Industry 4.0 as Enabler for Effective Manufacturing Virtual Enterprises

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Abstract. Today, the variety of complex products, low volume and decreasing life cycles require a combination of multiple skills that, often, do not exist in a single organization. This raises the need to extend the traditional organization towards the extended virtual enterprise. During the last decade several research projects developed concepts, methods and tools to support the design and operation of the virtual enterprises. However, the impact in industry remains low mainly due to the lack of vertical and horizontal integration, both at business and technical level. Industry 4.0 may be the missing enabler for effective virtual enterprises, once it integrates both business entities and technical entities into a single concept - the Industry 4.0 component – thus enabling enhanced interoperability. This paper presents innovative Industry 4.0 approaches, concepts, methods and tools applied to real manufacturing environments, showing how they enable the creation of cyber-physical production systems leading to a flexible, efficient and seamlessly virtual enterprise.

Keywords: Virtual enterprise · Industry 4.0 · Internet of things · Cyber-physical systems · Intelligent product ecosystems

1 Introduction

During the last decades, increasing competitiveness pressure led companies to look at efficiency improvement opportunities obtained from a higher integration level between the design of the products, the design of production processes and the design of the value chains [1]. Mass customization and servitization are perhaps the most prevalent examples of responding to such competitive pressure [2]. Nowadays, companies seek to explore new organizational models such as virtual enterprises, in order to ensure a faster response to new business opportunities, and to offer differentiated products at competitive prices [3]. Sustainability, high variety, low volume and shorter product life cycles require a combination of multiple skills that is not easy to find in a single company. This raises the need to extend the organization, including skilled business partners, thus forming virtual enterprises [4, 5].

Collaboration is moving from the classical supply chain, with stable relationships between stakeholders with fully defined roles, to unprecedented dynamic structures.

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Some of these organisational forms are goal-oriented, that is, focused on a single project or business opportunity [6]. In this business context, virtual enterprises have been widely discussed over the past decades [7, 8]. In this research, the definition of virtual enterprise considered is based on the definition proposed by Camarinha-Matos, which states that "a virtual enterprise represents a temporary alliance of enterprises that come together to share skills or core competences and resources in order to better respond to business opportunities, and whose cooperation is supported by computer networks" [6]. A virtual enterprise is one form of Collaborative Networked Organisations that allows partners to exploit emerging business opportunities in a flexible way [9].

The effective implementation of a virtual enterprise raises several challenges: the integration of human and technical resources to enhance workforce performance and satisfaction; the need to instantaneously process information gathered from several sources into useful knowledge for an effective decision making and the ability to rapidly reconfigure manufacturing enterprises in response to changing needs and opportunities [10, 11]. Those challenges raise two main integration issues. The first is a business-oriented and addresses the integration of several business entities within a logistic value chain network. According to Reference Architectural Model for Industry 4.0 (RAMI 4.0), business entities can be represented as a component, exposing services, functions and implementing standard communication channels. The way how such business entities interoperate is typically described and analysed using a business process modelling notation such as BPMN. The second issue is mostly a technical one and addresses the interoperability of new and legacy resources (e.g., equipment, software, people) of the partners participating in the virtual enterprise so that cooperation can take place quickly, seamlessly and in a flexible way. Typically, a single task at the business process model is decomposed in set of tasks at the technical level (e.g. web services invocation). At the technical level, the interoperating entities are no longer companies, but equipment, software and people. However, in Industry 4.0, such resources are also considered entities that expose services and implements standard communication channels, as depicted in Fig. 1.

