Interoperability of the Future Factory: an Overview of Concepts and Research Challenges

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Abstract: Interoperability is a key factor in implementing a virtual factory. In European Union context interoperability is the ability of organisations to interact towards mutually beneficial goals, involving the sharing of information and knowledge between these organisations, through the business processes they support, by means of the exchange of data between their ICT systems. Interoperability of virtual factory synthesizes software components, application solutions, business processes and business context throughout the diversified, heterogeneous, autonomous procedure, assembled from multiple independent factories or smart/digital factory networks. EU H2020 "vF Interoperation suppoRting buSiness innovaTion" (FIRST) aims to provide new technology and methodologies to describe manufacturing assets; to compose and integrate existing services into collaborative virtual manufacturing processes; and to deal with evolution of changes. As a part of research results of the FIRST project, we present a comprehensive review on basic concepts of factories of the future, i.e. smart factory, digital factory, and virtual factory. The relationships among smart factory, digital factory and virtual factory are studied. In this paper, we define virtual factory interoperability and outline the research challenges related to interoperability of virtual factory.

Keywords: interoperability, virtual factory, digital factory, factories of the future, industry 4.0.

Reference to this paper should be made as follows: Author. (xxxx) 'Title', *Int. J. xxxxxxxxxxx xxxxxxxxxxx*,

1 Introduction

The manufacturing industry is entering a new era in which new ICT technologies and collaboration applications are integrated with traditional manufacturing practices and processes to increase flexibility in manufacturing, to enable mass customisation, to increase speed, improve quality and to improve productivity. Virtual factory models need to be created before the real factory is implemented to better explore different design options, evaluate their performance and virtually commission the automation systems thus saving time-to-production (EFFRA, 2013) and reducing costs. Virtual factories as a foundational concept to future manufacturing allow the flexible amalgamation of manufacturing resources in multiple organisations to model, simulate, test factory layouts, and processes in a virtual (reality) environment, virtual factory design and virtual factories, finally creating the real factory in shorter time, with demand driven product lines (UK FoF, 2013).

The project “vF Interoperation suppoRting buSiness innovaTion” (EU H2020 FIRST) provides new technology and methodologies to describe manufacturing assets; to compose and integrate existing services into collaborative virtual manufacturing processes; and to deal with evolution of changes. In this paper, we present a comprehensive review on basic concepts of factories of the future in Section 2, i.e. smart factory, digital factory and virtual factory; frameworks for development different factories as well as the applications of different factories. Section 3 studies the relationships between smart factory and digital factory. The relationships between digital factory and virtual factory are presented in Section 4. Comparison of smart factory, digital factory and virtual factory is presented in Section 5. We define interoperability of virtual factories in Section 6. Challenges of interoperability of virtual factories are introduced in Section 7. Section 8 summarizes and concludes the paper.

2 Terminology

One of the core initiatives for a factory of the future was introduced by Germany in their Industry 4.0 programme (Davies, 2015). This programme provides awareness into how a factory of the future will change businesses and lists the challenges organisations will face, especially for SMEs.

The Factories of the Future initiative prompts the use of new technologies such as Cyber Physical Systems (CPS), Internet of Things (IOT) and Virtual Reality (VR), to integrate and connect the manufacturer’s processors. Using these technologies allows a manufacturing organisation to improve its productivity, cost per item and efficiency adhering to customer order trends (Union, 2015). Industry 4.0 brings disruptive changes to supply chains, business models, and business processes (Schmidt, et al., 2015, June).

2.1 Smart factory

Lucke et al (2008) mentioned that the smart factory is a manufacturing environment, where humans and production processes as supported by the presence of intelligent, computer-based systems ensuring a seamless, continuous flow of production for increased performance and quality.

Smart factories interconnect systems which are integrated, equip manufacturing hardware with sensors, actors, and autonomous systems (Roblek, et al., 2016), as well as communicate via Internet of Things (IoT) technologies and Cyber-Physical Systems in order to be adaptive and reactive to changes that occur inside or outside the production process (Kang, et al., 2016), (Stock & Seliger, 2016).

Hermann, Pentek, and Otto (2016) define a smart factory as a factory that is context-aware and assists people and machines in the execution of their tasks. They are able to do this by gathering and using information from the physical and virtual world. It can be use information such as the position of a tool to electronic drawings of the product it is producing or of the tool itself.

Certainly, the smart factory is an integrated system, which always relates to possess machines equipped with sensors and executors. Data are collected, sent, received, processed accordingly (Stock and Seliger, 2016; Wang et al., 2016). The machines can communicate with each other to fulfil predefined tasks. The system of a smart factory are organizes and configures machines and sensors purposefully to reach the same objective (Suginouchi et al., 2017; Tang et al., 2016).

The smart factory has value creation modules. At the highest aggregation level, the value-added integration contains a hierarchical information flow from field level sensors to the ERP, through control systems, e.g. PLCs and Supervisory systems, e.g. SCADA (Chen, 2005) as well as integration of different production systems in an intelligent supply chain. At a lower aggregation level, the value-added integration includes as the manufacturing lines, manufacturing cells or manufacturing stations. Together it makes value-added integration occur horizontally and vertically in the manufacturing process (Stock & Seliger, 2016).

The Reference Architecture Model for Industry 4.0 (RAMI 4.0) defines three dimensions of enterprise system design and introduces the concept of Industry 4.0 components (VDI/VDE GMA, 2015), with thinking about the various efforts that constitute Industry 4.0. RAMI spans the entire product life cycle & value stream, hierarchical levels and architecture layers. This allows common understanding and placing of standards in the picture. RAMI 4.0 was not designed only for smart factories. On the hierarchical structure axis of RAMI 4.0 in Figure 1, from field devices to enterprise levels cover most of smart factory concepts. On the architecture axis, smart factory covers mainly the asset layer which contains physical things in the real world and the integration layer which includes transition from real to digital world. If the smart factory only refers to the shop floor automation, the product life cycle axis can apply to the smart factory when the products of smart factory are smart products. The product life cycle describes the product type and instances in term of development/production and maintenance usages as well as how smart products feedback the information to improve the smart factory processes.

