Science Arts & Métiers (SAM)
is an open access repository that collects the work of Arts et Métiers Institute of Technology researchers and makes it freely available over the web where possible.

This is an author-deposited version published in: https://sam.ensam.eu
Handle ID: .http://hdl.handle.net/10985/23287

To cite this version :

Chawki EL ZANT, Khaled BENFRIHA, Stéphane LOUBÈRE, Améziane AOUSSAT, Oussama ADJOUL - A design methodology for modular processes orchestration - CIRP Journal of Manufacturing Science and Technology - Vol. 35, p.106-117 - 2021

Any correspondence concerning this service should be sent to the repository
Administrator : scienceouverte@ensam.eu

A design methodology for modular processes orchestration

Chawki El Zant[a,*], Khaled Benfriha[a], Stéphane Loubère[b], Améziane Aoussat[a],

Oussama Adjoul[c]

[a] Arts et Metiers Institute of Technology, LCPI, HESAM Universite', 75013 Paris, France
[b] Pwc | Strategy&, Paris, France
[c] EMP, École Militaire Polytechnique, Alger, Algeria

ABSTRACT

Keywords:
Industry 4.0
Flexible manufacturing systems
Computer integrated manufacturing
Modularity
Modular process orchestration
Shop floor control system
Process control

Industry 4.0 is characterized by increased flexibility of production processes, a level of customization, a level of automation, smart manufacturing execution, and overall optimized production processes. Despite global competition, flexibility is a differentiation strategy applied by manufacturers to remain competitive. By incorporating flexibility in the manufacturing process of their products, enterprises can adapt faster to the demands. Enterprises need cost-effective, intuitive solutions to benefit from Industry 4.0 involving minimal efforts and integration costs. This study presents a new approach increasing the flexibility of manufacturing operations including robot trajectory, processing, and quality control. The results are tested in an industrial platform 4.0 installed in the laboratory. Our approach is to transform a rigid production system into an agile production system. For this, we break down the manufacturing process and reorganize it by programming core modules while maintaining the existing control structure but upgrading its programmable function to the Manufacturing Execution System Layer. Thus, the production manager can use the developed modules connected by flows to orchestrate a new production plan in a short time compared with the traditional approach.

Introduction

In a saturated and globalized market, producing in quantity 'Mass Production' is no longer an adequate response. It becomes necessary to adapt the manufactured products to the increasingly individualized demand 'Mass Customization'. Faced with this problem, the responsiveness and adaptability of production systems are a major asset to respond to fluctuations in demand [1].

Several studies were conducted in the literature in the context of product customization focusing on incorporating the configuration principle into process planning aiming to promote the process plan generation. Schierholt [2] identified the process configuration concept which is meant to simplify the process planning generation for new product variant using principles known from the product configuration concept. Two main concepts for process configuration systems were presented by Schierholt [2]: interactive process configuration and automation-based process configuration. Zheng et al. [3] proposed a systematic knowledge model for multiple variants of products and applied a process configuration method for rapid process planning by applying configuration rules. A tree unification approach is proposed by Zhang and Rodrigues [4] to develop generic processes from existing production data of product families helping companies to fulfil a diversity of customized products and therefore reducing cost and lead time.

While, in the context of Industry 4.0, an enhanced process configuration can be enabled through the flexibility and adaptability of the production systems. Traditional industries are currently undergoing a digital transformation and industrial processes are increasingly merging with modern information technologies. This new industrial revolution is mainly characterized on the one hand by connected and interoperable production machines which are driven intelligent. And on the other hand, by new functionalities such as flexibility, prediction, modularity, and mass product customization. In other words, Industry 4.0 contributes to enhance the process configuration in order to produce increasingly individualized products with a short lead-time to market and conform to the required quality. A lot could be saved in the reconfiguration reuse of the production equipment or indeed dynamic changes in the product at the top end of high agility [5].

From the implementation perspective, industries are still holding doubts in implementing the new technologies offered by Industry 4.0, because of uncertainties, lack of clear

---

[*] Corresponding author.
E-mail address: chawki.el_zant@ensam.eu (C. El Zant).

implementation details, and the seemingly large investments required [6]. According to Zhou et al. [7], the implementation of Industry 4.0 faces many challenges in the way, from various areas such as scientific challenges, technological challenges, and economic challenges.

Although, several research and studies are undergoing in the industrial firm aiming to introduce fast, effective, and cost-effective solutions in order to enhance the flexible manufacturing concepts in the existing production lines. Based on the promised facilities of Industry 4.0 technologies and its ability to integrate the business processes and activities, including Big Data and Analytics, Autonomous Robotic Systems, Cloud Computing, Industrial Internet of Things, Simulation and Prototyping, Additive Manufacturing, Augmented Reality, Horizontal and Vertical Integration, and Cybersecurity [8], the manufacturing system can increase the flexibility of the manufacturing processes [9].

From another side, Mes and Gerrits [10] addressed the fact that hierarchical control systems are not perfect for the need for a more diverse product mix. Therefore, more flexible and reconfigurable manufacturing concepts have been introduced consisting of autonomous and intelligent controller modules. These modules dynamically interact with each other to achieve local and global objectives. Some of the industrials such as ABB [11] started developing what is called the Modular Type Package (MTP), an initiative to change the control process infrastructure in the shop floor, driving the way of a small automation concept as defined by Strategy& [12]. According to Mourtzis et al. [13], Computer-Aided Process Planning (CAPP) must consider highly customized product variants in a dynamic manufacturing environment, rather than operating in isolation from shop floor production data and suffering from the lack of interfacing with Information Technology (IT) systems. Therefore, they proposed an Internet-based service-oriented system for adaptive process planning based on machine availability monitoring assuring the real-time collaboration between process planning and execution.

In this context, the flexibility of production systems appears as a necessity to maintain the competitiveness of industrial enterprises. This evolution is part of the transition to Industry 4.0. The purpose of this research is to present a new control architecture that runs in a modular mode to define and reconfigure the production plan in a short time compared with the traditional approach. This novel modular approach is meant to overcome limitations without changing the whole existing control process but by moving the decision-making process to the Manufacturing Execution System (MES) layer to enhance flexible production operations. According to PwC Stratgy& Global Digital Operations Study [14], four digital ecosystem layers are the foundations of an Industry 4.0 system, Fig. 1:

- Customer Solutions Ecosystem: in our case, the capacity to capture the demand, its variability, and the needs for customization will feed the modular production system.
- Operations Ecosystem: in our case, the heart of the system is a Flexible Manufacturing System with a modular approach.
- Technology Ecosystem: in our case, MES, Application Programming Interface (API), machines, and sensors with connectivity are the key technological elements.
- People Ecosystem: in our case, the ordinary skills of production people to manage production are taken into account to avoid complex programming of API.

This article proposes a methodology for designing a 4.0 production system characterized by fluid operational flexibility and modularity by acting on three axes. The evolution of the existing control system, the extension and evolution of the network architecture and finally the development of software for advanced management of production operations. Our added value lies in the proposal of a new method that defines the main stages for a gradual transition to the digitalization of production processes.

Fig. 1. The four digital ecosystem layers [14].

In the next chapter, a state of the art dedicated to the flexibility and modularity concepts is conducted. Following Chapter “Reviewing flexibility and modularity in the context of Industry 4.0”, our approach is presented in Chapter “New approach to enhance flexible manufacturing”, which consists of reorganizing production operations into multi-task (autonomous) functional modules, which makes it easier for manufacturing engineers to orchestrate a production plan. Chapter “Industrial appication, production platform 4.0” is reserved for experimenting this new approach in our industrial platform 4.0. Chapter “Discussion” discusses our methodology before concluding in Chapter “Conclusion and future work”.

Reviewing flexibility and modularity in the context of Industry 4.0

The flexibility of the production machines and the modularity of the manufacturing operations are two indissociable concepts to achieving new functionalities in terms of flexible production. This means that machines will operate independently or in coordination with humans to manufacture a customer-oriented product [15]. In order to achieve these goals in the industry, special attention should be paid to several level of manufacturing, particularly machines (shop floor tools & equipment), control, and manufacturing execution systems. Therefore, the concept of Flexible Manufacturing System (FMS) and modular process are presented in this section. The FMS is a requirement prior to the implementation of a modular process of manufacturing operations.

