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A Networked Production System to Implement Virtual Enterprise and Product Lifecycle Information Loops

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Abstract: This paper is aimed at considering supply chain and related data management within an integrated vision of the product lifecycle management (PLM) implemented through the unified approach which is proper to the Industry 4.0 initiative. In particular, with the proposed manufacturing system architecture, decision support tools can use a unified repository fed by a factory replication application, powered by data from the field, even from remote production units. Such data allow to monitor the behaviour of the digital twin of the real machine and produces a digital twin of the real product, incorporating its actual characteristics measured by means of suitable acquiring systems (in the treated example: a 3D laser scanner). Moreover, it is provided a description of the plant technological subsystems that allow to share designing and manufacturing activities across multiple similar units located in remote areas. In this context of virtual enterprise, the supply chain management results as a key factor in enabling a cooperative approach.

Keywords: Smart manufacturing systems, Supply chains and networks, Life-cycle control, Internet-of-Things, Intelligent decision support systems in manufacturing.

1. INTRODUCTION

The last decades were characterized by a dramatic increasing of supply chains organized with an international perspective. The growth in globalization, and the related challenge in management, has motivated both industrial and academic interest in new paradigms of supply chain management (SCM) able to cope with increased lead-time, larger distance and greater trade-off cost which concur to determine more complex decision making processes. At the same time, differences in cultures, languages, and local practices affect demand forecasting and material planning.

As a consequence, each organization seeks to establish relations with partners to turn internal processes into interlinked ones and to expand the traditional limits of single firms with the final result that physical logistics become more and more influenced by information technologies and a collaborative approach is needed to integrate core processes across organizational boundaries. The basis of integration can be characterized by cooperation, collaboration, information sharing, trust, partnership, shared technology and a fundamental shift away from managing individual functional processes, to managing integrated chains of processes (Akkermans et al., 1999). The integration process begins with the product design and finish with the ultimate sale of the item. However, it includes all the activities throughout the useful product lifespan. Thus, in order to reach a complete integration, new production facilities are needed. The last years have been characterized by the focused on the establishment of intelligent products and production systems. In future manufacturing, factories will have to enable rapid product development and flexible production in a complex environments (Vyatkin et al., 2007). In that contest, customized products carry manufacturing processes specification, as well as consumer information and independently lead their way through the supply-chain (Spath et al., 2013). The current status quo, where process adaptions are decided by humans on the basis of their personal knowledge and experience, will be replaced in the future by self-optimizing and knowledgeable manufacturing systems (Yan et al., 2007). Totally cloud-based data collection and storage makes possible an improvement in the collaboration between separate companies that operate along the same supply chain. Even in the past were available systems that could be connected to each other, but only at the cost of great efforts and considerable resources. The ease and flexibility of the new infrastructure for managing data paves the way for one of the great opportunities brought by the Industrial IoT, namely making possible for every actor to see the same things in the same way.

Next to this collaborative model, it is possible to conceive a networked, modular structure of small production unit making possible to manage each project or production batch as if all the local and remote machines could be used in the same way. To explore the potential of this concept, here is proposed a practical example of pilot line, which summarizes the vision of a smart production system, coherent with the pillars of

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Industry 4.0 and the integration of new technologies with the final goal to reach a more effective SCM.

2. PLM SYSTEMS FROM SCM PERSPECTIVE

The whole of described production and logistic requirements leads in the first instance to consider new organizational models and new control and production management systems. Still, for a deeper analysis it can be observed that customised products, launched onto the markets faster, whose lifecycles are getting shorter and which, finally, are in most cases complex entities at least in part transformed through servitization to put in the centre customers' needs.

Product data then aren't anymore a static set of information to be used in the early stages of production system design, but need to be collected into company's IT systems to support decision-making during operation along all the supply chain. To organize data associated with the entire life cycle of the product is not necessary, of course, reinventing the wheel, but there is a strong necessity to fully exploit the potential of PLM systems through their integration with the company ERP.