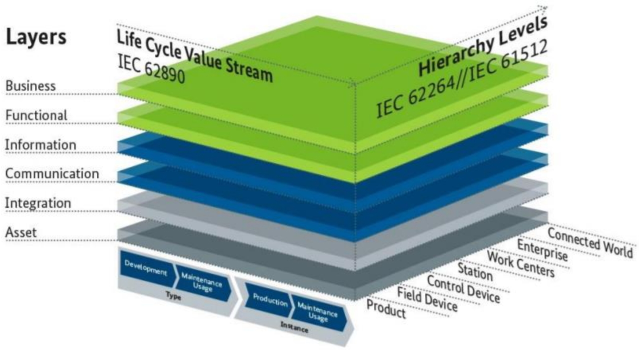

Figure 1: Reference Architecture Model for Industry 4.0 (RAMI 4.0) (VDI/VDE GMA, 2015)

The FITMAN smart factory architecture in Figure 2 is targeted to support: application services (e.g., legacy systems), through which production processes are managed, and workers. Finally it aims improving the workplaces and offer works customized views of the production facility and processes or to provide them the opportunity to act on these elements.

The sources of the data require to achieve the management objectives of the Smart Factory systems. The data can originate from the outside of the production plant as well as from within the production facility. Two middle layers provide functionalities to manage collected events from the back–end layer as well as to manage device and data adaptation from shop floor and external events.

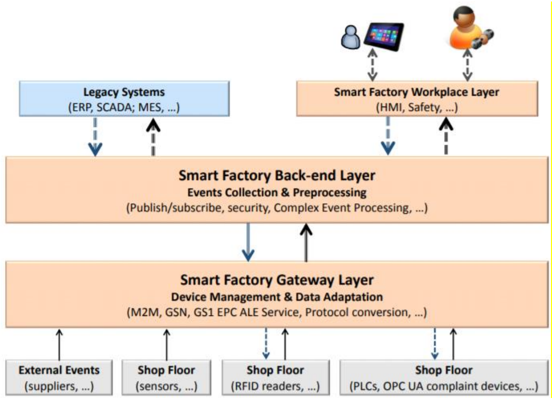

Figure 2: FITMAN Smart Factory Reference Architecture (FITMAN, 2013)

The FITMAN smart factory architecture was later on developed into FIWARE smart factory reference architecture in Figure 3 (FIWARE, 2015a) , which aims at enhancing physical processes and at enabling a more efficient, flexible and safe shopfloor by supporting machine-vs-machine and human-vs-machine convergence (FIWARE, 2015a).

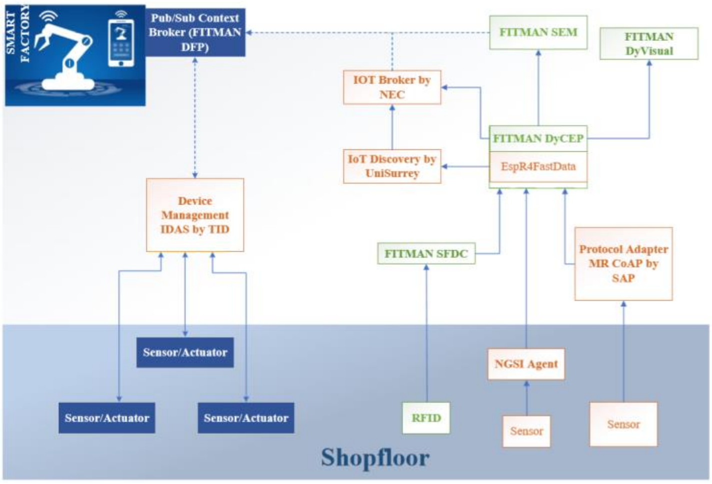

Figure 3: FIWARE Smart Factory Reference Architecture (FIWARE, 2015a)

An example of smart factory is a case where A Whirlpool manufacturing process which is characterized by and sub-optimized decision process in which workers acting at different levels of factory organization are asked to make decisions with poor IT support. At a lower level an event happens at the production shop floor. It is constituted by intelligent equipment such as industrial PCs, which are controlling and gathering signals from production processes. The middle level is where signals and raw data are firstly correlated one each other and stored.

Currently, users can access data through the interface at both lower and middle levels in a proactive manner to query for an event, correlation of events, examine related data, and then makes a decision. Despite a huge quantity of events being detected and recorded at the shop floor level, very few of them are effectively used to help decision-makers. This inefficiency could be a driver of poor quality; cost increases, customer dissatisfaction, etc.

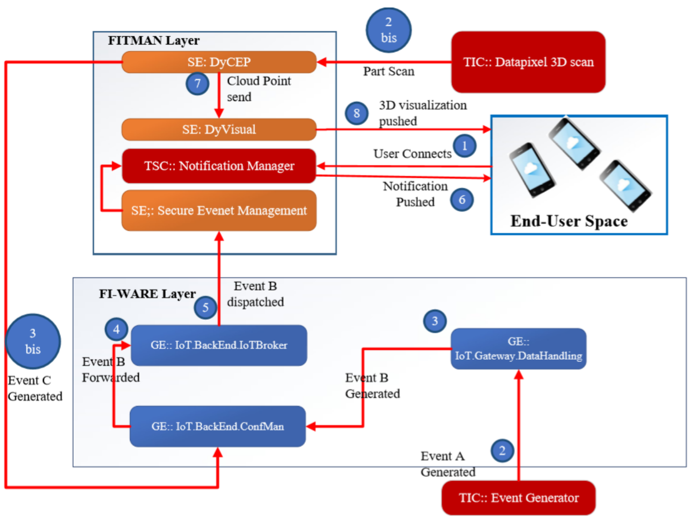

Figure 4: Implementation Architecture of Whirlpool Smart Solution (FITMAN, 2015)

The low part of Figure 4 is FIWARE layer which supports IoT data collection and deviser management. The events from the bottom level are dispatched through Secure Event Management to be analysed further. The upper part of Figure 4 is FITMAN layer, Dynamic CEP (DyCEP) is expected to broaden the range of monitored shop-floor events and to apply AI techniques to their analysis. This pro-active solution detects critical situations with little or no hard-coded event processing logic. At the same time, Dynamic Visualisation (DyVisual) provides an alternate, more advanced end-user terminal for Whirlpool personnel, which will improve the real-time situation awareness on the assembly line.