Flexible manufacturing systems FMS in the context of Industry 4.0

Industry 4.0 is a complex combination of innovative functionalities and technologies, integrated to enhance the production performance [16]. The realization of a flexible manufacturing system is highly dependent and driven by the ability of companies to invest in new flexible manufacturing machines [17] and robots, especially when reinforced by advanced technologies introduced by the 4.0, without which no modular process of production operations can be developed. For example, the Robotics Process

Automation (RPA) or robotics' integration are key elements to increase productivity and shorter lead times, and to increase customer experience and scaling of automation [18].

A Flexible Manufacturing System (FMS) is differentiated from a traditional production system by its ability to perform multiple operations from a limited number of resources. The FMS thus becomes an interesting concept to adapt the production to a constantly changing environment, since it makes it possible to avoid long periods of downtime related to the reorganization of processes. According to Kaschel et al. [19], flexibility refers to the ability of a manufacturing system to respond cost-effectively and rapidly to changing production needs and requirements. This capability is an essential key to the design and operation of manufacturing systems to overcome unpredictable market movement. The scheduling flexibility has to be integrated, offering reliable decision-making response to the clients' order and the market evolution. By reducing the number of operations necessary for its reconfiguration, an FMS improves performance in terms of costs and deadlines, and allows quality benefits. Fragapane et al. [20] claims that manufacturing flexibility enhances productivity with a fast adaptation to the ever-changing client demands, thus, reducing costs and resources. Fragapane et al. [20] investigated the decentralization of material flow which can provide more flexibility for production systems using Autonomous Mobile Robots (AMR) in the Process Industries (PI) for high mix production and addressed that new planning and control models are needed for production networks and decision-support systems in order to control material flow in the era of Industry 4.0.

According to Qin et al. [21], the reconfigurable manufacturing system is the closest to a smart factory system, followed by the flexible manufacturing system. Mabkhot et al. [22] identified suggested requirements in terms of design principles of the smart factory, mentioning the 'modular machine tools' referring to the flexibility of machines and workstations to be reconfigured in terms of changing the shop floor layout and adjusting the process function, and 'modular material handling' equipment referring to the possibility of reconfiguring material handling equipment (i.e., conveyors, Automated Guided Vehicles AGVs) on the shop floor or changing equipment capability to transfer the required product. Mourtzis et al. [23] studied the flexibility regarding product and volume changes in the design phase, considering alternative solutions such as conventional press, CNC, and laser machines for a system's punching department producing commercial refrigerators. Based on investment cost and return performance, Mourtzis et al. [23] proposed a methodology using Penalty of Change (POC) method to evaluate the implementation of critical capital investment decisions in the manufacturing technology. Mourtzis et al. [18] presented the design and development of a flexible manufacturing cell as a learning factory with the goal of minimizing the human intervention in the production processes using a robotic arm mounted with an HD camera to perform the quality control task. Mazars and OpinionWay [24] summarized the advantages and disadvantages that arise from the operation of an FMS. To be mentioned on the benefits side, the rapid adaptation to market evolution both in quantity and customization, reduction of stocks, better control of production by providing real-time information, better use of equipment, reduction of direct labour (contribution of automation), and reduction of the general expenses (fewer expectations, losses, . . .). On the disadvantages side, it is relevant to take into consideration the high cost of realization, the complexity/sophistication of the implementation, the heavy incidence of uncertainties in certain cases (grouping of operations on the same means), and the need for qualified personnel and specific skills in modern technologies.

Modularity in the context of Industry 4.0

Modularity is a principle of Industry 4.0 and one of its essential functionalities. Answering the client demands, the modular production systems give the possibility to adapt and adjust modules of the production process in a more comfortable and useful way depending on the production and the product evolution. Modularity is concerned with shifting from linear manufacturing and planning, toward an agile system that can adapt to ever-changing circumstances and requirements, without the need for a huge and sophisticated redevelopment and reprogramming work. In other words, the modularity is a potential solution enabling what is called product customization [25], the key principle of Industry 4.0. Modularity involves the entire production and manufacturing levels, and builds on agile supply chain, flexible material flow systems, modular decision-making procedures, and flexible processes [26]. According to Weyer et al. [27], the high product variability with shortened product life cycles for new products demands requisites an agile and flexible production structure. They addressed Cyber-Physical Systems (CPS) and Internet of Things (IoT) to be implemented along with the need for coordinated standardization between technologies and automation for interoperability purposes in order to assure modular factory structures and enable dynamic re-engineering processes.

In terms of investment decisions, modularity in FMS moves the trade-off between the other traditional production systems [28]. By switching easily in a high range of volumes or variety, modular production systems can replace shop floors with stand-alone machines or dedicated lines and improve the capacity of the production system for dealing with uncertainty, Fig. 2. More specifically, a production system can be defined as a set of modules connected by flows, with the function of transforming raw materials into a product. The overall flexibility of the production system stems logically from the flexibility of the modules and flows that compose it.

Modularity is not only being able to change the layout of the shop floor simply but also have a flexible structure that allows the extension of the module to increase production capacity or integrate new functionalities [22]. A module is loosely coupled and can be moved, added, or removed from the system in a plug-and-play manner. Gorecky et al. [29] described a module as a puzzle block that can work alone or in combination with other modules to form a production system.

The planning phase of production operations has a crucial technical aspect which requires, on the one hand, defining the production capacity of the machines, this parameter is classic and

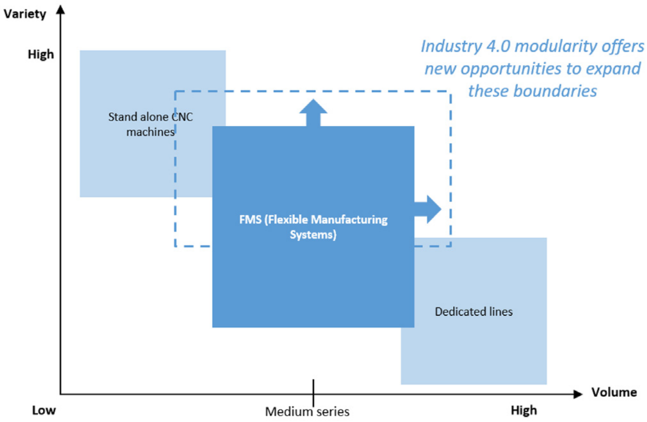

Fig. 2. Application characteristics of FMS, adapted from Kaushal et al. [28].

not much variable. On the other hand, to know the way in which the production operations are structured, this parameter is recent and has been introduced recently by various works published in 2017 for the automation of modular process plants. Bloch et al. [30] introduced the concept of modularity of production operations within the framework of a joint project between TDU and the ABB research centre on the theme 'Information Models and Architecture for Modular Concepts in the Process Industries'.

Several research and development contributions have been published in the context of modular production systems. Weyer et al. [27] presented the SmartFactoryKL, a modular production system and a novel project for cross-vendor solutions, addressing standardization as the crucial challenge for highly modular, multi-vendor production systems. Bloch et al. [31] of the IAT institute published works in 2018 where they consider the problematic of modular operations as an approach that meets the increasing demands for flexibility in the manufacturing industry. They also addresse the problem of conventional control systems that do not properly support flexible production systems. According to Perzylo et al. [32], instead of producing high quantities of similar products over a long period of time, companies have to satisfy the market demand for customized or even individualized products. As a result, their production lines may have a multitude of different variants, which may only be produced in small lot sizes. Bloch et al. [11] suggested the modularization of the process control system, using different process modules. These process modules will provide encapsulated process functions as services to the superior control system SCS. Within the SCS, services are orchestrated by the plant operator to achieve the desired production process. Fan et al. [33] proposed Function Block (FB) based Closed-Loop Adaptive Machining (CLAM) for adaptive process planning and execution. IEC 61499 FBs enabled High-Level Controller HLC are designed to plan and execute the finishing process planning referring to initial process planning and instantiation. Low-Level Controller (LLC) are implemented to manage low-level tasks, such as motion control, and data acquisition.