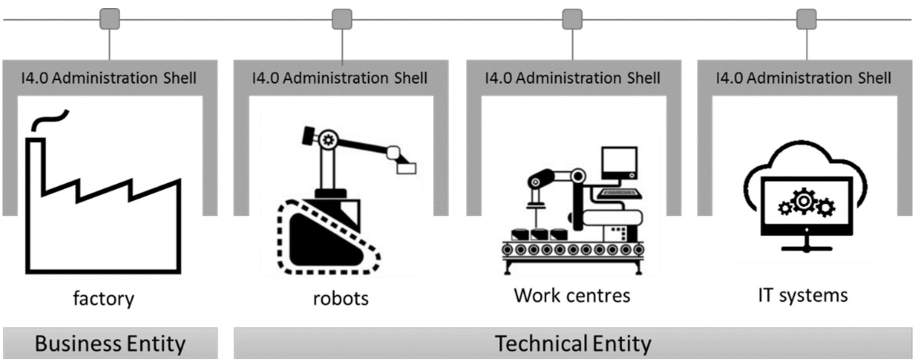

Fig. 1. Business entities and technical entities as Industry 4.0 objects

The Industry 4.0 paradigm seeks the complete digitalization and integration of the industrial value chain in order to produce goods using the most advanced information and communication technologies. The motivation behind this new paradigm stays on the increased digitization of the economy and society, which is changing the way the production will be held in the future. After the steam engine, the introduction of assembly lines and the use of electronic and computer systems in the production, the so-called smart factories with cyber-physical systems (CPS) come now to determine the fourth industrial revolution. The adoption of Industry 4.0 concepts, their related service platforms and innovation business models will help European SMEs to grow and boost European gross domestic product. Nevertheless the ability to adopt Industry 4.0 technologies by SMEs is still very scarce. Benefits of the adoption of these technologies include increased productivity and efficiency improvement, but obviously it is necessary to guarantee a return of investment [12]. Hence, there is the need for cloud based, scalable, secure and modular tools so that they can be introduced gradually and seamlessly in all manufacturing levels, from the shop floor, to the management level, without the need of a huge initial effort.

The essential issue tackled in this paper and the underlying research question refer to the Industry 4.0 concepts and technologies applied to virtual enterprise. In this research, it is of interest to face the following questions: (i) Which are the existing key enabling technologies to manage Industry 4.0 virtual enterprises? (ii) How to implement the Industry 4.0 technology in the European SMEs successfully?

This paper proposes an innovative cloud based framework to address these issues and enable collaboration in future Industry 4.0 compliant virtual enterprises. The rest of the paper is organized as follows: Sect. 2 presents the main phases considered in the research methodology. In Sect. 3, the current state of the art in the field of industry 4.0, including recent European project results are presented. Section 4 describes the considered business case. Section 5 present the implementation issues as well as the validation process. Finally, overall conclusions and further developments are mentioned in Sect. 6.

2 Research Methodology

The work presented in this paper has followed a research methodology that encompasses three main phases, as described hereafter:

(i) Industry 4.0 enabling technologies, where existing Industry 4.0 concepts and reference models as well as enabling technologies are presented and analysed. A comprehensive framework, founded on collaborative platforms, Internet of Things (IoT) and CPS is presented, answering the first research question (Which are the existing key enabling technologies to manage Industry 4.0 virtual enterprises?).

(ii) Business case presentation and analysis, where a practical case in the field of Automotive stamping planning is presented. Several workshops were conducted, in order to collect qualitative and quantitative data and relevant information, taking into account the expertise of all team members and experts. After analysing the as-is situation, current industrial challenges and issues and consequent improvement opportunities were identified, the to-be business processes were designed and validated by the industrial partners, leading to the definition of requirements for the design, specification and development of new suitable and accurate supporting methods and tools. Industrialists, technology providers and researchers did participate in this task, bringing their multi-disciplinary expertise to the project.

(iii) Framework implementation and validation, where the framework was implemented and validated. In order to guarantee its sustainability, criteria for the framework evaluation were established and measured, paving the way for a successful exploitation and pointing out the strong points as well as aspects to be improved. This answers the second research question (How to implement the Industry 4.0 technology in the European SMEs successfully?)

The next three sections are directly related to the three stages of the methodology presented.

3 Industry 4.0 Enabling Technologies

The notion of enterprise systems architecture is crucial to understand and manage virtual enterprises. From an internal perspective, services are characterized by a modular structure with building blocks that are combined to create a Cyber-physical Production Systems (CPPS). From an external perspective, they are a part of a larger CPPS (i.e., a virtual enterprise), often found in industries where product design increasingly determines the organization of partners, such as high technology and automotive industry [13]. In this context, concepts such as Smart Objects (SO), Internet of Things (IoT), CPPS and finally Industry 4.0, have emerged over the past decade aiming at address the technological requirements imposed by virtual enterprises [4, 6, 14]. The concept of horizontal integration and decentralization of production processes push the boundaries of collaboration between organizations in the field of CPPS to an unprecedented dynamic level. According to the RAMI 4.0 [15], the paradigm of service-oriented architecture plays a key role in support to CPPS. SOA allows to describe and use services in any of the automation pyramid levels: from the sensors and actuators, machines, through work centres and production lines, up to enterprise management levels. These services encapsulate well defined functionalities implemented through software artefacts [12].