From the ICT point of view, PLM can be defined as the tool with which to allow the connection of design software to production and supply chain management software, taking into account the dispersed nature of the extended and collaborative enterprise. They became fundamental with the introduction of Computer Aided Design (CAD), as the growth of the amount of digitally stored information generated by software tools raised a need for a place to store files in a rational, to manage their version control and to automatically create links among all the related products. Today, this relationship increased remarkably due to the need to cope to customization need, above mentioned.

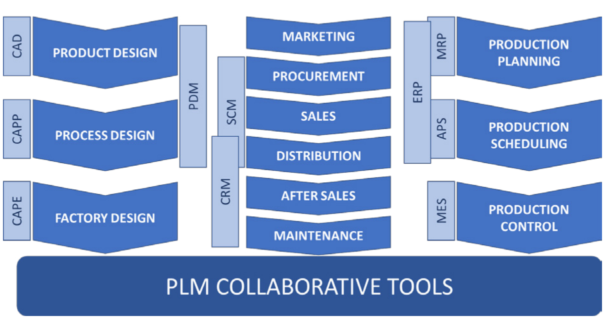

Fig. 1. PLM software context

To allow a true integration of ERP and PLM systems, they should converge in a framework usually indicated as *virtual factory replication* which indicates the capability of the system to manage data coming from the physical level (e.g. quality control camera) and the digital one (e.g. a parametric model of the product), allowing a comprehensive digital model of the factory which is not limited, as a traditional simulator, to show what should happen, but which is able to emulate, on the basis of real time data, what is in fact going on and how it affects the performances of the product, calculated as effects resulting by its model of the measured process parameters. This also provides the technological substrate for a science-based support decision system, that flows along the whole system (see Fig. 2).

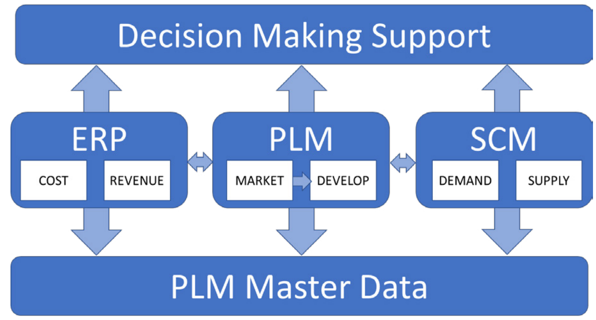

Fig. 2. Decision making support structure

Data homogenization, centralization and synchronization are the key aspects of control system to collect information in a structured, integrated and flexible database. This new scenario, where real time monitoring system allows to elaborate instantaneously the production data set with respect to quality/energy/ cost prognosis, represent a guarantee in SC optimization. Indeed, introducing a networked between actors results to be effective as working with a single and integrated company. In light of this, all the SCM technique should be re-adapted according to a new point of view in which the users turn into a separate network. In this framework, the efforts carried out by the actors will focused on the entire production optimization as a unique entity (i.e. splitting the production of a specific batch), with the goal to reach a global optimum with an emphasis on the user needs and their constraints, such as their sales network.

In summary, there is the need to develop concepts, models, methodologies and technologies allowing information flow management. In particular, the concepts below discussed aim to provide a way to close the product lifecycle information loops, enabling the transformation of product lifecycle information to knowledge, as shown in Fig.3.

