the digital world by the 'Integration Layer', which deals with the easy processing of information and can be considered as a link between the physical and digital worlds. This layer involves computer control of the process, system drivers, human-machine interface devices, humans, bridge wires, switches, hubs, sensors, RFID (Radio-Frequency Identification), etc. The next layer is the 'Communication layer', which provides standardized communications between the 'Integration layer' and the Information layer. The standardization is achieved with a uniform data format, which is used in the Information layer, which provides the control of the 'Integration layer'. The 'Information layer' holds data in an organized way. The basic purpose of this layer is to provide information about the total number of sales, purchase orders, suppliers, and locations. It holds information about all the products and materials that are manufactured in the industry. It also gives information about the machines and components that are used to build the products. It gives information to customers and saves their feedback. The 'Information layer' is software based, i.e., it might be in the form of applications, data, figures, or files. In this layer the transformation of the received events in data suitable for higher layers takes place. The next layer on the vertical axis is the 'Functional layer', which is responsible for production rules, actions, processing, and system control. It also facilitates users as per product features, like cloud services (restore/backup functionality). Moreover, it involves various other activities, like the coordination of components, system power on/off, testing elements, delivery channels, user inputs, and functions including, but not limited to, alert lights, snapshots, touch screen and fingerprint authentication. The 'Functional layer' includes remote access and horizontal integration. The last layer is the 'Business layer', which is composed of the business strategy, business environment, and business goals. Moreover, it deals with promotions and offers, target locations, advertisements, customer-relationship management, budgets and the pricing model [25, 27].

The horizontal axis on the left-hand side of Fig 1 shows the life cycle and value stream of the industrial production process (Fig. 2). It has two phases: Type and Instance. When the product is under development then it is in the Type phase. When the product is in production it is in the Instance phase. Whenever the same product is under development again it is in the Type phase again. When customers buy products, the products are in the Type phase again. When the products are installed in a system, they are in the Instance phase again. Changing the phase from type to instance can be repeated multiple times [7, 25].

The second horizontal axis represents the Hierarchy Layer, which is shown in Fig. 1 on the right-hand side. The Hierarchy Layer is based on the international standards for enterprise control system integration (IEC 62264 and IEC 61512). In addition to the four layers named 'Enterprise', 'Work Centers', 'Station', and 'Control Device', the last two layers at the bottom are added (but are not included in standards) and are called 'Field Device' and 'Product'. The layer 'Field Devices' makes it possible to control the machines or systems in an intelligent and smart way, e.g., smart sensors. The layer 'Product' takes into account the product homogeneity and the production capacity with their interdependencies. The layer named 'Connected World' is at the top. In this layer the factory can reach external partners through service networks. These layers show the fundamental views for Industry 4.0 organization [28-30]. The RAMI 4.0 model takes into account flexible systems and machines [7].

Based on a detailed analysis of the reference model RAMI 4.0 that includes all the elements of the vertical and horizontal axes, there is no exact definition with regards to how the individual elements inside each layer are interconnected with the elements. In our opinion, those interconnections are crucial and have to be defined when planning a new smart factory or upgrading an existing factory to create a smart factory. One of the other important aspects is the integration of digital twins and digital agents into distributed systems, and not as decentralised systems in each vertical layer. This part is still missing from RAMI 4.0.

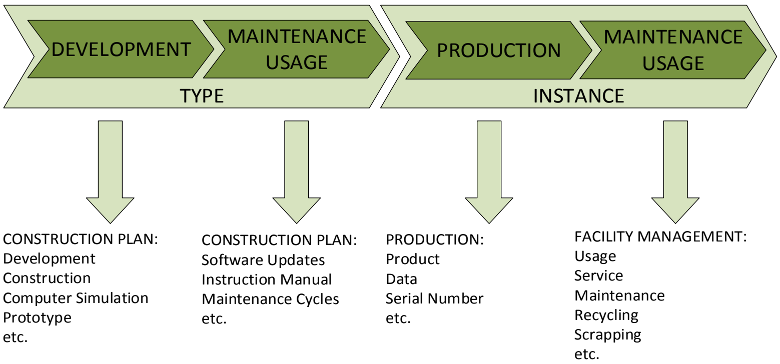


Fig. 2 Product life cycle: From the first idea to the scrapyard [7]