Recent research results from two major European Projects - ADVENTURE [16] and Apps4aME [17] - show how to introduce semantics to optimize and automate the modelling and execution of distributed production processes as an orchestration of such services. These research and innovation projects demonstrate that there are different approaches for managing virtual enterprises depending on its nature. For instance, Make-to-Stock (MTS) environments, where the factory and process configuration is inflexible and fixed to produce in large quantities, are suitable for totally automated processes, where typical workflow systems are able to manage and orchestrate the entire process. ADVENTURE project has developed a fully automated process manager [18]. On the other hand, an Engineering-to-Order (ETO) environment imposes, flexible, adaptive and knowledge based processes [19, 20]. Based on these concepts, Apps4aME project developed a hybrid process manager capable of manage knowledge intensive processes with high level of human interactions and decisions [17].

Process description languages like business process execution language (BPEL) allow the composition of various services to simple or complex processes and semantic annotations are designed to express the context of a virtual service functionality [2, 4]. This approach has been widely adopted, with the goal of providing companies with the ability to generate, adapt and control production processes in distributed organizational networks, integrating from the so-called smart sensors and machines to production and enterprise level management systems, or other legacy systems. Based on the definition of individual production steps such as services and making use of a production-oriented approach to services, it was possible to model manufacturing processes for assembly services based on the capabilities of real factories of different business partners. These physical services are combined in production processes and take advantage of SOA technologies [4]. The results of several projects were combined to develop a framework for integration and interoperability within organizational distributed networks that meets what is now the concept of horizontal integration described by RAMI4.0, reducing market access barriers for Small and Medium Enterprises (SMEs), which do not usually have the ability to control the entire production life cycle, neither the marketing strength to impose their own interfaces and standards. Thus, it becomes easier for SMEs to get involved in Industry 4.0 compliant distributed organizational networks [4]. If CPS are not in accordance with a common standard, the integration of systems in the decentralized and virtualized production environment will require multiple peer-to-peer interfaces, exponentially increasing complexity. With a SOA based platform, each entity publishes its services in a central repository in accordance with a common standard. When it is necessary to produce a specific product, a specific process model previously stored in the production support system is applied. This process relies on cyber services on the available physical resources (e.g. machines, work centres, software) [14]. Note that in the case of knowledge intensive processes such as engineering, people also play a central role as they are the main decision makers on the orchestration of the process [16].

The RAMI 4.0 introduces the concept of Industry 4.0 component as a model to describe in detail the properties of CPS, i.e. real objects in a production environment linked to virtual objects. The real objects (production systems, machines, systems and modules) necessarily need to contain a set of defined RAMI 4.0 properties in order to be considered compliant with RAMI 4.0 objects. One of the properties is the ability to communicate in real time and to expose its functions and data. This definition is aligned with the concept of SO developed under previous European projects such as ADVENTURE. An important Industry 4.0 requirement is that a component collects all the relevant data throughout its lifecycle, providing these data to the companies involved in the virtual enterprise. The data storage and respective communication are provided by the so-called administration shell [21]. An Industry 4.0 administration shell contains a large amount of data and information provided by manufacturers, such as CAD data, connection diagrams, datasheets, manuals, etc. Integrators and operators can add important information about the maintenance or connection with other hardware or software. The Industry 4.0 defines data security measures and ensures data availability, confidentiality and integrity. The administration shell also provides some functions such as planning, configuration, operation, maintenance as well as complex functions related to business rules. Data and functions are available within the component itself, inside a corporate network or even in the cloud. The advantage is that information is stored only once and may be provided in a transparent manner through IT services for any user in any use case. The horizontal and vertical integration is facilitated by a combination of Industry 4.0 compliant communication protocols [22].

In Summary, all information is fully available for the engineering as well as operation and maintenance. The data stored on the component can be expanded as desired. Intelligent systems vendors and integrators can implement services through the creation of new information, information models and technical functions. Thus, information can be provided to stakeholders within an Industry 4.0 network. This enables the intelligent virtual enterprise. In this context, companies should develop their new systems and adapt the existing ones taking into account these concepts in order to be aligned with Industry 4.0 standards [21].