2.2 Digital factory

A digital factory utilises the capability to quantify large amounts of data, which is typically received from the smart factory level hardware for decision-making processes and on creating simulations of designed prototypes for speeding the process of going to market, etc. (Bracht & Masurat, 2005). Based on the data collected,

The front-end stages of manufacturing include early concept modelling, simulation and evaluation as well as acquisition of knowledge to allow better-informed manufacturing decisions to be made. Digital factories provide a better understanding and design of production and manufacturing systems, thus improving the product lifecycle management through the use of modelling, simulation, and knowledge management from the product conception level down to the manufacturing, maintenance, disassembly, and recycling (EFFRA, 2013).

Thus a digital factory is also an integration platform for design, engineering, planning, simulation, communication, and control on all planning and manufacturing levels (Kuhn 2006). Overall they imply that the digital factory is a link between the ‘what’, product development (CAD), and the ‘when and who’, process planning (ERP), with the use of common data to provide the ‘how’ within the product lifecycle.

The Digital factory concept is also viewed as a mapping of most of the technical and business processes into the digital world (Maropoulos, 2002), (Kádár al et, 2010), (Monostori, 2014), which collecting data from smart equipment enables the performance of flexible and adaptive processes along the entire value chain optimisation. Information exchange is facilitated through integrating ERP systems with manufacturing equipment through CPSs or M2M communication methods.

Digital factory provides a high level of integration and the autonomous exchange of information will allow real-time requirements changes (Pereira & Romero, 2017). It is especially useful for detailed requirement changes, not the changes such as numbers of orders. Besides communication broadband, IoT, and sensors networks, main enable technologies are big data analytics and cloud computing for innovations of digital factory.

As mentioned before RAMI 4.0 was not only designed for smart factories, but also for digital factories. At the hierarchical structure axis of RAMI 4.0 as shown in Figure 1, the enterprise level and the connected world level cover digital factory concepts, for example legacy systems ERP, CRM and SCM systems for one organisation belong to these levels. At the architecture axis, digital factory covers mainly from the communication layer to the business layer which contains collecting lower level data from the shop floor, analysing the data to combine the managerial data to form information to implement transition from physical world to digital world. When the product life cycle axis applies to the digital factory (see Figure 5), it covers both product type and product instance. The product type of development and maintenance usage reflects to the product instance for production and maintenance usage reflect the construction plan, the production and facility management respectively. The product could be a physical product or a digital product.

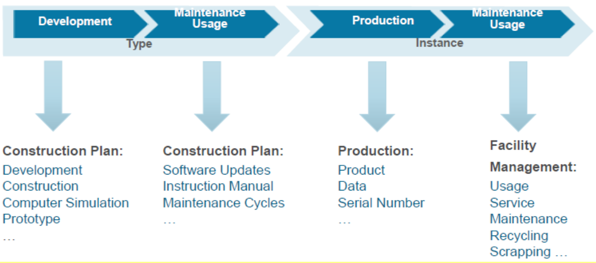

Figure 5: Product Life-cycle of RAMI 4.0

FITMAN digital factory reference architecture in Figure 6 provides two middle layers in which the lower layers access the data (collected from the shop floor, machines, etc) as well as aggregate and manipulate these data. The upper layers use data from the lower layer as and the dada from legacy systems to process and render data using rich and effective presentation and virtualization features to support advanced business processes. The legacy systems in the middle of the figure have a double role as storage systems, which manage products related data and the legacy systems and process and integrate to fulfil the objectives of the digital factory architecture. The legacy systems provide services to be integrated within the overall functional architecture. The proposed functions of the digital factory includes daily activities for both within and outside the manufacturing company, such as product design, production line design, operation, maintenance, etc.

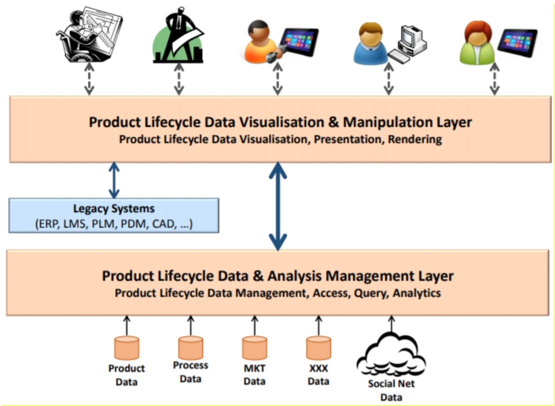

Figure 6: FITMAN Digital Factory Reference Architecture (FITMAN, 2013)

The FIWARE digital platform reference architecture (FIWARE, 2015b) organises the FIWARE assets to support the development of knowledge-based manufacturing processes aiming at improving the time-to product and time-to-market of products and services, managing more efficiently the product life-cycle information from heterogeneous sources (ERP, social networks, CRM, PLM, social data).

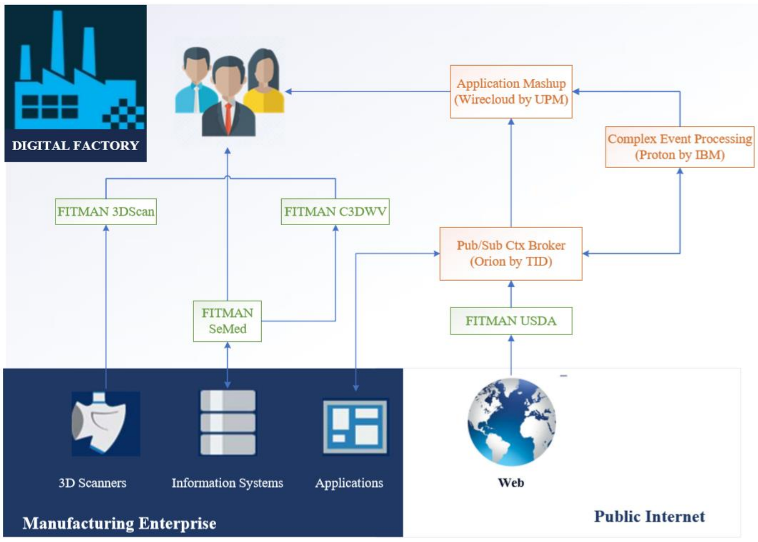

Figure 7: FIWARE Digital Factory Reference Architecture (FIWARE, 2015b)

AIDIMA is the technology institute on furniture, wood, packaging and related industries (AIDIMA 2017). Especially the furniture manufacturing sector of AIDIMA focused on trends forecasting and collaborative product design in. Currently, trends analysis is handled by a multi-disciplinary team of experts that follow a very manual process.