New approach to enhance flexible manufacturing

Flexibility is enabled in a manufacturing system mainly through the integration of flexible machines and the implementation of flexible and alternative production routes [34]. This flexibility could not be achieved without having an efficient and advanced Shop Floor Control System (SFCS). The core concept of Industry 4.0 is to build an intelligent and self-optimised manufacturing system based on the processed data and rely on the data mining gathered and supervised in real time. Therefore, a different configuration of our production systems to allow the real-time autonomous optimisation of the production process is needed, which is not supported by the conventional control systems due to its actual inflexible approach.

The contribution of this paper is in the implementation of a novel advanced modular SFCS approach where the control process is upgraded to the MES Software. This novel approach impacts classic Computer-Integrated Manufacturing pyramid (CIM), in particular by transferring the decision making and the scheduling control to the MES layer rather than being stacked into the Programmable Logic Controller (PLC) control layer. This novel architecture is enabled thanks to the new implemented configuration of the shop floor and the shop floor control system, along with the integration of new technologies such as advanced robots, a 3D scanner for quality control, and the integration of IoT sensors and embedded camera systems. The proposed modular approach is meant to overcome the control limitations without changing the whole existing control process but by moving the decision-making process to the MES layer, using a new interoperable and advanced industrial and production process Service-Oriented Architecture (SOA) software as the MES.

While in conventional production system, the data flows are not perfectly conducted in all directions. In other words, the data flows from the production control system as order signals and commands, another flow of data is coming back from machines and sensors and collected by the production system. These data should be processed in real time in order to optimise the ongoing manufacturing processes and adapt the production system itself depending on the customised production planning first and the mined data base for optimisation concerns. Additionally, Industry 4.0 enables interoperability between different layers and entities in the manufacturing processes. The idea figures in keeping the control process layer at the PLC level in order to maintain the production communication standards at the shop floor but moving up the decision-making process to the MES layer and limiting the control layer processes to logical functions.

The potential of MES is in the capability of easily creating production programs using allowed standard programming languages to develop complex scripts, which will be very difficult to develop on logic controllers or even impossible sometimes. This allows going further with the optimisation of the production processes, as well as easing development for the operators and production engineers without having to make changes continuously at the logic controllers and shop floor developing layer. Two main use cases with this new modular process could be identified:

- For the industrialization of a new product: the capacity to reduce time to market for the production of a new product by reusing existing modules.
- For the production scheduling: the capacity to launch a new production with no lost time and to switch easily from one routing to another one.

In this chapter, the modular process methodology is presented in "Modular process methodology", the evolution of the SFCS is clarified in "Shop floor control system SFCS", followed by "Modular process design patterns", where our modular approach is discussed.

Modular process methodology

Production management consists of ensuring the successive or simultaneous execution of manufacturing operations in accordance with the qualitative and quantitative requirements of customers. Management takes into account both the manufacturing modules and the necessary logistics in terms of tools, raw materials, maintenance, and the hazards that may arise during production. Industrialization, which is preparatory work, upstream of production, aims to define all the operations grouped into modules which will be implemented in a flexible production plan. To this end, the functionalities of the MES required should respond, mainly, to its ability to design a production plan from identified and recorded operations as well as its ability to drive production through data. Fig. 3 presented the flowchart of the proposed methodology discussed below.

The "Standardized Parametrized Operations" phase is reserved for the definition of basic production operations for a specific product, encapsulated to the MES and parametrized. The implementation of basic operations in MES is organized in two stages. The first takes place on machine-specific systems, such as Computer-aided manufacturing (CAM) tools dedicated to the generation of tool paths for CNC machines. Indeed, all the operations necessary for a product production plan are validated upstream. Then comes the second step, which consists of preparing their integration into the MES through an encapsulation

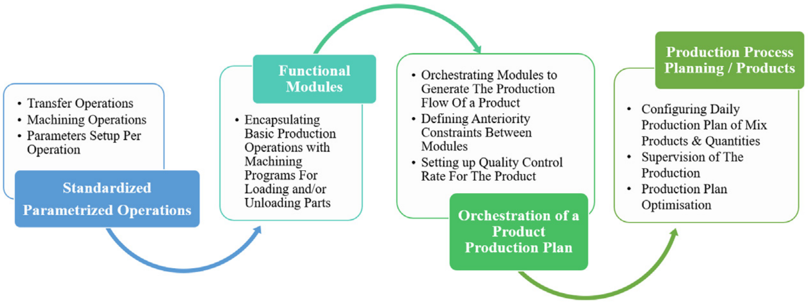

Fig. 3. Modular process methodology.

action in order to make them compatible with its operational environment. This process is based on the advanced technical knowledge of the production line and obeys specific codification in order to be identifiable in different interfaces. Production operations of the “standardized robot trajectory” type are interesting illustrative examples to mention. In the platform 4.0, the dedicated line to this project, all possible trajectories of the robots have been analyzed and defined in 33 trajectories that can be used in a combined way and thus cover all needs in terms of transfer in the workspaces of the platform 4.0. This approach helps to increase the flexibility of operations and thus facilitates the design of a production plan by assembling standardized operations.

The “Functional Modules” or “industrialization” refers to the preparation of modules, where each module can group together, in a precise schedule, several operations from the previous phase. These modules can constitute the sequence of logical production operations dedicated to a specific product. For various reasons, any module must be able to be simulated and executed. For example, the engineer can develop a specific quality control module **M1** which consists of using the Mobile Robot (RM) to transfer the component and drop it to the rotating plate of the 3D scanner through RM_Drop_Scanner operation, and activate the scanner using Scan_ProgX which recovers the point cloud and compares it to the native 3D model of the part X. Another module **M2** will be created to pick the controlled part and transfer it to the Transition Store (TS) using respectively RM_Pick_Scanner and RM_Drop_TS operations Fig. 4. This phase allows production engineers to prepare modules by overcoming the issues of interoperability, robot programming, scanner control, etc. which provides a real advantage in productivity.

The 3rd phase called “Orchestration of a Product Production Plan” is dedicated to finalizing a production plan for a given product. This phase consists of orchestrating modules to generate the production flow of a product, defining anteriority constraints between modules, and setting up quality control rate for the product. The production engineer collects all the modules necessary for the execution of a given production order and imposes the constraints of inter-module anticipation. Some modules are configured, in particular the quality control modules, which must be activated in proportion to the number of components manufactured. In this phase, the MES should offer several options, the first consists of taking into account the constraints imposed between modules and proposing all possible scenarios for scheduling production modules for a defined product.

Fig. 4. Functional modules examples.

Finally, the 4th phase “Production Process Planning” or “piloting” is a logical continuation of the previous phase. The objective here is to prepare launching the production and to ensure it is managed in real-time.

Shop floor control system SFCS

Actually, in the case of fully automated production, one of the flexibility locks is located at the controller level. Indeed, once the process is frozen in the Application Programming Interface API layer, only reprogramming the controllers allows the workshop to be used for another task than the active/configured one. For each new product, it will be necessary to create and redevelop a new program, allowing to produce another product rather than the old one. This situation represents the conventional industrial architecture type 3.0. In order to overcome this limitation for an improved manufacturing system, the proposed approach is to deport the control of automation logic functions of the API layer to the upper layer of the CIM pyramid, so that they are accessible to users of the workshop. For this purpose, logic functions should be adapted to be used without requiring the intervention of an automation redevelopment action. Master grafcets are no longer used to manage the operations, it is the Manufacturing Execution System MES (supervision & execution) that will perform this function.

Concretely small parametric production sequences are generated, to be used separately by the engineer as standard operations or assembled to form functional modules in order to build a complete production plan. These standardized operations and modules activate the logical functions of the controller, keeping this way a clean path by using the standardized automation protocols to controlling machines. Fig. 5 presents the proposed command architecture.