3. Proposed architectural model LASFA – LASIM smart factory

3.1 Global description

The LASFA architectural model (LAsim Smart FActory) is a concept for how to approach the planning and implementation of smart factories. The model was built based on RAMI 4.0, from where we took the hierarchy of the layers. We focused on one of the most important features of smart factories – the communications between systems in the smart factories' distributed systems. Using this model, users will be able to understand the principle operating smart factories.

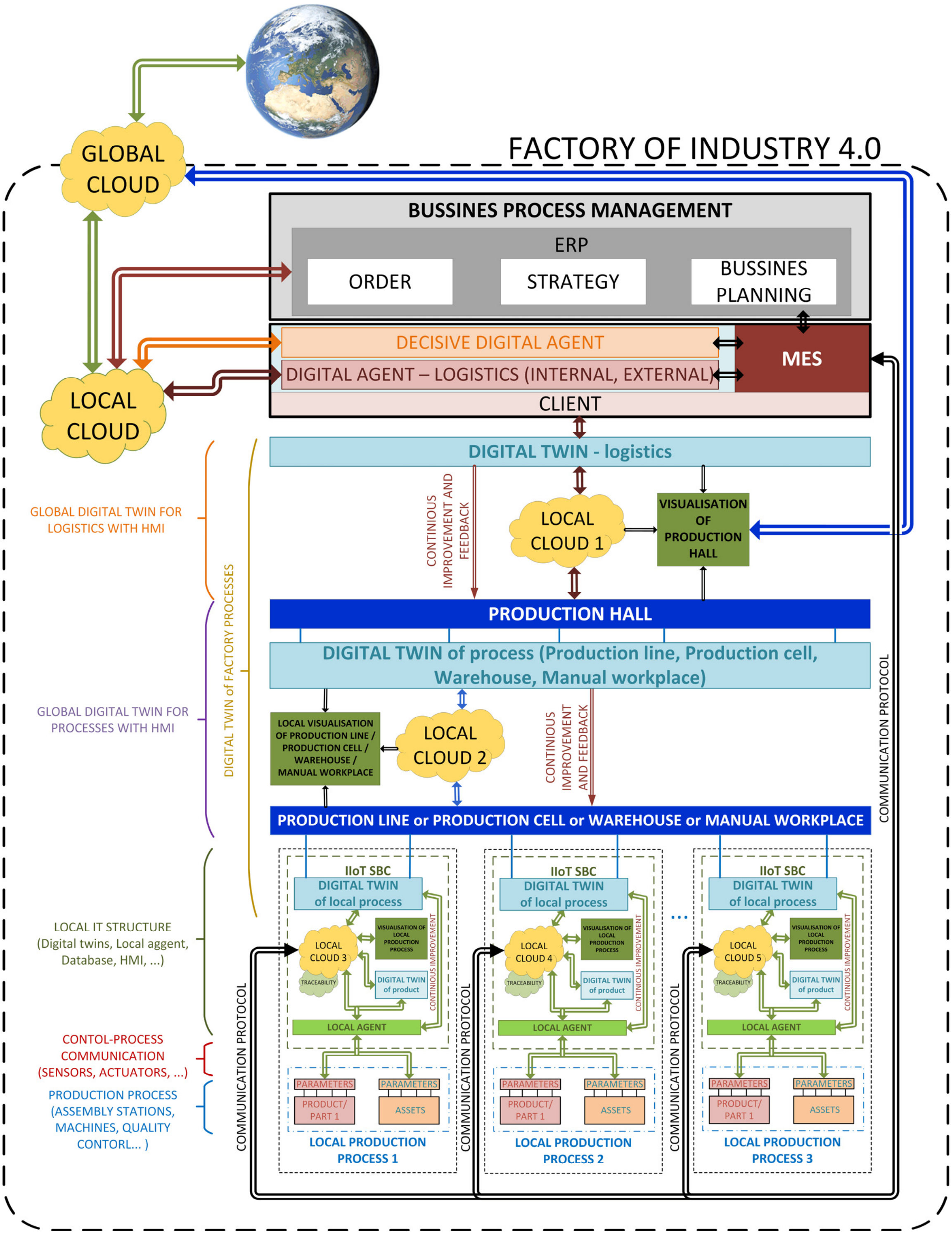


Fig. 3 LASFA model with all systems and processes

The architectural model is based on the results and insights of research projects and information from various European industrial manufacturers. The LASFA model is focused on the main aspects of Industry 4.0, such as horizontal integration, vertical integration, consistent engineering and systems that follow people's needs [7].

The development of the proposed architectural model is based on the reference architectural model RAMI 4.0. Unlike RAMI 4.0, the proposed model is two-dimensional, which makes the concept of a smart factory easier to understand. The RAMI 4.0 reference model is an abstraction for planning smart factories and is therefore not so easy to understand and is not so useful for industry users.

The LASFA architectural model, shown in Fig. 3, presents the individual systems that are combined into a smart factory. It includes several layers, as well as a business process, that result in a product in the production layer. The business layer includes the company's strategy and its leadership in the future as well as the monitoring and the delivery of orders.

Every manufacturer has one or more production lines (more production lines, production cells, warehouses, manual workplaces, etc). The production line consists of several local production systems that are, in this case, treated as distributed systems. Each local production system requires its input and output data. In the following section we will present all the elements in Fig. 3 in more detail.

3.2 Detailed description of the model

In this model we are focused on digital twins in different layers, which means a virtual copy of the real world. The model consists of digital twins for logistics, production lines, and local production processes.