The design of AIDIMA digital factory aims to detect furniture trends from different sources; to decrease the time to collect potential trends from well-reputable sources; to connect to the sentiment and opinions of furniture from the final customer; and to make key decision through collaborative tools in the creation of new products (FIWARE, 2015d).

The AIDIMA architecture solution in Figure 8 is an instantiation of the digital factory general reference architecture in Figure 7. The *unstructured and social data analytics SE* provides functionality to tag tweets and facebook posts with sentiments, *virtual obeya SE*, along with *collaborative 3D web viewer*, *PLM iLike SE* and *integrator SeMED* provide a collaborative solution that integrates diverse information from web applications already in used by AIDIMA. *UPV* has developed *text indexer engine* and *weak signal server*, a couple of the specific components that execute text mining on RSS sources and identify trends that can be manage, promoted and store on SQLServer databases. Finally, a set of specific interfaces, such as *furniture opinion analyzer*, *weak signal forecasting* and *collaborative innovative widgets*, have been developed for analysts and managers to tackle with all the previous information.

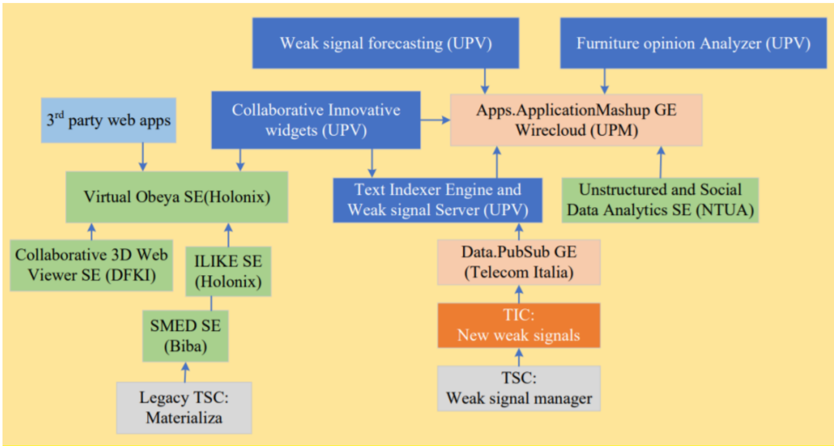

Figure 8: AIDIMA Digital Factory Architecture (FIWARE, 2015d)

2.3 Virtual factory

The concept of *virtual factories* is a major expansion upon virtual enterprises in the context of manufacturing (Xu et al. 2017). The virtual organization approach integrates collaborative business processes from different enterprises to simulate, model and test different design options to evaluate performance, thus to save time-to-production (Debevec, Simic, & Herakovic, 2014). In contrast, creating virtual factories requires the integration of product design processes, manufacturing processes, and general collaborative business processes across factories and enterprises. An important aspect of this integration is to ensure straightforward compatibility between the machines, products, processes, related products and services, as well as any descriptions of those. It also requires that the nature of the manufacturing processes is sufficiently well understood (and modelled) to support their efficient integration (aspects such as reconfiguration, maintenance, or warm-up time can be significant factors).

A virtual factory consist of a multi-layered integration of the information related to various activities along the factory and product lifecycle manufacturing related resources (Chungoora, et al., 2013) as well as real and virtual worlds. With support of cyber-physical systems, smart electronics, sensors, robots, and embedded systems (Da Xu, He, & Li, 2014; Monostori, 2014) data is constantly gathered to enable context-aware enterprise management to extensively support and speed-up the decision process (Davis, Edgar, Porter, Bernaden, & Sarli, 2012) not only in the design stage but also for management decisions (Bi, Da Xu, & Wang, 2014).

From a different perspective a virtual factory not only provides an integrated platform for manufacturing systems design and analysis cross different organisations (Tolio, Sacco, Terkaj, & Urgo, 2013), but it can also be an integrated simulation model of the major subsystems in a factory (Ghielmini, G. et al., 2013). The model considers the factory as a whole and provides an advanced decision support capability (Sanjay, Ngai Fong, Khin Maung, & Ming, 2001). To avoid terminological confusion we will call this a *virtualised factory*. The virtualised factory normally is an integrated simulation model for a factory which does not necessary cross different organisations.

Another term ‘digital twin’ is a digital replica of a living or non-living physical entity. Similarly there are there digital twin concepts for future factories, digital twin in the smart factory, digital twin in the digital factory and digital twin in the virtual factory.

Extending this virtualised factory concept, a virtual factory can also be seen as utilising a new piece of technology in the form of Virtual Reality. Using this technology, organisations can create 3D interface models with their designed production process, to have a better view of the intended process without the need for a prototype in its design process (Hao & Helo, 2017).

According to (EU, 2013), the virtual factory is a IT platform, which can be considered as the hardware, system architectures and software necessary to undertake a range of related tasks. The foundational concept to virtual factory allows the flexible amalgamation of manufacturing resources in multiple organisations to model, simulate, and test factory layouts and processes in a virtual environment, to finally create the actual factory in shorter time, with demand-driven product lines or to simulate a desired factory before committing to investment.

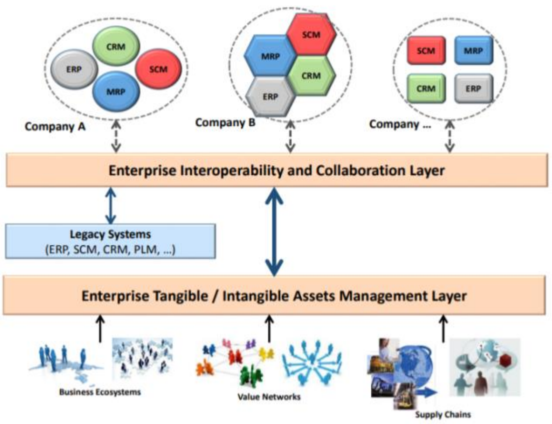

Figure 9: FITMAN Virtual Factory Overall Architecture (FITMAN, 2013)

Figure 9 presents the *FITMAN virtual factory reference architecture*. The lower layer includes a set of sources of information and data related to tangible and intangible assets that span from *supply chains*, *value networks*, and *business ecosystems*.