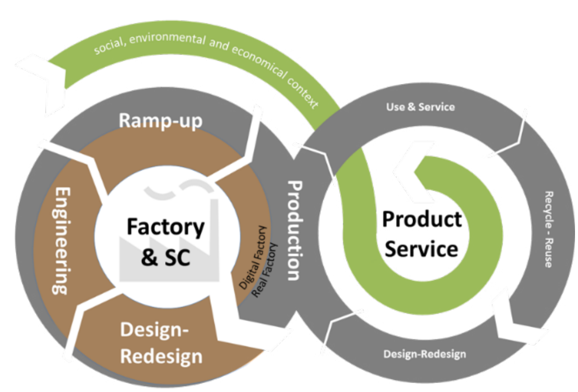

Fig. 3. Information loop

3. DIGITAL FACTORY REPLICATION INTO INDUSTRY 4.0 FRAMEWORK

Industry 4.0 idea involves concepts as the computerization of traditional production systems in order to realize plants based on connected and 24/7 available resources handling. In general, the aim is to carry out smart manufacturing plants characterized by high adaptability, resource efficiency and worker safety. In addition, the step forward is to provide systems able to integrate customers and business partner in the entire value process. According to Hermann et al. (2015), Industry 4.0 promotes vision of smart factories and is based on the technological concepts of Cyber-Physical Systems (CPS) and Internet of Things (IoT). Indeed, it is possible to reach new levels of efficiency as well as new opportunities by taking advantage of the exceptional progress in the ICT field. Indeed, nowadays it is possible to utilize features such as managing real-time data, communication and visualization (Masood et al. 2014; Posada et al. 2015). According to Sha et al. (2009), it is essential to have an integrated framework to represent the huge types of data and application contexts in several different domains and interpret them under the correct context.

In particular, this work is focused on the concept of a digital equivalent to a physical product, also called Digital Twin. The idea is to provide a rich and highly faithful virtual representation of the physical product. Nowadays, it is possible to realize a reliable digital product counterpart, thanks to the rise of data collecting at the floor level. This collection phase is carried out through several technologies such as sensors, lasers, vision systems which shall guarantee the effectiveness. In summary, the relationship between physical and digital product allows to optimize the whole SC by reducing costs through smart manufacturing systems.

3.1 DIGITAL TWIN CONCEPT

The concept encompasses three parts:

- Physical product,
- Virtual product,
- Their connections in terms of data and information.

Due to the increase of collecting values methods, there are innumerable data referred to the product. Therefore, there is the chance to visualize the digital product and simultaneously test it taking into account its performance capabilities. Moreover, this deep knowledge of the product allows creating light model of the virtual product according to the specific needs. This means that we can study the product behaviour focusing the efforts on specific attributes (i.e. geometry) without accounting unnecessary details. The result, is that it is possible to study the entire systems with appropriate level of details ensuring at the same time a cost effective compute expense. Obviously, these models allow also a cheaper cost of communication. Moreover, they can be shared also along the entire supplier network, ensuring a reduction in time and an increasing into depth understanding of the products' evolution. On the physical side, it is possible to collect more information about the product into the real world. For example, we can analyse performed tasks by the machine in real time, in order to know which operations and with which features (i.e. forces or speeds) have been performed. Finally, all the information carried out can be embedded into a manufacturing system simulation, in order to consider all the elementary tasks that compose the whole manufacturing process. However, although the recent years shown an increase in terms of amount of information for both sides, a connection between them was barely observed, especially on the factory floor. Establish a link between physical and digital product means to have the possibility to check in real time the production system (even through 3d-model) including the real dimension of the plant. In particular, Fig. 4 shows an example of digital twin applied to a physical machine, allowing the exchange of data and information process.

Fig. 4. Physical robot and its digital twin in the proposed pilot plant

According to PLM concept, the digital twin concept works also with a central shared repository. This is indeed the tool with which the connection between physical and virtual product are provided. More in detail, into the product design phase, a storage cell, including all the expected features, are created and stored into the repository. This cell is compared to the physical side, when the product has been built. Once this comparison has been performed the feedback is incorporate into the factory simulation model. Moreover, today simulation is seen as a tool of primary importance to obtain a better knowledge of system behaviour (F. H. Hajihosseini, 2009). It results to be extremely important because it allows to understand the system from an analytical point of view, which can hardly be otherwise reached. However, provide a connection between both physical and virtual environments means to turn a traditional factory simulation into a factory replication. The substantial difference is that in this way is provided a tool not for simulate what should be happening in the factory but what is happening in real time and for each step referred to each product.