Several production lines / production cells / warehouses / manual workplaces, together form a production hall. As we mentioned before, the proposed model of the smart factory includes its own digital twin for the production hall. Digital twins placed at different levels present a virtual copy of the systems in the real world. One of the important facts is that the digital twins without digital agents do not play an important role in a smart factory, as it only represents a virtual model of a real production system. With the help of various digital agents (each digital twin also has a digital agent – local or global) we get a digital twin that continually sends feedback and new production plans to the real world in real time. The LASFA model includes a decision-making digital agent, despite the fact that all the digital agents are connected. At the current stage of development, the decision-making agent is still human (i.e., a worker). In the future, we can expect that in the cases of production processes, where decisions about improvements to a single production process or production plan will have to be taken in real time, the expert will be replaced by a computer and advanced smart algorithms or artificial intelligence. But the absolute decision-maker should still be the expert. With such an approach we will be able to make the production process more flexible and agile, but the security and other “real-life” decisions will be taken by the expert to ensure the stable functioning of the production processes. Otherwise, if the absolute-decision maker was to be a smart algorithm, this could lead to the uncertainty, instability and insecurity of the production processes.

Fig. 3 shows the links for information exchange between individual systems in a smart factory and different local clouds. The model of a smart factory is built in such a way that each system is an independent unit with its own PlugAndProduce local control unit – distributed systems. This also allows us to add or remove an individual system without major changes to the global system. All the systems inside the model are interconnected. As it is with other models of smart factories, ours also does not have the classic pyramid shape [13]. For the smooth operation of a smart factory, it is also necessary to record and collect the data from sensors and save it in a local cloud.

The LASFA model includes the concept of remote access to the smart factory’s data. The concept provides access to some data via the Internet. Users can access specific data within a database (Global cloud) over secure Internet connections. The Global cloud can be inside or outside the Industry 4.0 factory. Users or customers of the product can perform condition monitoring and check the progress of the product being manufactured. The user will be able to change the product’s configuration during its manufacturing or production process (changing the colour, components, and accessories, if it is still possible). All the exchange of data is performed in real time, so customers of the product can monitor the production and assembly of the product.