The two middle layers include *enterprise tangible/intangible assets management layer* and *enterprise interoperability and collaborative layers*. The *enterprise tangible/intangible assets management layer* manages discovery, classification and management of data pertaining to tangible and intangible assets involved in virtual factory business processes. The *enterprise interoperability and collaborative layer* supports cooperative business process design and management to assure cross-enterprise boundaries interoperability and collaboration. The *enterprise legacy systems* stress the relevance of the interoperability and integrability across enterprises.

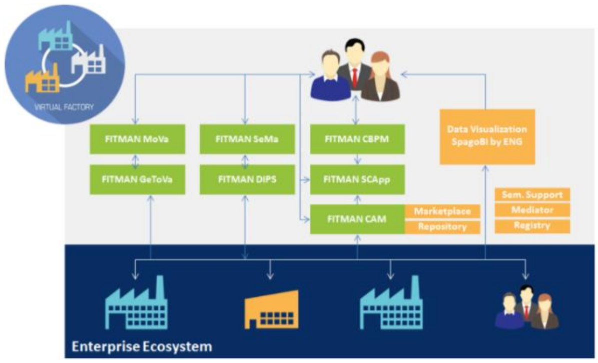

Figure 10*: FIWARE Virtual Factory Reference Architecture (FIWARE, 2015c)*

The *FIWARE virtual platform reference architecture* extends cloud manufacturing and digital marketplaces, targeted at distributed organizations and virtual enterprises (FIWARE, 2015c). The virtual platform brings the business ecosystem framework from FIWARE's Apps Chapter into the manufacturing domain: six GEs, dealing with enterprise collaboration/ interoperability and with digital asset sharing, are the foundation of a higher-level software layer.

FITMAN CAM performs collaborative assets management which a platform for the virtualization and management of digital assets. *FITMAN SCApp* supports supply chain and business ecosystem apps, which is a web-based application for exploiting digital assets in the context of capacity scheduling and team building processes. *FITMAN CBPM* provides collaborative business process management which is a web-based design and execution environment for semantically-annotated business processes (FIWARE, 2015c).

FITMAN DIPS runs data interoperability platform services, which is a platform, based on open standards like WSMO and WSMX, supporting semantic-based web service interoperability. *FITMAN SeMa* represents metadata and ontologies semantic matching is a desktop application which helps users to define conceptual mappings (i.e., translations) between different OWL-based ontologies and XML schemas (FIWARE, 2015c).

TANet demonstrates to forma a virtual factory instance, which describe intuitively how to generate, compose and transform virtual representations of in-/tangible assets (VAaaS) through a user-centric graphical interface for dynamic discovery and flexible composition of Virtualized in-/tangible Assets (as a Service). The other SE from STI is the Generation and Transformation of Virtualized Assets (GeToVA), which supports semi-automatic generation and clustering of *Virtualized intangible Assets (VAaaS)* from real-world semi-structured enterprise and network resources.

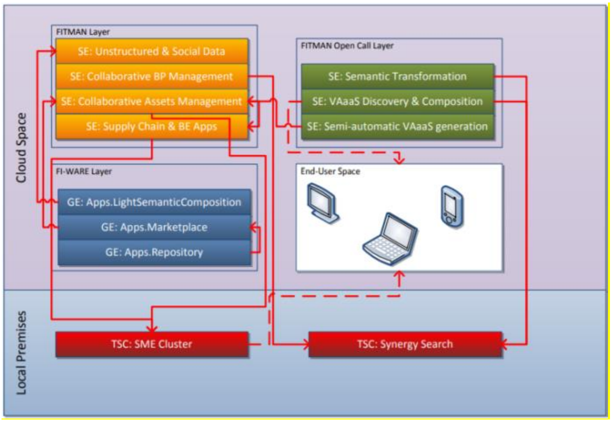

Figure 11: Virtual Factory Reference Architecture Instantiation (FITMAN, 2015b)

All suppliers are registered in SMECluster. Information such as their productions, assets will be gathered into *SE: Collaborative Assets Management*. A workflow diagram for the supplier to support future decisions could be designed using *SE: Collaborative Business Process Management*.

Facilitators will be able to enter tenders into the system. Facilitators will also be able to identify trends in tenders using *SE: Unstructured and Social Data Analytics*, such as the number of tenders in a particular industry area, or the rate at which tenders become available over time.

Once opportunities and assets exist within the system, the facilitator can choose an opportunity they wish to fulfil. This will use *SE: Supply Chain and Business Ecosystem Apps*, consuming data in *SE: Collaborative Asset Management*. *TSC: Synergy Search* will be used to create a number of asset clusters capable of fulfilling the opportunity. The facilitator will then use their experience and business domain knowledge to select the most appropriate cluster to form a virtual factory.

3 Relationships between smart factory and digital factory

Smart factories consist of interconnected systems which are integrated and communicate via Internet of Things (IoT) technologies in order to be adaptive and reactive to changes that occur inside or outside the production process (Kang, et al., 2016). A smart factory does not imply deeper horizontal integration of the smart manufacturing process. The smart factory mainly focuses on the hardware layer of a factory floor.

When smart and digital factories are both implemented in one organization, the smart factory enables the collection of data which is utilised at the digital factory level. The smart factory is integrated with a digital factory by enhancing the virtual models created within the digital factory with real time data to improve decision making.

In general, when a factory includes both smart and digital factories, there is no clear line as to where the transition from a smart factory to a digital factory occurs. This separation can be very situational with respect to the design of the framework. IoT devices are an integral part of a smart factory's architecture and enable the connection between a digital and smart factory to exist. Yet the management of these devices can occur in either framework. Additionally, there is ambiguity over where the management of the data created by the IoT devices can be situated. Key is that the data is collected and managed such that it semantically meaningful at the digital factory level. In other words, it must go beyond providing metrics of a single device for purely human consumption.

