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RESEARCH ARTICLE

How to Design Scheduling Solutions for Smart Manufacturing Environments Using RAMI 4.0?

DUARTE ALEMÃO, ANDRE DIONISIO ROCHA, (Member, IEEE), SANAZ NIKGHADAM-HOJJATI, AND JOSÉ BARATA, (Member, IEEE)

Department of Electrical and Computer Engineering, NOVA School of Science and Technology, NOVA University of Lisbon, 2829-516 Caparica, Portugal
UNINOVA—Centre of Technology and Systems (CTS), FCT Campus, 2829-516 Caparica, Portugal

Corresponding author: Duarte Alemão (d.alemao@uninova.pt)

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ABSTRACT The scheduling applied to manufacturing represents a huge opportunity for companies to stand out in a world of fast and big changes. Having a reliable scheduling system will allow factories to deal with the significant demand for highly customized products. Although manufacturing scheduling has been deeply studied for decades, there is still a gap between academia and industry, namely because the lack of flexibility and homogeneity among scheduling solutions, which makes them very use case-oriented. Furthermore, the absence of standardization is also making it difficult to implement smart scheduling solutions in industrial scenarios. Thus, this work presents a set of requirements and design principles based on axiomatic design concept, to make the first steps to standardize the designing and development of manufacturing scheduling solutions in the context of Industry 4.0. At the end, is presented a scheduling generic framework targeting smart manufacturing and evaluated in a practical use case.

INDEX TERMS Manufacturing scheduling, scheduling framework, industry 4.0, cyber-physical production systems, RAMI4.0, design principles.

I. INTRODUCTION

Manufacturing has been changing very quickly in the last decades, mainly due to the tremendous advancements in technology. The large demand for more customized products forces the companies to quickly adapt to the new trends in the market. Therefore, it is crucial to build mechanisms that allow to have more flexibility and reconfigurability within the factories. One of the areas that may benefit greatly from these advancements is manufacturing scheduling, since scheduling is a very complex task that needs to deal with a substantial number of constraints in very different environments. Manufacturing scheduling has also been studying for decades now and some advances have been verified. However, mainly due to its implementation complexity, scheduling solutions are not widely adopted in industry. Usually, scheduling solutions proposed in literature are too specific and not generic enough to be deployed in different scenarios, being very different among them. Moreover, the requirements and constraints considered in those cases are not accurate when applied to the real-world [1], [2]. This creates a big gap between the academia, where new technologies are studied, and the industry, where those technologies may be deployed. Consequently, it is necessary to build guidelines to help designers and developers to create scheduling solutions oriented to Industry 4.0 that can be easily followed and applied to different use cases. This paper aims to propose a set of generic functional requirements and corresponding design principles to help in the designing stage of manufacturing scheduling. Furthermore, the document presents a generic framework to provide the integration between the different components of the scheduling process, as well as a possible architecture.

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II. LITERATURE REVIEW

The recent development and advances in technology as well as the market demand for highly customized and personalized products have been pushing the manufacturing companies to develop new solutions in order to become more dynamic and flexible to face these emergent trends and the quick changing markets. Most of the existing production systems, are based in automated systems built to achieve high performance and high delivery rate, coming from the second and third industrial revolutions, but have no capability regarding autonomy, adaptation and flexibility. Consequently, a group of expert technicians is needed to solve a problem each time a disturbance occurs in the production line [2]. Besides these restrictions, the emergence of new manufacturing paradigms, the appearance of new technologies and processes, the cheaper development of IT infrastructures, the emerging possibility of digitization, between other factors led to a disruption in the industrial scene, known as Smart Manufacturing or Industry 4.0 [3].

A. SMART MANUFACTURING

Smart Manufacturing can be described as a collaborative system which reacts in real time to reach the demand of the factory and the customers [4]. It makes use of concepts such as Cyber-Physical Systems (CPS), Internet of Things (IoT), Cloud Computing, AI and data analysis merged with sensors, communication protocols, control and predictive engineering to build the manufacturing systems of today and tomorrow [5]. According to [6], Smart Manufacturing covers three main characteristics: a) Horizontal integration across the entire value creation network - this covers the integration of different players of the value chain during all the product life cycle, which allows to optimize the entire production process; b) End-to-end engineering across the entire product life cycle - the linking and digitization between the different phases of the product life-cycle, namely the acquisition of raw materials, product manufacturing, product use and the product end of life allow to collect, store and process data to acquire new knowledge and improve the entire production process; c) Vertical integration and networked manufacturing systems - the vertical integration brings up the concept of smart factory, which aims to interconnect all the resources and software application inside the factory. This characteristic allows the system to be more flexible and deal with unexpected disturbances more quickly and efficiently, by having real-time control from what is happening internally. The well known Cyber-Physical Production Systems (CPPS) may contain significant information regarding the hardware of electrical and mechatronic devices, as well as software information and real-time data [7]. The combination of data coming from the physical environment, such as machine wear, with the data coming from simulation tools, such as stress or deformation, as well as maintenance records may provide a more accurate representation of the system and, consequently, more reliable manufacturing solutions [8]. In order to achieve economic, environmental and societal advantages, sustainable and highly reconfigurable factories need to be developed [9]. Reconfigurable manufacturing systems, that entail characteristics such as scalability, customization, and modularity, allow to increase the capability to dinamically change the syste to meet the market demand in an efficient and flexible way [10].