The production line in Fig. 4 shows several different local production processes with different properties and requirements. Each local production process has its own single-board computer (SBC). SBCs are powerful enough to run standard operating systems and mainstream workloads [31]. Information and data exchange with a local cloud is provided through a wireless network or an optical cable for large amounts of data and information. The data and information exchange is bidirectional due to the feedback control performed by local digital agents. Each agent uses the input data and executes the optimization process to calculate the new parameters that are sent back to the real local system. The digital agent with its own database can make decisions independently.

Fig. 6 shows a detailed overview of the production process. All the process parameters are recorded and saved into the local clouds. Due to the bi-directional communications all these parameters are exchanged through the local clouds. This enables all the digital agents to have access to this data and to send new data, as well as to exchange data with other local and global clouds. Each local production process involves a local digital agent that receives information from a local cloud (database). A local agent is a mathematical model or an advanced intelligent algorithm that can also include artificial intelligence (AI). In today's factories, this segment is covered by a human being. The local digital agents use reference parameters and tabulation lists to change the parameter values. In the case of an unusual deviation, the local digital agent detects an error, reports it and can even react. The trend of changing parameters makes it possible to find out when it will be necessary to perform maintenance work (changing a cutting knife, matrix, changing oil and filters, etc.).

An important part of the LASFA model is the clear and concise visualisation. This visualisation enables internal and external users to access information about the condition of their manufactured product using a secure local or global Internet access point. Users, as well as workers on the assembly line, can monitor events with personal computers, smartphones or tablets, as proposed and shown in Fig 5.

Sensors installed in the real systems are used to capture the process parameters and visualize them (for example, the total production in the enterprise, which means the amount of raw material stock, the number of pieces manufactured, the defects of the production system, the identity of a line, the number of workers on a line, the number of shifts on a particular line, a product design plan, etc.) and also in digital form, another digital twin. The data captured from the production line and the data from the digital twin are collected in local clouds. The local clouds are synchronized with the global cloud. The local clouds also include the concept of digital agents that decide which data is important enough to capture and which is not required for subsequent operations.