At the smart factory level, it can provide both the device management and data management within its domain. The FIWARE for Industrial IoT Reference Architecture, shown in Figure 12, demonstrates this by placing the device management at a lower level of the smart factory architecture and the data management at a high level. This can be beneficial for a factory that wants to focus on the fundamental behaviour of their shop floor. The devices and data they produce are able to be monitored and acted upon without the need to look at the product lifecycle as a whole.

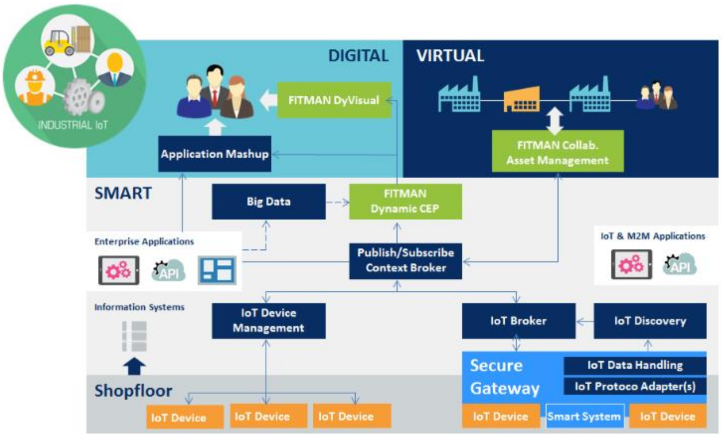

Figure 12: Industrial IoT Reference Architecture (FIWARE, 2015d)

Additionally, a digital factory can provide device and data management within its domain. The BeInCPPS reference architecture (BeinCPPS, 2016), as shown in Figure 13, demonstrates this by placing the field device management within the factory block, which can be translated to the digital factory domain. The architecture also shows that data management happens within the digital factory domain, through big data and event processing. The device management within the digital factory will appear at a lower level of the architecture whereas the data management will appear at a much higher level. Placing these within the digital factory domain allows an enterprise to define better knowledge-oriented decision making processes that impact the whole product lifecycle.

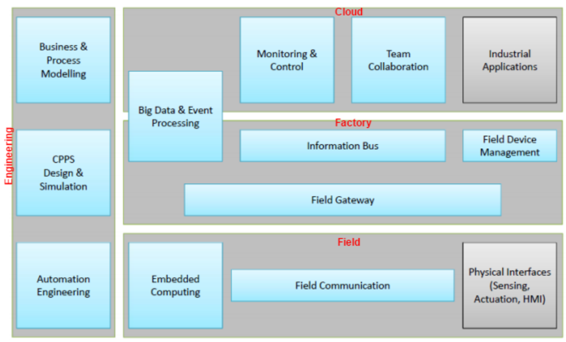

Figure 13: BeInCPPS Block Reference Architecture (BeinCPPS, 2016)

Virtual engineering objectives (VEO), virtual engineering processes (VEP), and virtual engineering factories (VEF) are a specialized form of CPS (Shafiq, et al., 2016). A VEO is a knowledge representation of an objective capable of capturing, adding, storing, improving, sharing, and reusing knowledge through experience. VEP is a knowledge representation of manufacturing process/process planning of artefact having all shop floor level information regarding operations required their sequence and resources needed to manufacture it. VEF is an experience based knowledge representation for a factory encompassing VEP and VEO within it. At the final phase, VEF could create a complete virtual manufacturing environment which would make use of the experience and knowledge involved in the factory at all levels. Virtual models of the factory can be enhanced with the data collected by IoT sensors to assist in the decision making process of upgrading the shop floor to improve a current product or make room for a new product. Within this research, it shows a relationship between smart factory and virtual factory without a digital factory in between.

In conclusion, there are two unique areas where there is overlap between the smart and digital factory domains. The first area identified is the management of IoT devices; it was observed that it can function within the low level of a smart factory or the low level of a digital factory. The second area identified is the management of data created by the IoT devices within the smart factory. It was observed that it can function within the high level of a smart factory or a high level of a digital factory. The observations will be important requirements to include in the creation of the artefact. The relation between smart factory and virtual factories could be also direct represented without a digital factory in between.

4 Relationships between digital factory and virtual factory

The FITMAN project has done extensive work in the area of digital and virtual factories. Within this project, the explored solutions (FITMAN, VOLKSWAGEN Trial – PLM Ramp up reducing Time to Market, 2015) are integrated from product inception to high-volume manufacturing across the factory and also the company boundaries. Within FITMAN, the aim of a virtual factory is to support the integration and exchange of data and physical assets through global networked operations to gain clear and exact useful knowledge while enabling and supporting the decision making process. Thus, from this perspective, the virtual factory deals with the collaboration of design, production process, and the extended supply chain.

Similar to the ambiguity in the distinction between smart and digital factories, there is an ambiguity with respect to where a digital factory stops and where a virtual factory begins. This ambiguity can lead to scenarios where both accomplish the same tasks depending on whether virtual or digital factory reference architectures are used. Traditionally, a factory would have a supplier management module located within their supply chain management system (SCM). The SCM is located within the enterprise information system of the supply chain owner. Suppliers linked to the supply chain would have access to the SCM system. However, within the realm of Industry 4.0 and increased competition for the prices of supplied materials, the SCM can be implemented within the virtual factory architecture through the means of a virtual supplier community. The virtual supplier community allows for more efficient operations and a reduction in administrative cost.

A key aspect of a virtual factory, in this definition, is that of being able to collaborate with other businesses through the use of software solutions expanding outside the company boundaries. The virtual factory offers the opportunity for the business and its suppliers to collaborate on business processes that affect the supply chain.

A lower level view of Figure 3, produced by Industrial IoT Reference Architecture (FIWARE, 2015c) shown in Figure 4, allows us to see how the collaboration between the factory and its community of suppliers can occur. The (FITMAN, 2015) generic and specific enablers, for example the FITMAN SCApp which stands for Supply Chain and Business Ecosystem Apps which facilitates the collaboration among supply chain and business ecosystem partners. It allows the factory to easily engage with 3rd party suppliers or partners over a network depending on the business opportunity.