4. DIGITAL TWIN'S APPLICATION FRAMEWORK

The concept of digital product twin, applied in the pilot plant just proposed, allows to improve productivity as well as the tasks performed by humans. In fact, the connection between physical product and digital product provides also a tool for supporting to the decision makers, providing a step forward to a new problem solving process. Substantially, the system also offers a support for the human beings abilities of comparison, conceptualization and collaboration. The first one is referred to the natural process of comparison that everyone does between any expected data and the real ones. Usually, considering this situation from a production point of view, the data concerning the real product and the virtual one are separated. As consequence, the comparison process, done in order to fill the gap between expected and obtained data, is inefficient. On the other hand, by using in symbiosis both real and desired data we can make a more intuitive and fast comparison, allowing also to take instantaneous decisions. Moreover, that decision making process is also suitable for taking choices with the goal to adjust future operations. Conceptualization means the human ability to analyze the problem taking into account also the contest in which it is set. Nowadays, the employees must translate, into symbols or parameters, all the available visual information concerning a specific problem and after that they must re-conceptualize them. Therefore, the result is a time consuming process also influenced by the high risk to lose important information during these phases. Obviously, by using a visualization tool based on the concept of digital product it is possible to directly have the situation's overview and so to take the correct decisions. Finally, the last aspect to take into account is the human capability to collaborate with each other in order to obtain more points of view of the same problem and a better problem solving situation. More in detail, it is possible to provide a shared visualization of the same digital twin model. In particular, an unlimited amount of persons is allowed to take the same information without sharing the same location. This concept is particularly suitable for a networked production, that is one of the goal of the developed line. In addition, it is possible to share the digital model to all the stakeholders along the whole supply chain, involving also more factories at the same time. In addition, this feature allows to exchange information, to all the factories, about a specific problem and its resolution before that it is occurred.

5. PILOT APPLICATION CASE

This section aims to provide a potential application of the concepts before discussed into a real production pilot plant. In particular, a Flexible Manufacturing System (FMS) has been developed. FMS can be defined as a system designed for a possible rapid change in hardware and software structures, so that production capacity and functionality could be quickly adjusted (ElMaraghy, 2006). Generally, from a manufacturing point of view, flexibility embodies complementary concepts such as machine flexibility, product flexibility, volume flexibility, process flexibility (ElMaraghy, 2006). Therefore, due to its features it is particularly suitable to be used as tool with which to match all the concepts before mentioned. In fact, it is possible to match the Industry 4.0 pillars by providing in the same time the integration with both PLM software and digital twin concept. More in detail, the idea is to produce customized biomedical devices through 3D printing process. Moreover, the line has been designed in order to address the needs of a continuous production process. In fact, because of the high customization, each product requires long printing times. Hence, there is the need to have a nonstop production, that is achievable only with a highly atomized production plant.

In particular, the line involves several technologies such as:

- Additive manufacturing stations,
- An automated warehouse,
- a pick-and-place robot for assembly workstation,
- a linear motion based transport system,
- a 3D laser scanner.

Moreover, Fig. 5 shows the general layout of the line. Due to this configuration the line is capable to match the constraints referred to the continuous production concepts discussed before. In particular, the additive manufacturing process, through the use of 3D printers, allows the integration with IoT systems for the real time monitoring as well as the continuous monitoring of the critical sensors' values. In addition, the line involves also the digital twins for all the robots that compose the system. Finally, through the 3D scanner it is possible to create the product digital twin ensuring the link between the physical and the virtual product sides.