Modular process design patterns

Weyer et al. [27] identified the issues of the design of a heterogeneous production line by new control architectures, new engineering and programming paradigms, communication standards, and IT security challenging the digital evolution of the production systems. Three paradigms were identified by Weyer et al. [27] to specify the central aspect of Industry 4.0 concerning the production systems Fig. 6. Starting from the smart product in the meaning of product-oriented production configuration, where the product embedded its own operational data and requirements to be processed in a modular production system. Secondly, machines getting smart when being transformed into Cyber-Physical Production Systems (CPPS) enabling its self-organization, decentralization of the decision making at the shop floor level, and allowing an easy plug-and-play integration. Lastly, the augmented

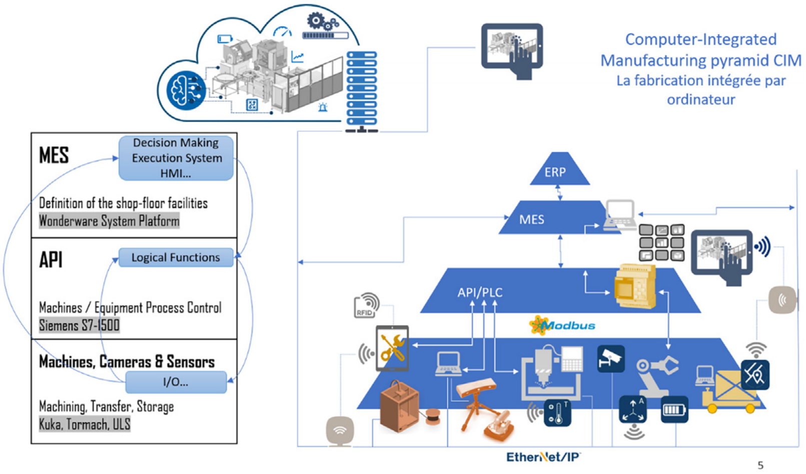

Fig. 5. Platform new control architecture [37].

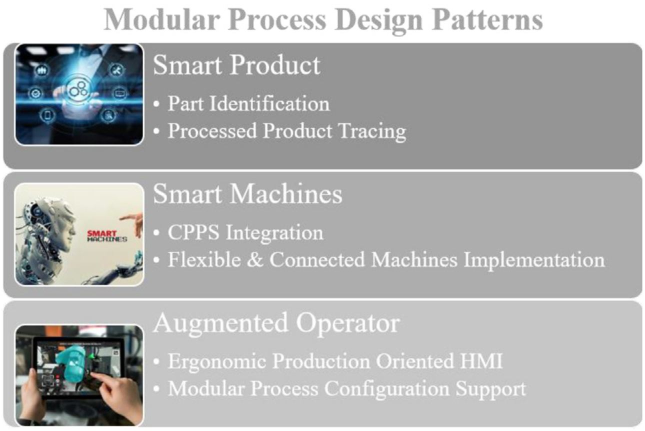

Fig. 6. Modular process design patterns [27].

operator considering the smart working environment as a requirement for technicals as for production engineers technological support when dealing with highly flexible and modular production systems.

The first dimension 'Smart Product' is considered in our configuration in a holistic way since polyethylene plastic is used as material without an RFID tag nor an embedded memory but categorized by ID series lot, identified by the fixed camera system and an ID number is given by the MES for the part. The MES itself manage the production processing modules in our case rather than embedding the operational information into the product. Hence, this identification is used first to recognize the raw part for a specific product based on its ID series and its dimension (diameter), second to trace and track the part in the production processes and its place ID in different stores using its ID number, third to build a processing information data base of the processed parts on the robots bay shared between robots and the MES and updated instantly using internal robots functions taking into consideration loading/unloading/transferring parts as well as machining data. This data base serves in addition to assure the self-organization and collaboration between fixed and mobile robots in order to manage the transition stores as it serves as well in securing the robots vs parts loaded in the stores and the machines.

The smart machines as the second dimension is our essential concern since the interoperability and the compatibility issues were not at all considered when designing the line with its basic conventional configuration 'automatic mass production'. Starting from turning the robots into smart and connected CPPS by implementing innovative configurations considering the internal data base developed and integrated into the production system, and its connection to the trajectories programs enabling the transfer functions between different part stores and machines by creating loop points per area to eliminate any collision between robots and machines/obstacles. These trajectories are well optimized consequently by adding the speed of the robots' motion to the transfer operations in order to recompensate the time loss when following the loop points as starting and ending points in each trajectory.

Regarding CNC machines, other initiatives were implemented concerning machining flexibility. An access issue was crucial avoiding remote controlling the machine in updating machining programs, activating the program, and launching the activated one. First, the G-code transfer problem was resolved using a USB Networking Adapter with the CNC controller since the controller supports network access for file transfer – a fast and convenient method to transfer G-code programs directly to the controller from the MES where the activated machining programs list is set. The MES in his turn is connected to a CAD/CAM software where the machining programs are generated. Second, the activation issue is resolved by creating a main conditional G-code program to be activated when initializing the line, which in his turn call for each machining program of different parts as a subroutine stored in the subroutines file shared with the MES. To do so, machines controller was extended by additional I/O modules to allow remote access to machines and activating several machining sub-programs with parametrization ability such as cutting depth and cutting speed. Additionally, the fact is that automatic production machines are not well developed to be connected, intelligent, and open to exploit. To solve these issues, an IoT layer was added overlaying the manufacturing machines in order to exploit data and useful information to enhance and supervise machines working states. Therefore, vibration sensors are added to the machines along with temperature and position IoT sensors depending on the functional requirements of each machine in order to discover and gather the maximum useful machining information. Concerning the quality control task, a 3D scanner is installed for advanced quality control function. Adding to this, another camera system is embedded to the robots and has two main functionalities, a supplement conformity control in-situ, which means parts will be controlled on machines before getting recovered by the robots and readjusted if needed, and an extra security check of robots vs machines and robots vs parts in order to avoid any accident due to a wrong signal or a manual manipulation.

Taking into account these technological aspects in terms of decomposition of operations and their parameterization is a necessary prerequisite for the development of modularity and the flexibility of production processes. Furthermore, this flexibility implemented to machines at the shop floor is reinforced and assured by the new configuration of the control system layer as presented in Section “Shop floor control system SFCS” discussing the shop floor control system configuration which enables not necessarily the physical integration but simply the plug and play modules integration in the form of standard programmed operations.

Lastly, the augmented operator dimension is considered clearly at the MES stage where an ergonomic production-oriented HMI is developed using Intouch OMI, enabling the production engineer to develop the product production plan by assembling core functional modules connected by flows and supporting the modular process configuration. The production engineer when receiving the order for a new product starts from creating the correspondent machining programs using the CAD/CAM developer in case of not having the samples in the library, and imports them directly to the MES. He builds a list of all machining and transfer parametrized programs at the operations stage, before creating functional modules composed of one or more basic operation in order to transform this group of operations into a meaningful process such as recuperate a part from the transition store by the mobile robot, load it to the lathe machine and run a specified machining program. The step forward is to arrange these modules and connect them by flows with the ability to add anteriority constraint between two consecutive modules if needed along with setting the quality control rate corresponding to the percentage of controlling this product’s lot when finished using the 3D scanner. Finally, the production engineer creates the list of products for the daily production planning. This organisation helps the production engineer and the operators to deal with the new modular configuration, saves plenty of time at the industrialization phase integrating a new product and a variety of products, and also simplifies the industrialization phase avoiding the production engineer from re-engineering processes, reprogramming machines, and reconfiguring the control system any time a new product processing is required.