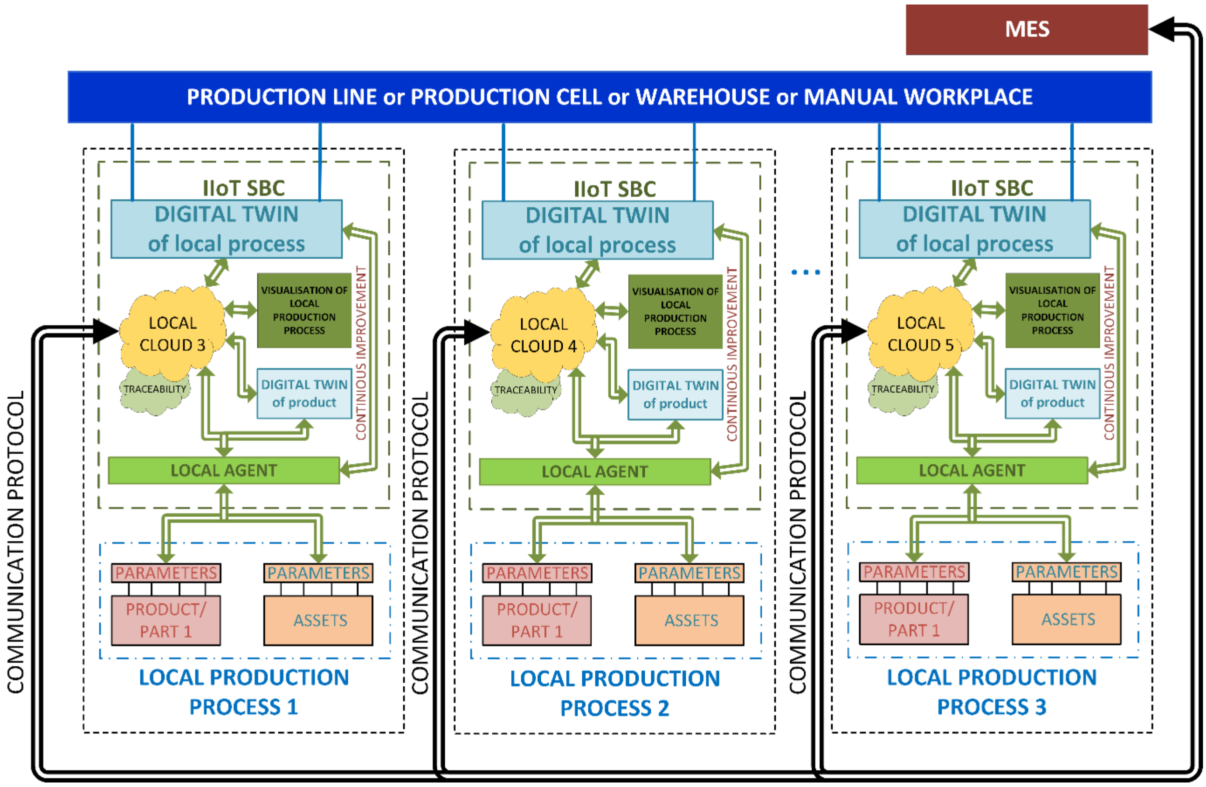
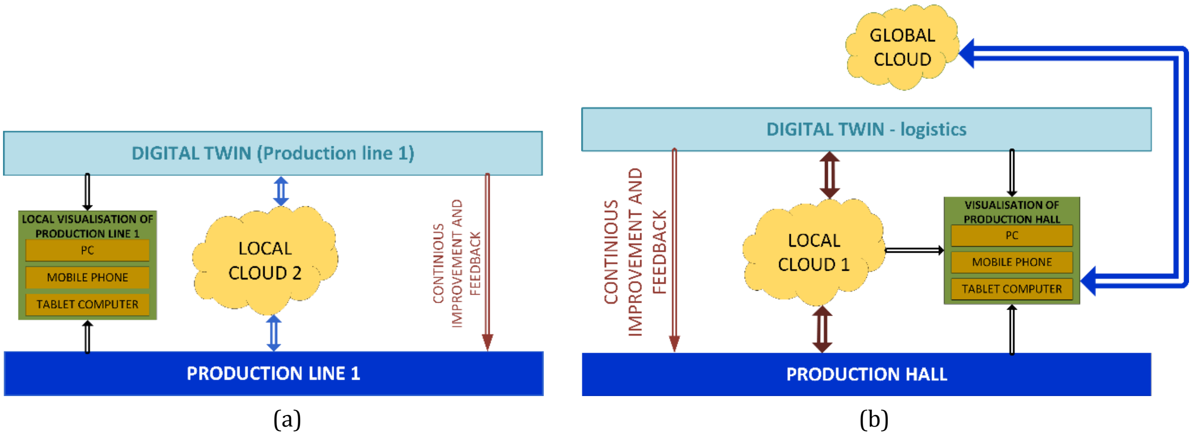


Fig. 4 Detailed view of a production line / production cell / warehouse / manual workplace



(a) (b)

Fig. 5 Visualisation of the production processes (a), the production logistics (b) and the local production process

The main goal of digital twins is to provide continuous control of the production operations, systems and processes. In the event of an unexpected change or shutdown, the digital twin simulates different scenarios and provides the best solution at a given moment in real time. In this way, we have constant improvements to the real system through a feedback loop. Using communication protocols, the local clouds exchange data with the global cloud. Usually, factories include several production lines, manual assembly workplaces, warehouses, production cells and other production systems. Like with the entire production hall where the digital twin for logistics cooperates with local clouds, this layer also includes a digital twin of the production line that works together with its own local cloud. Each system or process has its own local cloud; therefore, we attain a completely distributed system. In the case when a system or a process stops operating, only one part of the production is disabled and not the entire production, as was the case in factories with a centralised database system. The data captured in the production line is stored in the local cloud.