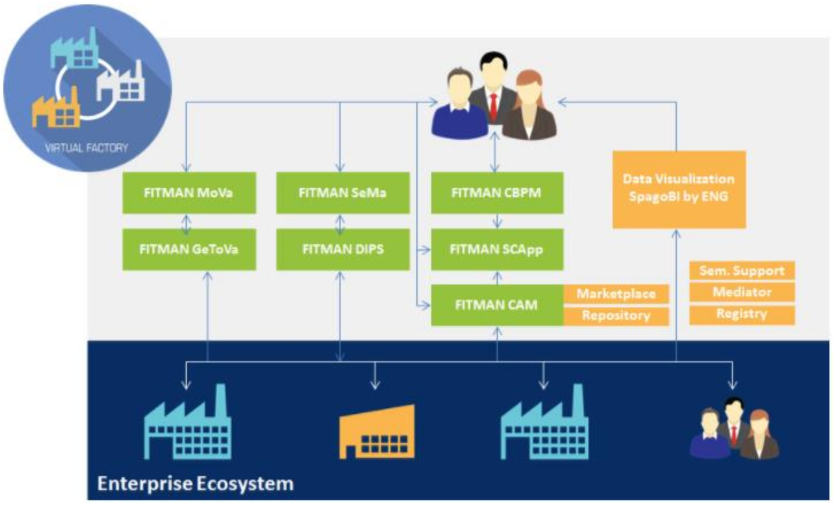

Figure 14: Industrial IoT Virtual Factory Reference Architecture (FIWARE, 2015c)

The virtual factory model is suited towards a business that requires many independent suppliers with frequent design changes or product changes, for example, a mobile phone company. They are able to use the community to quickly and easily collaborate with different suppliers for new phones that require new or upgraded hardware.

One notices in Figure 4 that the design and simulation engineering module is located in line with the factory block, which is associated with the digital factory. This means that the design of new products can be kept within company boundaries. However, it can also be seen that the team collaboration is located within the cloud block, this implies that the design assets can be the object of collaboration by teams within the company and the suppliers. It is important to note that no business processes will be changed by the collaboration, but the product designs are likely to change.

The digital factory is suited for businesses that need long term relationship with their suppliers, typically on a fixed term. A natural example of where this architecture best fits is an automobile manufacturer. Although they may release new products frequently, the lifecycle of the product is much longer compared to the production, and parts will need to be manufactured for many years. The parts that are required from the supplier are unlikely to change and therefore a network connection between the two businesses is not essential.

Overall, we can see that there is a strong situational overlap between the digital and virtual factory. A virtual factory can provide collaboration between design, production and the supply chain of a product with a networked community of suppliers and 3rd party applications. In contrast, a digital factory provides collaboration between design, production and the supply chain of a product within the company boundaries. It can thus be said that a virtual factory provides collaborative business processes with different partners whereas a digital factory can provide collaborative asset management with different partners.

5 Comparison of smart factory, digital factory and virtual factory

Smart factory, digital factory and virtual factory are realizations of potential transformation from machine dominant manufacturing, digital manufacturing, to distributed manufacturing respectively. They are also bringing the emergence of new business models that better meet customers' changing requirements, through the real-time communication capability along the whole supply chain (Erol, S., 2016).

Smart factory uses smart machines, smart materials, and smart products are tracked along their whole lifecycle time, allowing a high degree of customization. Digital factories are connected to a value chain in order to fulfil market requirements and consist in the integration between machines and materials through standardized interfaces. Virtual factories not only allow connecting to a value chain in order to fulfil market requirements and consist in the integration between machines and materials through standardized interfaces, but also allow the distributed manufacturing to deliver the product to customers in a smart and eco-friendly fashion.

These new industrial paradigms can be described as the manufacturing environment's increased digitization and automation in addition to an increased communication enabled by the creation of a digital value chain (Oesterreich, T. D., & Teuteberg, F. 2016). According to Kagermann et al. (2013), the main features of the Industry 4.0 concept are characterized by three dimensions of integration (Kagermann et al., 2013): (1) horizontal integration through value networks, (2) vertical integration and networked manufacturing systems and (3) end-to-end digital integration of engineering across the entire value chain.

Table 1 presents, based on Sections 2, 3 and 4, a brief comparison among smart factory, digital factory and virtual factory. We look at 10 different aspects. The triggering technologies present enable technologies. The technology requirements mentioned what the related results need to be achieved after applying the technologies. The system control indicates which aspects of the factory could be controlled. The potential development platforms are categorized in the key development platform. Different types of innovation related to the different future factories are mentioned in the focus of innovations. The connectivity requirements of implementation of the different future factories are provided under the row connectivity requirements. The different types of future factories have different integration perspectives through value networks. The target organisations specify who will be the organisation will adopt different future factories. The key risks are related to potential risks of the different future factory.

Table 1: Comparison of smart factory, digital factory and virtual factory

	Smart factory	**Digital factory**	**Virtual factory**
Triggering technological discontinuity	IoT, CPS, sensor networks, robotic	Data analysis technologies: machine learning, deep learning, big data, etc.	Cloud manufacturing; International data space, etc.
Technology requirements	Precision of production and manufacturing processes	Predictive production and manufacturing related processes	Self-aware, predictive production and manufacturing, enable environment adaptation for ecosystem
System control	Lean operations: work and waste reduction	Self-configure and self-maintain productivity	Self-aware and self-organizing, environment friendly productivity.
Key development platform	IoT reference architecture, RAMI 4.0, FIWARE framework ,	RAMI 4.0, FIWARE framework	RAMI 4.0, FIWARE framework
Focus of innovation	Hardware innovation	Software innovation	Business innovation
Connectivity requirements	Limited or no connectivity	Limited connectivity	Fast ubiquitous connectivity
Integration through value networks	Horizontal integration through value networks	Horizontal and vertical integration through value networks	End-to-end digital integration of engineering across the entire value chain
Target organisations	Manufacturer;	Manufacturer;	SMEs/manufacturer associate service providers
Key risks	Strong hardware system lock-in; high direct switching cost; de-facto standardization. data interoperability	Strong software system lock-in; high direct switching cost; de-facto standardization. process interoperability	Ease of use, benefits of network externalities and complementary offerings, participations as co-developers. Trust, service interoperability

6 Interoperability of virtual factories

Interoperability is one of important principles of Industry 4.0 required to implement a smart factory, digital factory, or virtual factory (Shafiq, et al., 2016). Interoperability is defined as “the ability of two systems to understand each other and to use functionality of one another’’, which implies the capability of two systems exchanging data, and sharing information and knowledge (Chen, et al., 2008). According to European Union, (European Union, 2017), interoperability is the ability of organisations to interact towards mutually beneficial goals, involving the sharing of information and knowledge between these organisations, through the business processes they support, by means of the exchange of data between their ICT systems.