Figure 2 shows a cloud based Industry 4.0 virtual enterprise management platform architecture based on Industry 4.0 concepts allowing vertical and horizontal integration that also includes the components described in the following paragraphs. The services repository provides a model and tools for representation, publication and discovery of companies and its services, required for the design, management and operation of virtual enterprises. The process manager orchestrates all the interactions within a virtual enterprise according to the process models defined in the process manager designer. Process manager interacts with the simulation and optimization tools, in order to ensure the highest efficiency. As described above, the process manager must suit the business

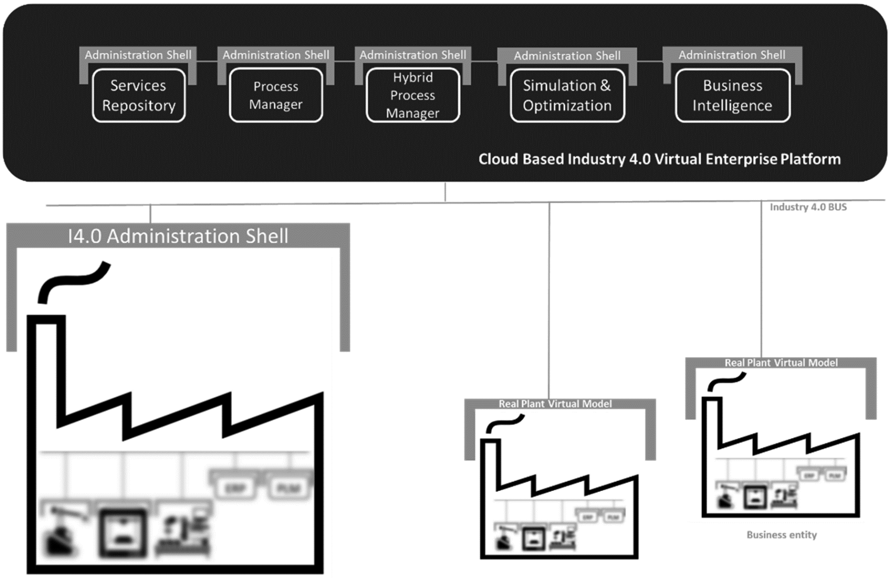

Fig. 2. Industry 4.0 virtual enterprise architecture

environment in terms of automation degree. In fact, lessons from industry tell us that many types of industry involve collaborative knowledge intensive processes (e.g. ETO equipment manufacturing considered in the next Section) where fully automation is not possible as process management depends on several human decisions taken on the fly. The simulation and optimization module relies on the process manager and uses Industry 4.0 shell services to get temporal and execution events from partners, supporting decision makers against particular partners. The optimization module provides a means to optimize virtual enterprises regarding the assignment of services to the business process steps and tasks. The business intelligence provides data extraction and transformation scripts and loading of real time and historical data relating to finished processes and instances. It also implements data mining techniques to generate useful information from big data sources towards a more proactive decision making in virtual enterprise environments [23–25]. All these software modules are also considered Industry 4.0 components and therefore are able to expose services and communicate using internet standards.

4 Business Case Presentation and Analysis

The business case presented hereafter was firstly considered in the context the FP7 apps4ame research project research project and you may find additional information about this project at http://apps4ame.eu.

The business case is based on a flexible automotive plant using a mixed production system (several models in one assembly line). During a new car model launch process, a set of stamping dies have to be planned, designed, produced and tested. Planning is a critical stage whose results directly impact the global performance of the virtual enterprise. This stage involves several activities, such as the setup of the team, process simulation, die set feasibility, resources assignment and die set design. Each technician handles a set of dies being allocated to several suppliers. At that point it is important to execute the right re-enactments and achievability tests, with a specific end goal to comprehend if the specialized particulars of every die are right from an item and assembling perspective. After validation of the technical specification for each DS, it is imperative to comprehend if the plant, where the DS will be utilized, has the assets to apply the composed DS.

Known and accepted the DS, and in addition the essential assets, it is possible to produce a 3D model of every DS, and also to arrange the DS development, as far as spending plan, time and quality. Here it gets to be basic to determine the quality norms to be approved toward the end of the procedure execution. In house try-out is likewise a basic assignment. The machining stage, is where the supplier needs to change the 3D model into a last and usable DS, proficient to create the parts as indicated by the item manager. The last stage must be centred on the assessment and change of the DS model produced, towards the effective creation of the admired parts. Therefore, as first activity, experts must form some model parts keeping in mind the end goal to approve if the DS satisfies the quality norms. After all item needs are approved, the assembling procedure is tried thought a pre-arrangement assessment.