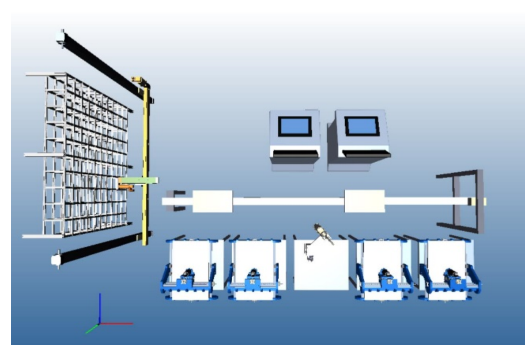

Fig. 5. General line layout

Due to this configuration the line is capable to match the constraints referred to the concepts discussed before. In particular, the additive manufacturing process, through the use of 3D printers, allows the integration with IoT systems for the real time monitoring as well as the continuous monitoring of the critical sensors' values. In addition, the line involves also the digital twins for all the robots that compose the system. Finally, through the 3D scanner it is possible to create the product digital twin ensuring the link between the physical and the virtual product sides.

Finally, the developed line concept allows to manage the production scheduling from a new prospective. In fact, the system is capable to be used for a networked production. Due to the highly degree of innovation, the line is also connected to the web by allowing the exchange of both input and output data. In this sense, an order, arrived as CAD file from the web, can be processed taking into account all the constraints in terms of Production Lead Time (PLT), available working time, raw material's refill times and total production costs. This means that for example, a huge order could be split across more of one production system, allowing to overcome the geographical constraints. Finally, an overview of the networked production structure is provided in Fig.6.

Fig. 6. Networked factories

5.1 LINE DESCRIPTION

A pilot has been developed on the basis of the requirements previously described. Paragraphs that follows illustrate the main technological choices on which it has been designed and implemented.

The hardware architecture of the system, shown in Fig. 7 and 8, provides for the integration of industrial PLC and touch panel HMI with microcontrollers and PC. Such integration is carried out through the use of OPC servers for all the computerized systems. On one side, industrial devices (PLC and HMI) have in charge the control of the transport subsystems, the handling robot and the Cartesian warehouse, which can be

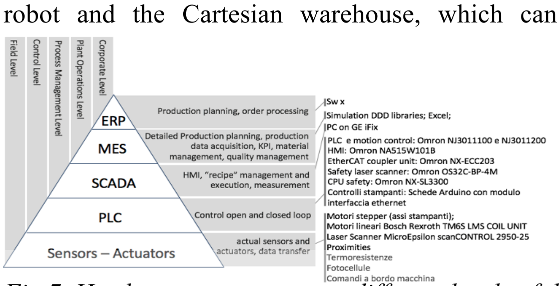

Fig.7. Hardware components at different levels of the CIM pyramid model

managed according to the standard approach for industrial machinery. On the other side, microcontrollers are used to automate the control of 3D printers with significant advantages in terms of costs, miniaturization and flexibility. Beside all these control devices, PC are used to implement the digital twins of each subsystem, whose 3D real time simulation is developed in DDD Supervisor environment by TTS. This software suite allows to obtain both the remote supervision of a real plant and the simulation of a virtual plant, for example for debugging or operation optimization purposes. The adopted PLCs integrate motion control modules for the directly positioning the axis of the automatic warehouse and of the SCARA robot used for the operations of pick and place and boxing.