The production line has several local production processes (e.g., a deep-drawing process, product-assembly process, a wire-bending process, a plastic-injection process, etc.). Fig. 6 shows the connections between the systems and the processes in the local production processes. Each local production process has its own digital twin, which constantly improves and optimizes the real system and generates a feedback loop. If we look deeper into the local production process itself, we can recognise many links and locations for data exchange. Each local production process performs a process (in our case a deep-drawing process). The local production process consists of several sub-processes, in our case it consists of measuring systems, a hydraulic process, a control process, and others. The sensors ensure that various data is captured on each subsystem. The data is collected in a local cloud. With this data, it is possible to set up a digital twin of the local production process. The concept is illustrated using various local digital agents and intelligent algorithms. The concept also includes predictive maintenance algorithms, which can be found in the literature [12]. When the parameter values change outside the acceptable range, the algorithm recognizes the error and the system receives the information that the part must be replaced (cutting knife, matrix, etc.). The goal of the digital twin is also to reverse influence. It can change the parameters in the sub-processes. This gives us the best solution at a given moment. The data in the local cloud enables us to use artificial intelligence and machine learning. At the moment, a human is still the main decision-maker, but in the future, the control will be taken over by an agent and a computer in the background. The result of the local production process is a product or a semi-finished product. In the smart factory, the product will also have its own digital twin (see Fig. 4). For this reason, it is necessary to capture all the information that describes the product as well as possible (dimensions, roughness, manufacturing tolerance, geometric tolerances, etc.). As is the case with all the other data, the concept also includes storing this information in a local cloud.

Field devices are also a very important part of smart factories. The data captured in the field devices (sensors) are collected in a local cloud, and this data is shared with other clouds. This

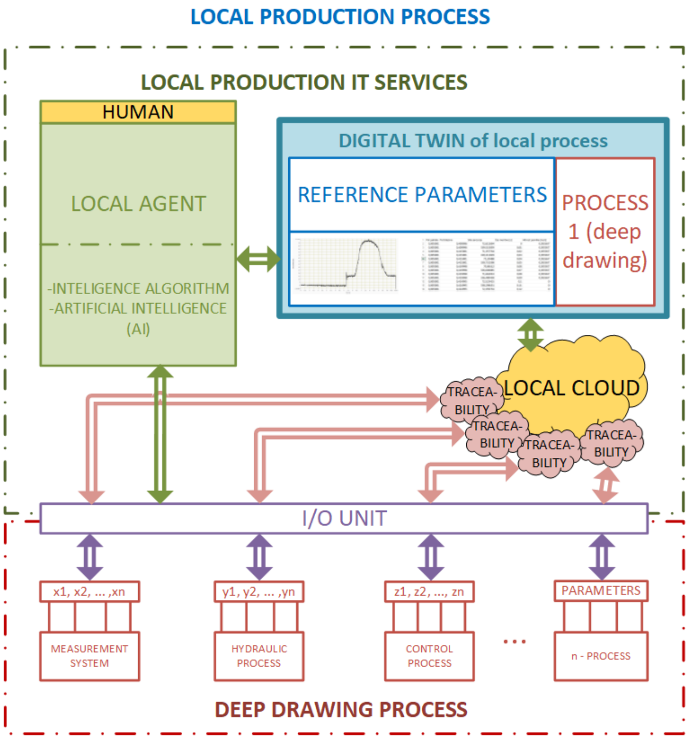


Fig. 6 Detailed view of the local production process

system represents the data captured using RFID, temperature sensors, humidity sensors, presence sensors, different control points, etc. Field devices used for manufacturing process control (valves, breakers, etc.) are controlled via a local agent.

4. Comparison of the LASFA model with RAMI 4.0

When discussing the LASFA and RAMI 4.0 models, and comparing them, we must be careful, because they are different types of models. Nevertheless, we can still make some comparisons between the RAMI and LASFA models in terms of the usefulness and clarity of the data and the information flow between the building blocks of the smart factory for the end user. RAMI 4.0 is based on standards for automation and is very generic. It offers a good overview of all the key technologies of Industry 4.0 and offers various layers and vertical axes as the backbone of the smart factory. As explained at the end of the Section 2, it leads to some limitations regarding an understanding of the exact positioning of different technologies and functions as well as the connectivity between them. This means that the planners of the smart factory do not know exactly where to place and how to interconnect some of the very important technologies, like different kinds of digital twins and digital agents, which is the main challenge for all the planners of smart factories.