Industrial application, production platform 4.0

Our approach has been experimented on a production platform 4.0 developed and installed in the research laboratory. Basically, this platform is built from different machines and robots: one fixed Kuka robot, one mobile Kuka robot, a fixed camera system for raw parts identification and classification, an embedded camera system, a lathe, a milling machine, a laser cutting machine, and a 3D scanner for quality control. Previously, the platform can manufacture, assemble, and transfer components with a closed and inflexible automatic control. This mode of operation corresponds to 3.0 mode and is subject to uncontrolled disturbances. The aim of the platform 4.0 project is to experiment an intelligent and flexible manufacturing process by integrating several technologies in order to create its digital twin. The production cycle is not limited anymore due to the low level of the PLC intervention.

The platform is controlled through Wonderware System Platform (WSP) – Schneider product [35], where alarms, trends and all data from machines and sensors are collected Fig. 7. The production line, thanks to developing this flexible layer is able to produce different products and drive different manufacturing plan.

Shop floor flexible machines

Due to the shop floor flexible machines configuration, the development of the standardized parametrized operations is enabled. Several configured parametric operations were created representing all the production operations adapted to the potential of our 4.0 industrial platform. The parametric dimension expresses a variability that allows the operation to adapt to the context, in particular to the variability of the components manufactured. The operations can be defined in different ways, it all depends on the standardization sought. Corresponding to the platform, operations are grouped into 4 categories, summarized in the first column of Table 1. The interest here is to identify all the operations necessary for manufacturing, controls, transfers, assembly, etc. which allow the production of a component to be ensured, starting from the initial stock until the delivery of the finished product and the controlled one where it could be recovered from the accumulation table. In other words, production processes are organized into multi-task production operations as follow:

- Transfer operations between machines and stores (Robots trajectories).
- Machining operations including CNC machining operations (G-codes for machining processes), and laser cutting operations.
- Quality control operations including 3D scanner operations for quality control, and Dimensional quality of parts being manufactured using robot embedded cameras. The main dimensional and geometric quality control operation is conducted through the 3D scanner which compares the point cloud of the part being controlled to its native model. A dimensional quality control operation is performed by the embedded camera

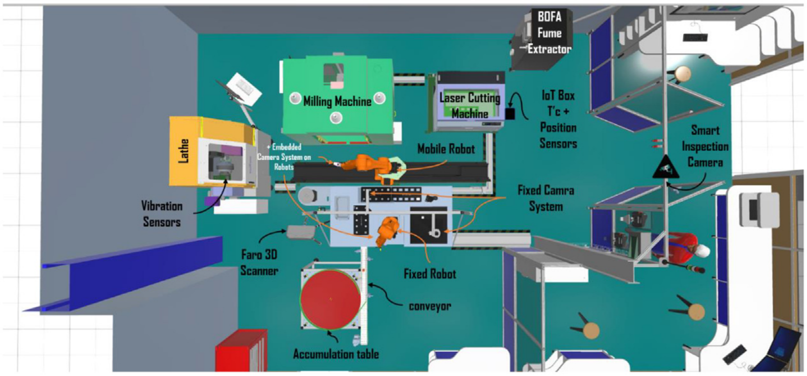

Fig. 7. ENSAM industrial platform 4.0, 3D-model.

Table 1
Standardized production operations.

Operations	Functions	Materials
Transfer	Robotic transfer between the transition store and the machines	Kuka Agilus 1100
	Robotic transfer between machines and the 3D scanner	Kuka Agilus 1100
	Robotic transfer between the transition store and accumulation table	Kuka Agilus 900
	Robotic transfer between initial and transition store	Kuka Agilus 900
Machining	Lathe machining	Tormach
	Milling	Tormach
	Cutting – ULS	Universal Laser System
	Engraving – ULS	Universal Laser System
Quality	Dimensional and geometric quality	3D Scanner Faro
	Dimensional quality of parts being manufactured	Embedded Camera
Monitoring	Storage control	Fixed Camera
	Anomaly control	Supervision Camera
	Security control robots vs machines, robots vs parts	Embedded Camera

on the mobile robot in situ for parts being manufactured before recovering. This operation helps detecting deviations in order to readjust the manufactured part if possible before recovering.
- Monitoring operations using fixed and embedded camera including security checks, storage, and anomaly controls. Fixed camera system above the initial and the transition store assists in the storage control and management of raw and manufactured parts. The supervision camera helps monitoring the production line by detecting any human presence nearby robots to alert the operator and pause the machines [38]. Finally, supplement security checks are performed in addition through the embedded cameras to the robots to assure the availability of a place to drop a part as well as the opening of machines door to avoid any collision.

Certain operations may require specific configuration, in particular with regard to the flexibility of the platform. For example, the robot's gripper in terms of stroke and shape has to handle different workpiece dimensions. Indeed, the typology of the different components that will be manufactured suggests that we maintain the "Gripper Tool" aspect as an input parameter to transfer programs. The robot trajectories for transfer and machines loading are created as trajectory entities that can be assembled and used in any production process. For this, areas within the platform were defined, where starting and ending points of the robot trajectories are created. These points are called Loop Points and will be used at the beginning and the end of each trajectory and will ensure that each trajectory can be performed before or after any other trajectory. Indeed, the paths between each of these loop points have been tested to avoid any risk of collision with the equipment of the cell. Some additional trajectories dedicated to specific functions or security matters have also been added including basic security control sequences, such as controlling the opening of the doors of the machines to which they are heading. The chosen trajectories for programming correspond to every possible path connecting different zones and each machine. Table 2 illustrates in the second column an example of standardized production operations that can be requested in different production programs. The last column in the table presents some parameters dedicated for the correspondent operations. A robot trajectory is parametrized by the part ID, the diameter of the part, the height of the robot's gripper from the bottom of the part, and the robot's speed. The CNC machining operation is parametrized first by the ID corresponding to the subroutine program reference, the cutting depth, and the speed of cutting.

Modules

In fact, the MES transform basic production operations from the interconnected machines, robots, scanners, PLC's, actuators, and sensors, into modules which encapsulate machine programs but also information and commands linked to its operational environment. Several strategies can intervene in the definition of modules from the operations defined in the previous step. The first strategy is to define modules that group together a minimum of operations under an identification that can be understood by the different operator involved in development and production. The advantages are multiple, in real-time, this strategy increases the flexibility of production, in particular by its ability to reorganize the production plan in order to avoid the occurrence of undesirable events on the platform. On the other hand, in deferred time, this strategy offers the possibility of enhanced optimization in the scheduling phase of production modules. The second strategy is to define modules grouping together a sequence of operations such as transfer operation in order to facilitate visibility of the production plan but may result in increasing the number of modules to

Table 2
Example of parametrized operations.

Machines	Operations	Description	Parameters
Robot K900	W_RF_Pick_InitStore	Pick the part from the Initial Store	ID, Ø, H, S
Robot K900	W_RF_Drop_TransStrore	Drop the part in the Transition Store	ID, Ø, H, S
Robot K1100	W_RM_Pick_TransStore	Pick the Part from the Transition Store	ID, Ø, H, S
Robot K1100	W_RM_Drop_Tour	Drop the part to the Lathe	ID, Ø, H, S
Embedded Camera	W_RM_Control_Tour	Presence check of the part in the Lathe	ID, Ø, H, S
Tour Tormach	Prog_Tour_1	Turn on the referenced Lathe program	ID, D, S
Robot K1100	W_RM_Pick_Tour	Pick the part from the Lathe	ID, Ø, H, S
Robot K1100	W_RM_Drop_Scanner	Drop the part to the 3D Scanner	ID, Ø, H, S
Scanner FARO	Prog_Frao_1	Start Scanning (referenced part program)	Frequency $^{\circ}/_{\circ}$
Robot K1100	W_RM_Pick_Scanner	Pick the scanned part	ID, Ø, H, S
Robot K1100	W_RM_Drop_TransStore	Drop the part to the Transition Store	ID, Ø, H, S
Robot K900	W_RF_Pick_TransStore	Pick the part from the Transition Store	ID, Ø, H, S
Robot K900	W_RF_Drop_Conv	Drop the part to the final conveyor	ID, Ø, H, S

Table 3
Example of production modules.