Subsequent to breaking down the as-is procedures, it was possible to declare that the persistent reports on every DS status were expending a lot of time and assets, turning the process behaviour very reactive instead of proactive. It was additionally conceivable to see that the data was spread by various sources. The absence of business and specialized coordination is a major concern since it can be the reason for wrong or ease back choices because of falsehood in a procedure that is exceptionally time subordinate.

5 Implementation and Validation

After a detailed process analysis it was easy to recognise that many of the faults could be abolished by implementing Industry 4.0 key enabling technologies such as cloud based platforms, standard internet communication protocols and smart objects for manufacturing, in order to cope with the challenges and thus achieve a more pro-active approach in the die-set manufacturing process.

The aim of the proposed solution is to facilitate the flow of information among stakeholders, making it more reliable and actual, allowing a closer control and fast reaction. While collaborating with other departments and external partners, the stamping planning has to manage a package of DS, track the workflow process, schedule operations, state milestones, handle project changes, evaluate risks and define actions, keeping cost and available capacity controlled all along the project development. In order to successfully accomplish this mission, for each project the stamping department needs to collect and manage a huge amount of information and knowledge, coming from several heterogeneous data sources along the virtual factory. Indeed, managing all this information not only is intensively time consuming and slows down the decision-making processes, but also hinders project reliability. Cloud based Industry 4.0 virtual enterprise platform addresses the main challenges that are typical in this kind of environments by implementing horizontal and vertical integration: horizontal integration is addressed through a cloud based collaborative platform whereas vertical integration is accomplished using technologies from the IoT field, such as connected smart objects and

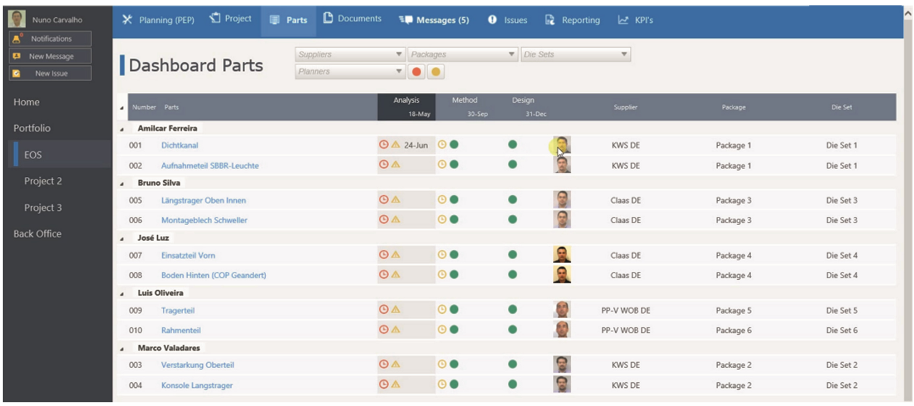

Fig. 3. Cloud based Industry 4.0 virtual enterprise platform dashboard

internet communication protocols. The total integration along these two axis leads to the development of a global dashboard (Fig. 3), enabling holistic view of project status, dynamic work planning and monitoring, real-time monitoring and control of ongoing work activities, knowledge and fully integrated document management and integrated communication/messages throughout the process.

Figure 4 depicts the architecture of the system, where the business process tasks are connected to the several resources along the value chain, including IT systems, industrial equipment, transportation as well as the product itself. The hybrid process manager orchestrates the flow, invoking services in the physical resources through the Industry 4.0 administration shell. The old equipment challenge has been overcome by the implementation of the smart object for manufacturing depicted in Fig. 5.