On the other hand, the LASFA architectural model is much more specific and offers the end-user a simple visualization of the entire architecture of the smart factory, with the definition of the exact locations and functions of the digital twins and agents, with exact information and the data flow between them. The model shows a very clear distribution and the autonomy of every single building block of the smart factory, from the product to the management. The LASFA model is, therefore, in comparison to the RAMI 4.0 model, ready for direct implementation in the industrial environment and guides the smart-factory planner step by step from the smallest detail of the smart factory to the big picture. It is developed specifically for smart-factory planning and design.

The links between the building blocks of the smart factory in the LASFA model are shown very clearly; they also include the direction of the communication. Connections can also be added and graphically presented in the RAMI 4.0 model by using the Sparx RAMI 4.0 Toolbox [26] software. In this case the connections are made manually by experts, who need a lot of knowledge to plan all the links in all the vertical layers. The RAMI 4.0 model does not come close to the detail and clarity of the links that are important for the design/planning of smart factories.

A very important area covered by the LASFA model is that the functionality of the well-known ERP (Enterprise Resource Planning), MES (Manufacturing execution system) and PLM (Product Lifecycle Management) subsystems are replaced with new digital twins, which have integrated digital agents supported by artificial intelligence. In the model, the location and communication links for exchanging the information and data between the different digital twins in a smart factory are clearly shown. These features are not incorporated into RAMI 4.0 in such a clear manner. RAMI 4.0 does not show the location where ERP, MES and PLM are integrated into the system and modules in smart factories, nor in which layers they are needed, and it does not show which data and information are needed for operation, etc.

Table 1 Feature comparison between the proposed LASFA model and RAMI 4.0

	LASFA model	RAMI 4.0 model
Communication connections between systems and processes inside a smart factory	All the necessary communication links between individual systems are described in detail as well as the direction of communication (the information flow).	Administration shell includes communication protocol in a very general form. The standard does not show the exact connection between different systems inside each layer or vertically between layers.
ERP	Included in the model, the location and interconnections to other subsystems are clearly defined.	May be included, but its location is not defined.
MES	Digital twins with integrated digital agents are used to cover the function of the MES system.	May be included, but its location is not defined.
PLM	Integrated into the architecture model, the location, connection with other systems and main function are defined.	It is not included, but may be added. Hard to define the exact location, interconnections with other system inside the layer as well as between different layers.
Digital agents, artificial intelligence	LASFA represents different local and global digital agents, which are based on mathematical algorithms/models.	No locations for integration of digital agents in the model.
Visualisation of production process and systems	The LASFA model incorporates visualisation in different layers. Visualisation in smart factories is available in the production hall layer, production line layer and in the local production process layer.	Not clearly defined.
Digital twin	The digital twin is the main feature of our smart factory model. The digital twin is necessary for visualisation in different layers, systems operation, and decision making. The data for the digital twin's operation is collected in several local databases.	The model does not show the exact location of the digital twins and its function within the structure.
Visualisation of a decentralised and distributed system	Every local production process has its own local cloud, which is connected with other local clouds over a wireless network. A local cloud and a microcomputer form a decentralised system.	Mainly the visualization of decentralised systems. Distributed systems are briefly visualized.
Defines all the smart factory systems and components with their bi-directional links	Most of the key elements are included.	Not clearly defined
Capture and exchange of data between processes and local clouds	Detail description of the local and global clouds and the direction of the data exchange.	Not clearly defined – sensors, smart data, connections
Included standards for automation	Some standards are included and more can be implemented.	Some standards are included, others are in progress, in development

Another advantage of our model, in comparison to RAMI 4.0, is that it includes different digital agents, which are based on mathematical algorithms/models as well as artificial intelligence, where necessary. In our model we propose two types of digital twins and agents: local and global.