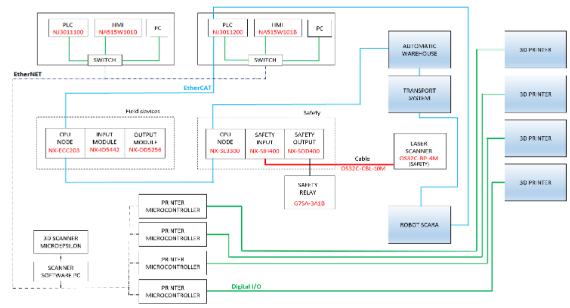

Fig. 8. System hardware architecture

The warehouse is designed to hold pieces of dimensions not smaller than the printers working volume and to be able to be assembled within local with limited heights, as are typically the cleanrooms, and more generally the production environments in biomedical and pharmaceutical sectors.
Furthermore, the warehouse structure is designed to be able to have a double access, with a clean side where production system is located and a dirty side where operators extract the products already enclosed in sealed packs at the end of the work cycle. On the dirty side there are two separate hatches for entering and exiting materials. Once the hatches have been closed, the warehouse control is able to rearrange the materials in its cells to allow further load/unload operations. A further requirement is given by the modularity of the warehouse, which must be able to be easily adapted in the number of available cells.

The transport system consists of a linear motion system that moves, via windings on the track, magnetic slides, as shown in Fig. 9. This choice, less common and slightly more expensive than a common conveyor, ensures important advantages related to the application peculiar characteristics. First of all, this system provides extreme flexibility, ensuring the possibility to use this equipment also in different configurations or after relocation. Moreover, this kind of mechanical design is the best possible choice for a transport system to be used in a clean room, being both a contact-free and lubricant free solution, which does away with mechanical drive components that could cause contamination as a result of friction.

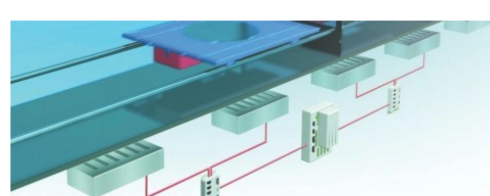

Fig. 9. LMS transport system (courtesy of Rexroth)

In particular, a **customized 3D laser scanning** system has been implemented, combining the slide motion with the use of a 3D linear laser scanner (whose working principle is shown in Fig. 10), both to use the line as a scan system for reproducing 3D objects and for quality control of items. The latter could be both dimensional controls related to the tridimensional shape of the objects and other controls obtained by analyzing the object image as it would be captured by a camera, because a laser scanner is, simultaneously, a triangulation system that locates a geometric point in space and a system for image acquisition detecting the intensity of reflected light. Often optical systems, especially in industrial environments, are difficult to use because the lighting conditions are not the optimum ones and this affects the operation robustness over time. Being able to combine the depth measurement, obtained by triangulation, with the image analysis allows to have simultaneously two different types of measurement that can be used in some cases to confirm the information detected, and in other to capture more information than using only one of the two technologies (Silvestri et al., 2013). Fig. 11 shows, in the image on the left, the acquisition of several reference surfaces.

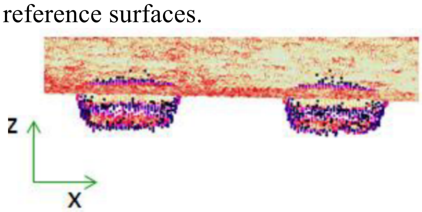

Fig. 10. Line laser scanner acquisition examples

6. CONCLUSIONS

The last decades, have been influenced by a fast world market changing in terms of demand needs and product life cycle. In particular, the more and more shorter product lifecycle moves the companies to re-think their production systems forward to a new prospective. Moreover, the whole supply chain must turn itself into a more responsive structure in order to cope to the quick demand changes. In this work a new concept of production system, based on the developing of a virtual factory replication, has been provided. The paper also has proposed a pilot production system highly automated and suitable for the topic of Industry 4.0. By developing a virtual factory replication, it is possible to take decision on the bases of the simultaneous values from both physical and virtual products. Therefore, by taking advantage from this synchronization it is possible to study a large amount of new use cases. In particular, the common factory simulation can be now translated into digital factory replication, by predicting not more how the product is to be realized but how it is, in real time, being manufactured. In addition, the virtual model allows to improve the human contribution in problem solving activities. In fact, it has been shown that it enables involved people to conceptualize, compare and collaborate. So, it can be used as a tool to improve the whole supply chain in terms of responsiveness to the market needs.

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