Modules	Operations	Module definitions	Settings
Raw transfer from initial stock to lathe	W_RM_Pick_TransStore ⮡ W_RM_Drop_Tour		
Presence control	W_RM_Control_Tour	In-situ control of the presence of raw part	% de *n*
Machining lathe – Pawn	Prog_Tour_1	Start the machining program	Lathe
Machined part transfer to the transition store	W_RM_Pick_Tour ⮡ W_RM_Drop_TransStore	Get the machined part from the chuck and evacuate it to the accumulation table	*n*

respond to different tasks. The interoperation prior constraints make it easier to group them into a module; therefore, the parameterization of certain operations is transferred to the module which returns the value of the parameter to the operation concerned in the production phase.

The first module in Table 3 represents the lathe machining module which consists of some consecutive merged blocks of standardized operations. This module starts from the MES order, a robot trajectory to pick the desired part from the initial store, and a robot trajectory to transfer the workpiece to the lathe. The second module concerns the verification of part handling in the lathe using an embedded camera. The robot will be evacuated outside the machine, then the proper machining G-Code program will be processed through the 3rd module. Afterward, a separated module is created as the Lathe Evacuation Module in order to pick up the finished workpiece from the Lathe. This module will be processed as follow: a robot trajectory will be activated to enter the machine, followed a robot transfer trajectory picking up the finished part outside the machine, along with collecting the operation data to the MES.

It can be seen in Table 3 that certain modules group together a single operation, for various reasons. The “Lathe machining – Pawn” module groups a single “Prog_Tour_1” operation, specific to the machining of a precise component. This choice is justified by the importance of the operation and the need to make it visible in the working production plan. The “presence control” module of the part in the lathe chuck also groups together a single operation, this is justified by the frequency set to this module request, which is lower than the production rate of the components concerned. In general, it is the engineers' experience that makes the difference in the configuration of the modules, anticipating production constraints and productivity requirements.

The possibility to create such separated modules, thanks to the developed modular process, provides the manufacturing system with a considerable level of flexibility since multiple modules could be launched in parallel depending on the availability of machines first and the queuing management generated by the manufacturing system based on the optimisation criterion (time, power consumption, machines priority, . . .). The development work of these modules requires multidisciplinary skills in automation, robotics, and machining, but it has a great added value for the following production engineering work because when it is done, no more important development will be required.

Production plan ‘Orchestration’

The 3rd phase of this section is the scheduling of production modules to generate a digital production plan and therefore orchestrate the created functional production modules. In our approach three types of production plans are distinguished. The first called “initial” which takes into account the precedent constraints in-between modules. This initial plan is not well optimised as it stands, it only gives a global overview of the initial production plan. The second version of the production plan, called “optimized”, will be subject to the capacity constraints of the platform 4.0 and the optimization criteria. To this end, the MES will propose several possible flow configurations Fig. 7 to optimize based on the weighting of the optimization criteria and machines availability. The criteria which can be used are cost, time, or energy. The optimization can be mono-objective, for example producing a production plan which minimizes energy consumption, or multi-objective, when a configuration of production plan is sought to offer the best production time at the lowest cost. Once the optimized production time has been validated and saved, the MES system can schedule its execution taking into account the current production load by managing the production flows (Queuing Management).

Fig. 8 illustrates a production plan for a Pawn organized into several possible flow scenarios. The first flow transfers the machined part from the lathe chuck to the 3d scanner, activates the scanner to measure dimensional deviations, then transfers it from the scanner to the conveyor. The second flow transfers the machined part directly from the lathe chuck to the conveyor without going through the 3d scanner. These alternative flows are conditioned by the frequency of dimensional control defined for this specific product. This parameter, controlled by the MES in the “production control” phase, can be fixed or varied depending on the evolution of dimensional deviations observed over the time. The historization of dimensional deviations of machined parts from their CAD model is a real source of optimization to maintain production at an optimal rate. Indeed, the dynamic quality control makes it possible on the one hand to limit interruptions for adjustment and on the other hand to limit the number of parts rejected for dimensional and geometric non-conformities.

Finally, the control in real-time of the operations and the scheduling are done through an HMI developed through Wonderware System Platform (WSP). WSP software applications offer

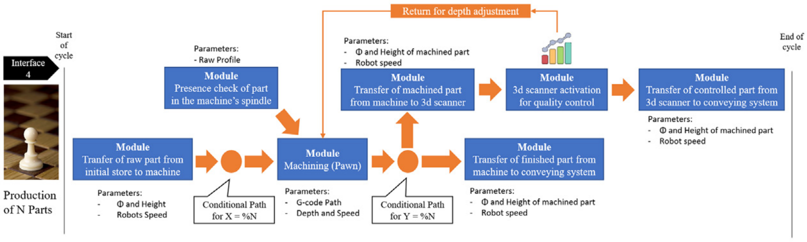

Fig. 8. Production plan example for a chess pawn.

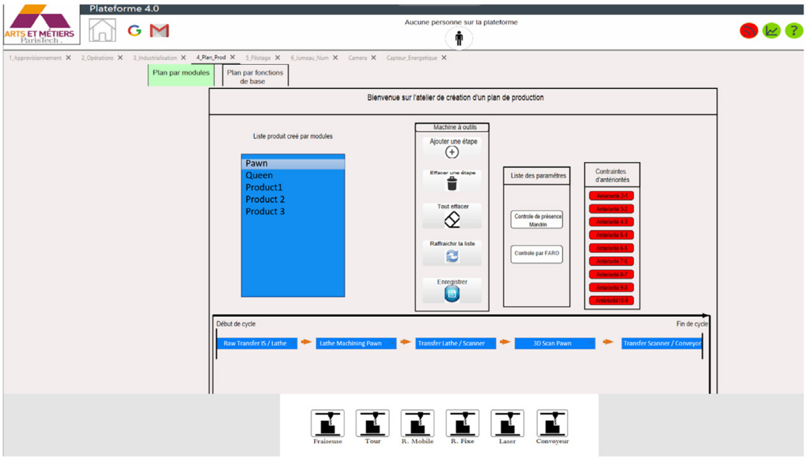

Fig. 9. Production HMI for the industrial platform 4.0.

enhanced integration and provide a common and strategic industrial application services platform on top of virtually any existing system built on the industry-standards based ArchestrA real-time SOA technology. This integration provides a development environment for MES, SCADA, HMI, Historization, and other manufacturing service applications using a single, unified SOA software platform. These new unified software solutions are designed to help manufacturers reduce inventory costs and improve production order lead time for rapid responses to changes in demand, as well as increase the capacity of existing assets through improvements in asset utilization [36]. An interface is developed using WSP to communicate with the robot's programs and machines via their identifier, in order to organize production operation in the desired order. Fig. 9 presents the experimental HMI version to test the reliability of the production system. The tab presented in Fig. 7 is dedicated to the orchestration of the modules composing the production plan of the product.

Production process planning

The production plans, selected and validated in the previous phase, will be loaded and positioned in priority execution order. The MES manages the synchronization of production plans with the capacity load of the platform. In our approach, synchronization is carried out at the modules level, bringing operational flexibility to modular flexibility. In its preparation phase, the MES takes into account the load plan of each machine, scheduled shutdowns, stocks, initial scheduling, the availability of reference documents, the constitution of batches, etc. In its active phase, it takes into account the real-time balancing of flows, failures, measured deviations, contingencies, traceability and batch release, etc. To this end, the MES developed here will be endowed with a level of autonomy and must therefore be able to make decisions based on ascending data almost in real-time. Thus, the ordering of modules, or grouping of modules, becomes dynamic and its updating depends on the one hand on the evolution of the situation in real-time and on the other hand on the hazards encountered.