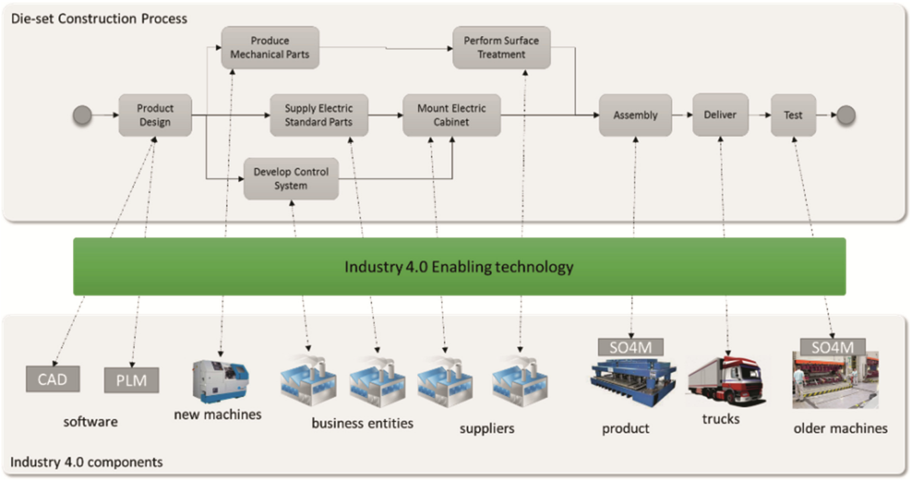

Fig. 4. Business and technical integration through process oriented approach

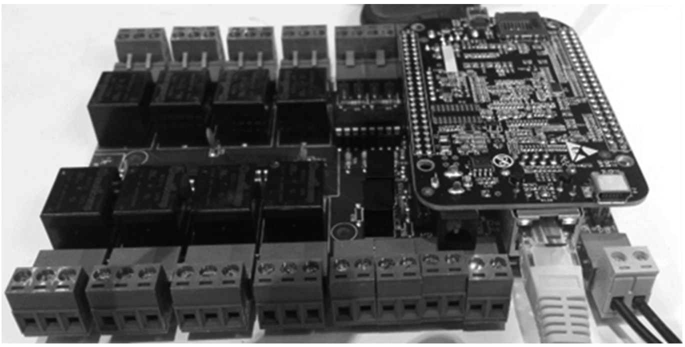

Fig. 5. Smart object for manufacturing

The cloud based hybrid process manager, supports company processes and enables a more reliable product development process. For instance, when a during the lauch of a new model, the chief manager defines some milestones that can be organised automatically. However, the real work tasks are not prone to be automated as they rely on intensive knowledge and decision tasks. The combination of well-defined and ill-defined activities is equally important in terms of leading a project to its success.

The communication tools that were developed allow linking all the stakeholders and interdisciplinary teams involved in the development of the product, guaranteeing real-time information regarding updated documents, machine breakdowns and quality related issues, thus saving time and improving the decision making processes. The platform was evaluated in real engineering environment, which involves part designers, die-set designers, planners, managers and suppliers in a unique virtual enterprise engineering environment.

Amid this assessment stage, a particular project has been utilized to test and check the functionalities implemented. Every partner has a particular certification to get to, test and approve the functionalities, giving criticism for persistent change [17]. This platform has proven to be very effective and efficient when applied in hybrid work systems and in particular in the automotive engineering collaborative processes.

This platform has ended up being exceptionally successful and productive when applied to this work frameworks and specifically in the car designing community oriented procedures.

The management system has also improved the communication, the cooperation and trust the exchanged information, which are key factors for a successful project. The virtual enterprise integration allow a proactive decision making, speeding up the product development process. The reaction time and resilience was also improved, making the process more responsive to unforeseen events.

6 Conclusions and Further Developments

Several technologies related to Industry 4.0 concepts have emerged during the past decade, however, due to the lack of technological maturity and also lack of capabilities for technology adoption, the supporting tools for virtual enterprises were not implemented successfully in industry, especially in SMEs. Now, with the new Industry 4.0 wave, several technologies from the fields such as IoT, interoperability, SO are being tested and introduced in industry. In this paper we presented several technologies and described the successful introduction of those technologies in a knowledge based manufacturing engineering environment. In summary, Industry 4.0 led us to the full automation world but lessons from industry show that there are several manufacturing environments where full automation is hard to achieve even with advanced technology. However, Industry 4.0 technologies, combined with flexible and suitable managing tools may be the missing enablers for effective virtual enterprise implementation and management.

Despite the success of the pilot business case implemented in the automotive industry, several challenges were identified related to the adoption of the technology and the with the enterprise interoperability, so that the entire CPPS can work seamlessly.

A large portion of today's IT frameworks are not completely integrated. Organizations, suppliers, and clients are once in a while connected. Capacities from the top management to the shop floor level are not completely coordinated. Indeed, even inside divisions, a full integration is as yet lost. Industry 4.0, is seen as the empowering influence to make organizations, divisions, capacities, and abilities more durable, as cross-organization, widespread information reconciliation systems develop and empower genuinely mechanized expanded virtual manufacturing plants.

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