In our opinion, the visualisation of the systems and processes is very important in smart factories. By comparing the LASFA and RAMI 4.0 architectural models, we can see that the LASFA model includes visualisation, which is presented in the various layers of smart factories. It is necessary to visualise the production hall, the production line and the local production processes. The proposed model includes different visualisations, such as a visualisation of the decentralised and distributed system, the visualisation of all the important and necessary modules and systems of smart factories, and the locations for capturing and exchanging data and information between local processes and local/global clouds.

The digital twin is the main feature of our model. The digital twin is necessary for the visualisation of different layers, for the optimisation of systems and processes and for decision making. The data for the digital twin is collected from every local production process as well as the production line and is stored in different local clouds (databases). RAMI 4.0 does not clearly indicate how the systems and processes of smart factories cooperate with each other.

The proposed architectural model of the smart factory enables more reliable, simple and easy modelling of a smart factory than the existing RAMI 4.0 on every scale, from the small and simple to the big and complex production systems. It enables professionals in the production environment to see clearly all the details of the distributed concept of the smart factory; they see very clearly where in the process and in the system they have to position the global digital agent and all the local digital agents as well as where to position the different types of digital twins of the processes, systems and products. The model also gives the end-user very clear information about how to establish all the connections for data and information flow among the digital agents, digital twins and all the other building blocks of the smart factory. Therefore, it is a very suitable and helpful tool for professionals in the production environment. A comparison of the main features of both models is presented in Table 1.

5. Conclusion

In this paper we proposed a new architectural model called LASFA and compared it with the RAMI 4.0 model. The LASFA model combines different layers and shows a clear graphical presentation of all the key elements as well as their interconnections in a two-dimensional platform, which are important for the planning and design of smart factories. Our conceptual model is constructed in a very logical manner and can help industrial companies transform their manufacturing processes and systems into the factories of Industry 4.0.

We explained why the LASFA model is better for planning smart factories than the RAMI 4.0 model, which is an architectural reference for Industry 4.0. We found many advantages of our model, especially the visualisation of digital twins, the integration of different digital agents at different locations and levels, an accurate inventory of the local production process with the location of data capture, links between systems, the concept of integrating ERP, MES, and PLM into smart factories, etc.

On the other hand, RAMI 4.0 integrates different standards for automation, such as IEC 62890, IEC 62264, IEC 61512. The RAMI 4.0 architectural model shows a global view of Industry 4.0 from different vertical layers (Asset, Integration, Communication, Information, Functional, and Business). This gives us a complex and not so transparent three-dimensional view, which greatly enhances the complexity of understanding. In this case each layer on the vertical axis is treated separately and therefore we get a two-dimensional view of each layer.

The research discussed in this paper contributes an innovative architectural model and key design principles of the future factories at our laboratory. The LASFA model enables users to easily plan smart factories with all the necessary systems and to study the communication links between them. The architectural model shows very clearly how the communications between systems take place, where it is necessary to capture the data for the planning of digital twins in different layers of a smart factory, and it shows the visualization and which layer the users can access, etc. The digital twin represents the main feature of a smart factory in the newly proposed model.

In our future research work we plan to constantly improve the architectural model according to the newest scientific and industrial demands. Our main focus will be the area of big data and smart data collection, which are needed as the inputs for the development of different digital twins in different layers.

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Appendix A

The list of the abbreviations in the paper:

AI	Artificial intelligence
BITKOM	The name of German's digital association
CPS	Cyber-physical system
ERP	Enterprise resource planning
IHK	Industrie- und Handelskammern
IIoT	Industrial internet of things
IIRA	The industrial internet reference architecture
IoT	Internet of things
I/O unit	Input/output unit
IT	Information technology
LASFA	LASIM smart factory
LASIM	Laboratory for handling, assembly and pneumatics
MES	Manufacturing execution system
PC	Personal computer
PLM	Product lifecycle management
RAMI 4.0	Reference architectural model Industry 4.0
RFID	Radio-frequency identification
SBC	Single board computer
SITAM	The Stuttgart IT-architecture for manufacturing
VDMA	Verband Deutscher Maschinen- und Anlagenbau