Discussion

Following the development of the experimental interface, a commissioning phase was held to verify the well-functioning of the flexible operations. Concerning the transfer functions, all possible combinations were tested in order to validate the secure and successful passage of the robots between all machines and production stages/zones. Regarding CNC machines, the flexible G-code is tested as well on both the lathe and the milling machine. The monitoring is confirmed through the ability to change the sub-program selection (from a list of 8 sub-G-code programs active on the machine) corresponding to a specific product. In order to validate the proposed architecture and comparing it with the traditional approach, several tests were conducted by a group of interns and production engineering students. The aim of the conducted experimentations is to validate the simplicity of creating a new production plan for a new ordered product along with the significant short-time consumed at the industrialisation phase to configure a production plan. The experimentation is supported by a library module created on the HMI to guide the operator and assist him with basic information concerning different types of operations with descriptions and annotations. Eight pawn chess pieces are identified to be produced through the system. The production engineer student started using the developed HMI by creating a new product called Pawn. The first step was assigning the different transfer operations needed to handle the part by the robots, along with selecting the proper parameters corresponding to the raw part dimension, knowing that all possible transfer operations are already defined, listed and well indexed on the HMI. Concerning the machining operations, the operator has the option to launch an external CAD/CAM application from the HMI in order to generate the G-code correspondent to the product based on its 3D model, and consequently import the generated g-code and share it with the CNC machine by updating the 8 sub-programs list. Once the transfer and the machining operations are configured and assigned to the product, the operator generates functional modules regrouping the configured operations as explained before. Thereafter, the operator creates the production plan as presented in Fig. 9, by adding a set of modules presented by a list box, and orchestrating the generated modules listed based on the selected product. Last phase is choosing the configured product in the production plan interface where the operator can add the quantity required of the product and launch the production.

The traditional approach of configuring a new production plan for a new product consists of creating all correspondent machining and transfer operations (and sometimes from scratch) required to manufacture the product. Afterward, a technical or a control engineer is needed to assign first logical functions to the configured operations and consequently create a new control program and deploy it to the PLC controller, followed by a commissioning phase. Two main dimensions are worth mentioning when comparing the new approach with the traditional one, mainly the technical competencies including the complexity dimension and the gaining time dimension. The first dimension is clearly addressed by the new approach since the operator or the production engineer does not need to have specific competencies in control, robotics and other technical fields any time a new production plan has to be generated according to a new product, hence reducing cost of external integrator intervention. The gaining time dimension is assured through reducing the configuration time needed for the industrialisation phase and eliminating the need of a commissioning phase since the new approach is meant to be flexible and designed to handle a diversity of products in the machines capacity. The paths are well configured, and the modular design of this production system worked very well, giving the operator the opportunity to drive the production plan in various configuration and combination easily through a simple HMI without the need for any additive coding or technical effort.

The work presented in the last section shows that the MES plays an important role in intelligent manufacturing processes. It also demonstrates that the notion of operational flexibility must be taken into account in the design phase of the advanced production control system, especially when working in a more complex manufacturing system with more machines, devices, and sensors. The modelling carried out showed the relevance of our methodological choices and research orientations. The perspectives consist in developing the autonomy of the "piloting" function as well as multicriteria production optimization algorithms.

Furthermore, and based on the developed methodology, the proposed architecture can be applied to other manufacturing system with specific requirements involving controllable and programmable robots playing transfer functions. The specific requirements abovementioned concerns first the degree of flexibility of machines at the shop floor and its ability to perform multiple operations from a limited number of resources. Machines flexibility requires at least solving issues such as interoperability, accessibility or remote access to machines, and enabling flexible configuration of the machining process in terms of dimensional capability to carry out a margin of parts, and in terms of parametrization. Second, a special attention should be paid to the configuration of logical functions at the API layer taking into consideration the operational flexibility of machines. Third, the digital MES platform developed or adapted to play the role of Production Planning and Control PPC system must handle new challenges created by Industry 4.0. MES needs to become logically decentralized and composed of decoupled objects or service applications with an external service responsible for the coupling of connected machines and CPS. Lastly, it is worth mentioning that applying the proposed design methodology should be driven by a new configuration insight of the shop floor taking into consideration the flexibility deployed and the expected patterns from the production system.

Conclusion and future work

The work done during this project is a valuable approach allowing increased flexibility of a production line. It allows us to easily control the manufacturing of various products through an HMI rather than reprogramming the industrial controllers that is normally required alternatively to enable a new product manufacturing process. The contribution of this paper is the development of this flexible and modular approach based on several advanced technologies such as advanced robotics, embedded camera systems, and flexible machine tools, along with implementing a novel control architecture that consists of moving the decision-making process to an advanced and interoperable MES. The operation of our architecture has been successfully tested. Despite interoperability difficulties, we have managed to develop a system to reconfigure the automated production space to manufacture a wide range of products from the same raw materials.

The performed work is an interesting development achievement for companies, as far as small and medium-sized manufacturers are concerned, especially when personalization plays an important role in nowadays ever-changing market. Further development will focus on the optimisation opportunities enabled by the system considering time, cost, and power consumption criterion through embedded sensors already mounted on the machines. Finally, along with considering the investment cost of integration, it is necessary to express the need for a multidisciplinary approach in projects of this type. The transition to Industry 4.0 is the paradigm of the intersection of multiple areas of engineering expertise and competencies. Capitalizing on the knowledge and the required competencies of each of these areas to transform the industry is, in our opinion, one of the major issues.

Conflict of interest statement

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

References

[1] Erol, S., Schumacher, A., 2016, Strategic Guidance Towards Industry 4.0 — A Three Stage Process Model.8 .

[2] Schierholt, K., 2001, Process Configuration: Combining the Principles of Product Configuration and Process Planning. Artificial Intelligence for Engineering Design Analysis and Manufacturing: AIEDAM, 15:411–424.

[3] Zheng, L.Y., Dong, H.F., Vichare, P., Nassehi, A., Newman, S.T., 2008, Systematic Modeling and Reusing of Process Knowledge for Rapid Process Configuration. Robotics and Computer-Integrated Manufacturing, 24:763–772. http://dx.doi.org/10.1016/j.rcim.2008.03.006.

[4] Zhang, L.L., Rodrigues, B., 2009, A Tree Unification Approach to Constructing Generic Processes. IIE Transactions, 41:916–929. http://dx.doi.org/10.1080/07408170903026049.

[5] Finance, A.T.C.C., 2015, Industry 4.0 Challenges and Solutions for the Digital Transformation and Use of Exponential Technologies.Finance, Audit Tax Consulting Corporate, Zurich, Swiss.

[6] Theorin, A., Bengtsson, K., Provost, J., Lieder, M., Johnsson, C., Lundholm, T., Lennartson, B., 2017, An Event-Driven Manufacturing Information System Architecture for Industry 4.0. International Journal of Production Research, 55:1297–1311. http://dx.doi.org/10.1080/00207543.2016.1201604.

[7] Zhou, K., Liu, Taigang, Zhou, Lifeng, 2015, Industry 4.0: Towards Future Industrial Opportunities and Challenges. 2015 12th International Conference on Fuzzy Systems and Knowledge Discovery (FSKD) (Presented at the 2015 12th International Conference on Fuzzy Systems and Knowledge Discovery (FSKD), IEEE, Zhangjiajie, China), pp.2147–2152. http://dx.doi.org/10.1109/FSKD.2015.7382284.

[8] Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., Harnisch, M., 2015, Industry 4.0: The Future of Productivity and Growth in Manufacturing.20 .

[9] Kamble, S.S., Gunasekaran, A., Gawankar, S.A., 2018, Sustainable Industry 4.0 Framework: A Systematic Literature Review Identifying the Current Trends and Future Perspectives. Process Safety and Environmental Protection, 117:408–425. http://dx.doi.org/10.1016/j.psep.2018.05.009.

[10] Mes, M., Gerrits, B., 2019, Multi-Agent Systems. in Zijm HH., Klumpp MM., Regattieri AA., Heragu SS., (Eds.) Operations, Logistics and Supply Chain Management, Lecture Notes in Logistics. Springer International Publishing, Cham, pp. pp.611–636. http://dx.doi.org/10.1007/978-3-319-92447-2_27.

[11] Bloch, H., Hensel, S., Hoernicke, M., Stark, K., Menschner (neé Hahn), A., Fay, A., Urbas, L., Knohl, T., Bernshausen, J., 2018, State-Based Control of Process

Services within Modular Process Plants. Procedia CIRP, 72:1088–1093. http://dx.doi.org/10.1016/j.procir.2018.03.037.