Interoperability in global manufacturing networks must address knowledge management across enterprises (Gagliardo, et al., 2015)(Terkaj, et al., 2014), while the generation and management of digital/smart factory data as well as enabling a machine-to-machine inter-organisation knowledge management and sharing are key problems of Virtual Factory approaches (Kádár, et al., 2013). Furthermore, data from digital and smart factories need to be in the matching of the data structures and analysed (Panetto & Cecil, 2013), It is difficult to get aggregate values for the analysis from different factories with an enormous amount of data (Li, et al., 2015) (Stock & Bildstein, 2014) (Wang & Xu, 2013). Nevertheless, the realization of a full-scale virtual factory needs the efforts of interoperability at different levels, such as data, models, services, assets and processes (Wang, et al., 2016).

Within the (Web) service area (Dorn, et al., 2007) there is a large body of work on (semantic) interoperability and process composition. EU projects such as SOA4ALL, ATHENA, SUPER and COMMIUS have made contributions in this area (but not in the context of manufacturing). The main focus of these projects has, however, not been on discovery directed by business users, but on lower level integration. There are some drawbacks to the outcomes of that research, such as the fact that the used semantic query languages, while powerful, are not known for their ease of use. The possibilities, however, are now well-understood, and the previous experience from EU FP7 SOA4All and FAST projects can be applied to manufacturing, recognising virtual factories as being composed of manufacturing services (such as the use of an asset for given amount of time).

Other previous research from EU FP7 Smart Homes 4 All (SM4All), Greener Building projects can also be applied to virtual factories in teams of dynamic business process management and scalable architectures for managing manufacturing data. Other EU FoF (Factories of the Future) projects such as VENIS, FITMan, MSEE, GlobNet, ADVENTURE, BIVEE, IMAGINE, ComVantage, EXTREMERMEFACTORIES, and VFF are in the domain of virtual factories. There are recognised knowledge gaps in that these projects do not comprehensively address end-user aspects such as allowing on-the-fly service-oriented manufacturing process model verification, or setting up a useable BPaaS (Business Process as a Service) to support virtual enterprise business innovation.

Our EU H2020 FIRST project therefore defines interoperability of virtual factory to synthesize software components, application solutions, business processes, and business context throughout the diversified, heterogeneous, and autonomous procedure at different levels, such as data, models, services, assets, processes and businesses in the manufacturing context.

7 Challenges for interoperability of virtual factories

The continuous upgrade, update and maintenance of virtual factory models and tools along the factory lifecycle faces practical challenges that hinder the usage of approaches typical of the design phase also during the operations of a factory. These VF models are usually not updated and usually fail to guarantee digital continuity (Terkaj, et al., 2015). Service-Oriented Architectures (SOA) and environments are designed for systems interoperability. Manufacturing service orientation, interoperability and service-based negotiation (Coutinho, et al., 2016) are seen as fundamental to a service-base for advanced collaboration in enterprise networks; an important solution to improve interoperability among manufacturing enterprise organisations.

Standards are the implementation of the technical requirements of interoperability of a virtual factory. Universal standards are required to be processed by manufacturing hardware assets and services among the participants and activities across diverse levels. It is a problem to determine exactly where virtual factory interoperability standards are need. A great amount of the existing standards are used in networked enterprises/manufactures, virtual enterprises, and virtual organisations, the diverse requirements of the different systems and the strong demands of the companies for immediate launching new standards for specific industrial sectors.

According to the position paper (Missikoff, et al., 2012) the Future Internet will enable enterprises to interact with other entities within (intra) and outside (inter) the enterprises (e.g. suppliers, business partners, employees, workers, customers) in a seamless way. Interoperability is basic factor of data exchange which must be extended from techniques and tools to all enterprise ICT systems. Interoperability of virtual factory is a must for effective cooperation of different Internet resources. Security is a key aspect of interoperability of virtual factory for across enterprise applications. Security means that policies are necessary to be conducted and conformed to, in order to keep the information and the process safe and reliable. Appropriate risk assessment activities and security measures are needed.

The ‘virtual factory’ is aiming to manufacture in adaptable networks linking small-, medium- and large-sized OEMs (original equipment manufacturers) with value-chain partners and suppliers of factory equipment/assets/services selected according to needs at a given time. The formed virtual factories are not limited by the presumption of physical co-location or long-term collaborations. Multilateral solutions allow the interoperability of virtual factory to be achieved with the fulfilment of different requirements from different partners. Variability of different solutions/virtual factory models and how to adapt the potential alternative solutions/virtual factory models are challenging for interoperability of virtual factory.

In general the interoperability of virtual factory related to any newly developed ICT related the production and the industrial environments requires complementary research and innovation efforts. An evolutionary view of the interoperability, change management will play a key role for generating and maintaining virtual factories among different industrial sectors.

8 Conclusions

Virtual factory and related technology are under development today, but the implementation of virtual factories is important for realizing a fourth industrial revolution (industry 4.0). Interoperability of virtual factory has a basic role for factories of the future, so an overview has been given on basic concepts of smart factory, digital factory, and virtual factory. The relationship between smart factory and digital factory as well as the relationship between digital factory and virtual factory are studied.

Based on our research, we further define virtual factory interoperability and outline the research challenges related to interoperability of virtual factory. It can be stated that important standards of virtual factories are missing. More efforts are required new standards for specific industrial sectors. Security is another challenge of distributed, cross-organisational virtual factories. Management and traceability of sensitive data, protected resources and applications or services are critical for forming and using virtual factories. Handling multilateral solutions and managing variability of different solutions/virtual factory models are also impact to the usability of the virtual factory. In short, the interoperability of virtual factory related to many newly developed ICT of the hardware and software innovation. An interoperation framework allows evolutional and handling changes, which is crucial for generating and maintaining virtual factories among different industrial sectors.

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