[12] Strategy&. 2015, Small Automation, Big Benefits [WWW Document]. PwC. URL https://www.strategyand.pwc.com/gx/en/functions/technology-strategy/big-benefits.html (Accessed 3.5.20).

[13] Mourtzis, D., Vlachou, E., Xanthopoulos, N., Givehchi, M., Wang, L., 2016, Cloud-Based Adaptive Process Planning Considering Availability and Capabilities of Machine Tools. Journal of Manufacturing Systems, 39:1–8. http://dx.doi.org/10.1016/j.jmsy.2016.01.003.

[14] Geissbauer, R., Lübben, E., Schrauf, S., Pillsbury, S., 2018, Global Digital Operations Study 2018. Digital Champions. How Industry Leaders Build Integrated Operations Ecosystems to Deliver End-to-End Customer Solutions..

[15] Sung, T.K., 2018, Industry 4.0: A Korea Perspective. Technological Forecasting and Social Change, 132:40–45. http://dx.doi.org/10.1016/j.techfore.2017.11.005.

[16] EL Zant, C., Charrier, Q., Benfriha, K., Le Man, P., 2020, Enhanced Manufacturing Execution System “MES” Through A Smart Vision System. Presented at the The International Joint Conference on Mechanics Design Engineering and Advanced Manufacturing (JCM 2020), .

[17] ElMaraghy, H.A., 2005, Flexible and Reconfigurable Manufacturing Systems Paradigms. International Journal of Flexible Manufacturing Systems, 17:261–276. http://dx.doi.org/10.1007/s10696-006-9028-7.

[18] Mourtzis, D., Angelopoulos, J., Dimitrakopoulos, G., 2020, Design and Development of a Flexible Manufacturing Cell in the Concept of Learning Factory Paradigm for the Education of Generation 4.0 Engineers. Procedia Manufacturing Learning Factories Across the Value Chain – From Innovation to Service – The 10th Conference on Learning Factories 2020 45, 361–366. http://dx.doi.org/10.1016/j.promfg.2020.04.035.

[19] Kaschel, C.H., Bernal, Y., L.M.S. 2006, Importance of Flexibility in Manufacturing Systems. International Journal of Computers Communications & Control, 1:53. http://dx.doi.org/10.15837/ijccc.2006.2.2285.

[20] Fragapane, G., Ivanov, D., Peron, M., Sgarbossa, F., Strandhagen, J.O., 2020, Increasing Flexibility and Productivity in Industry 4.0 Production Networks with Autonomous Mobile Robots and Smart Intralogistics. Annals of Operations Research, 1–19. http://dx.doi.org/10.1007/s10479-020-03526-7.

[21] Qin, J., Liu, Y., Grosvenor, R., 2016, A Categorical Framework of Manufacturing for Industry 4.0 and Beyond. Procedia CIRP, 52:173–178. http://dx.doi.org/10.1016/j.procir.2016.08.005.

[22] Mabkhot, M., Al-Ahmari, A., Salah, B., Alkhalefah, H., 2018, Requirements of the Smart Factory System: A Survey and Perspective. Machines, 6:23. http://dx.doi.org/10.3390/machines6020023.

[23] Mourtzis, D., Alexopoulos, K., Chryssolouris, G., 2012, Flexibility Consideration in the Design of Manufacturing Systems: An Industrial Case Study. CIRP Journal of Manufacturing Science and Technology, 5:276–283. http://dx.doi.org/10.1016/j.cirpj.2012.10.001.

[24] Mazars. OpinionWay. 2018, Les dirigeants face à l’Industrie 4.0 [WWW Document]. Mazars.fr.. URL https://online.mazars.fr/industrie-40 (Accessed 3.5.20).

[25] Kumar, A., 2007, From Mass Customization to Mass Personalization: A Strategic Transformation. International Journal of Flexible Manufacturing Systems, 19:533–547. http://dx.doi.org/10.1007/s10696-008-9048-6.

[26] Ghobakhloo, M., 2018, The Future of Manufacturing Industry: A Strategic Roadmap Toward Industry 4.0. Journal of Manufacturing Technology Management, 29:910–936. http://dx.doi.org/10.1108/JMTM-02-2018-0057.

[27] Weyer, S., Schmitt, M., Ohmer, M., Gorecky, D., 2015, Towards Industry 4.0 — Standardization as the Crucial Challenge for Highly Modular, Multi-Vendor Production Systems. IFAC-PapersOnLine, 48:579–584. http://dx.doi.org/10.1016/j.ifacol.2015.06.143.

[28] Kaushal, A., Vardhan, A., Rajput, R.S., 2016, Flexible Manufacturing System A Modern Approach To Manufacturing Technology.8 .

[29] Gorecky, D., Weyer, S., Hennecke, A., Zühlke, D., 2016, Design and Instantiation of a Modular System Architecture for Smart Factories. IFAC-PapersOnLine, 49:79–84. http://dx.doi.org/10.1016/j.ifacol.2016.12.165.

[30] Bloch, H., Fay, A., Knohl, T., Hoernicke, M., Bernshausen, J., Hensel, S., Hahn, A., Urbas, L., 2017, A Microservice-Based Architecture Approach for the Automation of Modular Process Plants. 2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA) (Presented at the 2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), IEEE, Limassol), pp.1–8. http://dx.doi.org/10.1109/ETFA.2017.8247573.

[31] Bloch, H., Grebner, T., Fay, A., Hensel, S., Menschner, A., Urbas, L., Hoernicke, M., Knohl, T., Bernshausen, J., Ag, B., 2018, Orchestration of Services in Modular Process Plants. IECON 2018-44th Annual Conference of the IEEE Industrial Electronics Society (Presented at the IECON 2018-44th Annual Conference of the IEEE Industrial Electronics Society, IEEE, D.C., DC, USA), pp.2935–2940. http://dx.doi.org/10.1109/IECON.2018.8591300.

[32] Perzylo, A., Grothoff, J., Lucio, L., Weser, M., Malakuti, S., Venet, P., Aravantinos, V., Deppe, T., 2019, Capability-Based Semantic Interoperability of Manufacturing Resources: A BaSys 4.0 Perspective. IFAC-PapersOnLine, 52:1590–1596. http://dx.doi.org/10.1016/j.ifacol.2019.11.427.

[33] Fan, W., Zheng, L., Ji, W., Xu, X., Wang, L., Lu, Y., Zhao, X., 2020, Function Block-Based Closed-Loop Adaptive Machining for Assembly Interfaces of Large-Scale Aircraft Components. Robotics and Computer-Integrated Manufacturing, 66101994.

[34] Singh, A., Singh, D.J., Ali, D.M., 2018, Some Control Strategies in a Flexible Manufacturing System — A Simulation Perspective. International Journal of Applied Engineering Research, 13:8.

[35] Wonderware System Platform — Fondation de l’Industrie du Futur [WWW Document]. Wonderware URL https://www.wonderware.fr/produit/supervision-et-controle/ihm-supervision-et-controle/system-platform-2 (Accessed 5.5.20).

[36] Wonderware Enhances Operations and Performance Software [WWW Document].. automation.com. URL https://www.automation.com/en-us/products/product18/wonderware-enhances-operations-and-performance-sof (Accessed 2.15.21).

[37] Benfriha, K., 2020, Conception, Modélisation, Architecture, Technologie et Pédagogique (Mémoire HDR).ENSAM, Paris.

[38] El Zant, C., Charrier, Q., Benfriha, K., Le Men, P., 2021, Enhanced manufacturing execution system “MES” through a smart vision system. in Roucoules LL., Paredes MM., Eynard BB., Morer Camo PP., Rizzi CC., (Eds.) Advances on Mechanics, Design Engineering and Manufacturing III, Lecture Notes in Mechanical Engineering. Springer International Publishing, Cham, pp. pp.329–334. http://dx.doi.org/10.1007/978-3-030-70566-4_52. In press.