B. CYBER-PHYSICAL PRODUCTION SYSTEMS

CPPS are a crucial element to achieve smart manufacturing. The benefits of integrating both cyber and physical components led to an increasing trend of developing new approaches where those are integrated in manufacturing systems. By using CPS, it is possible to develop a virtual representation of physical objects, contributing to the vertical integration referred before [11]. CPPS just expand the concept and benefits of CPS to the manufacturing context. CPPS rely on the integration of physical and virtual worlds through interaction interfaces, which are used to monitoring and control operations [12]. Internet of Things (IoT), facilitate the process of automatic data gathering and inspection. The data generated by the different resources during the production process is analyzed and converted in useful knowledge to be used in different scales to continuously improve and optimize the production process, for example, by using big data analytics and artificial intelligence algorithms [13]. CPPS can provide virtual capabilities to every physical component, high degree of automation, reconfiguring capabilities, interaction between components at different scales and integration at different spatial and temporal scales [14]. Although these concepts are not completely new in manufacturing systems, only now, with the advances in ICT, they are becoming reliable. In order to standardize the designing and development of smart manufacturing systems, some reference architectures have emerged during the last years, such as ISA-95 [15], the 5C architecture [16], the Smart Grid Architecture Model (SGAM) [17], the Industrial Internet Reference Architecture (IIRA) [18], and the Reference Architectural Model for Industrie 4.0 (RAMI 4.0) [19]. These architectures aim to assure a common comprehension, achieve standardization, enable semantic interoperability and to provide consistent operation models for the system. RAMI 4.0 is one of the most known and used reference architectures when considering one of the most recent manufacturing paradigms, I4.0. This reference architecture is becoming a global standard and is, nowadays, one of the most used architectures and very supported by industry companies in Europe, such as ABB, Bosch, Festo, Siemens or SAP.

C. RAMI 4.0

RAMI4.0 was developed to accomplish a common understanding of which standards, models and use cases are vital for developing a smart manufacturing. The architecture puts together key elements of I4.0 in a three-dimensional layer model. The procedures described in the standards allow smaller companies to adapt for I4.0, by implementing even partial standards which may allow to develop an early I4.0 application. RAMI 4.0 also enables the identification of standards required for relevant use cases [20]. From this architecture two important requirements arise [21]:

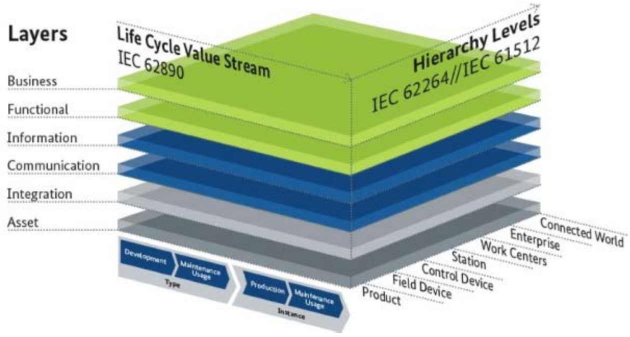

FIGURE 1. RAMI 4.0.

1) It must be possible to use, maintain or even extend the definitions and data in respect of an asset throughout its lifetime if the Use Case so requires;
2) It should be possible to preserve a link between "type" and "instance" definitions in respect of an asset throughout its lifetime.

RAMI4.0 makes possible to easily handle the different phases and aspects of the system (Figure 1), since it expands the Hierarchy Levels of IEC 62264 (by adding the product level at the bottom and the connected world, which encompasses individual factory boundaries, at the top), differentiates between type and instance in the Life Cycle Value Stream of products or systems, and depicts the structure of the IT representation of an I4.0 Component in the Layers axis [21]. This approach allows the description and development of higher flexibility solutions in the context of an I4.0 environment as well as the encapsulation of functionalities where appropriate, due to its three-dimensional model.

Next are described the three dimensions according to [22], [23]:

- Layer Axis: The Layers axis (Figure 2) that represents the different perspectives such as data maps, functional descriptions, communications behavior, hardware/assets or business processes is divided into Asset, Integration, Communication, Information, Functional and Business categories. The business layer maps the relevant business processes. This layer ensures the integrity of functions in the value stream, orchestrates the services in the functional layer, makes the link between diverse business processes and receives events for advancing of the business processes. It is in this layer where the rules the system has to follow need to be modelled. The Business layer explains what the end user needs are. The functional layer contains all the essential functions. It should contain a formal description of the functions and should be a platform for horizontal integration of the various functions. At the same time, should be a run-time and modelling environment for services which support business processes and for applications and technical functionality. Here are generated the rules and decision-making logic. Most exactly this layer defines what the asset is supposed to do and with what services. Linked to the functional layer is the information layer which comprehends relevant data about the system. The information layer is a run-time environment for (pre-) processing of events. Rules are applied here to one or more events to generate one or more further events which will initiate processing in the functional layer. The Information layer describes what data the asset has to provide. The communication layer is made-up to deal with protocols and the transmission of data and files. This layer should provide the services for control of the integration layer and a standardized communication between the Integration and the Information layers. The data should be handled using TCP-IP, HTTP, MQTT and OPC-UA protocols, transmitted through LAN or WAN, and communicate through Bluetooth or Wi-Fi devices. Basically, it defines how to access the data. Just before the asset layer is the integration layer, which allows digitization of the assets for virtual representation. This layer provides information on the assets that can be processed computationally. It also contains the elements connected with IT, such as sensors, RFID readers, HMI and so on. The Integration layer tells which part of the assets will be digitally available in the network. It is the integration layer that connects the asset to the virtual world. Finally, the asset layer represents physical components, such as metal parts, smart products and resources, documents, ideas, etc. In the simulation of a system, such as a machine, it is not only the information and communication functionality that is important. Its cables and its mechanical structure are also considered, although they are not able to communicate. Their information needs to be available as a virtual representation. Thus, the asset layer at the bottom enables an improved description of the machines, components and factories. Essentially, this layer describes how to integrate physical components.
- Life Cycle & Value Stream Axis: Along the horizontal axis is the product life cycle and its value streams, such as dependencies that can also be represented in the reference architecture model. The draft of IEC 62890 is a decent guideline for the life cycle considerations, which distinguish between type and instance. The type is created when a product comes to the development phase, which covers commissioning, development and testing up to the initial sample and prototype production. Here is where the type of a product or machine is created. In the case where an error is reported to the manufacturer or improvements should be done, the type documents may be revised. The instance is represented by each manufactured product of a general type, and it is assigned a unique serial number. These instances are then purchased by customers and delivered to them. For the customer, the products, which are originally just types, only became instances once they are deployed in a specific system. Digitization is a core element in Smart Manufacturing paradigm. The digitization and

linking of the value streams provide enormous potential for improvements in the system, once purchasing, order planning, assembly, logistics, maintenance, customers, suppliers and so on are all interconnected. The cross-linking between different areas is of significant importance, since it makes possible to see inventories in real time and know where are the necessary parts for production at any time, at the same time as the customers are able to see the completion status of the production.

- Hierarchy Levels: the Hierarchy Levels axis represents the vertical integration, specifically, the location of functionalities and responsibilities within factories and plants. In I4.0 there are smart products being operated in smart factories that are connected to an external world. This makes the systems more flexible, where functions are distributed through all the network and all the participants communicate and interact across hierarchy levels. The goal is to do a functional assignment that describes the functional classification of different stages of I4.0. It is based on ISA-95 and follows the IEC 62264 and IEC 61512 standards, the international standards series for enterprise IT and control systems and batch production processes respectively. The functionalities have been extended to include parts in production, i.e. Products, and also the connection between the system and the IoT and services as well as the link to other factories and external collaborations, i.e. Connected World. The Field Device was added below the Control Device in order to have consideration regarding a machine or system, and not only about control device. The Field Device represents the functional level of an intelligent field device, such as a smart sensor. The distinct terms Enterprise, Work Centers, Station, Control Device and Field Device are used to identify different functions in the shop floor and then cover as many sectors as possible from process industry to factory automation. Here are represented in a functional way the structure of technical assets such as products and resources organized into their different functionalities in the system as well as the external interconnected world.

FIGURE 2. RAMI4.0 architectural layers.

D. MANUFACTURING SCHEDULING

Companies, nowadays, need to pursue the development of solutions capable to solve the complex industrial problems that have been increasing. However, most of the existing production systems are based on automated systems built to achieve high performances and high delivery rates, but have no capability regarding autonomy, adaptation, and flexibility [24], [25]. Hence, they need to focus on predictive maintenance, energetic efficiency, simulation environments, production scheduling solution, and so on, in order to achieve the production KPIs as well as to reduce as much as possible the energy consumption and increase profits [2]. Enormous quantities of data are being generated by different tools in current industrial systems, although not all these data are being stored or made available for other tools in the ecosystem. The scheduling system needs to access and use these data, generated by different hardware and software systems, such as shop-floor-related information, maintenance predictions, or energetic analysis. The market heterogeneity associated to the demand for small lot sizes of highly customized products led to tremendous environmental challenges for companies regarding global warming, non-renewable raw materials depletion and, consequently decreased biodiversity. Mouzon *et al.* [26] found that there may be enormous energy savings when underutilized machines are turned off when they are idle for a certain amount of time. Thus, production scheduling is interrelated with the energy efficiency in the shop-floor, which means that to improve energy consumption and sustainability within factories it is of vital importance to develop efficient scheduling approaches [27]. In certain industrial environments, the optimization of the production and maintenance tasks may be enough to reduce the energy consumption [28]. It is necessary to overcome the lack of timely and accurate information and prediction capability regarding errors and possible faults of tasks being executed in the shop-floor. Considering the recent technological advances, there are more date to be extracted from the factories than ever before. This will help to have more precise information about maintenance needs, energy consumption, and other KPIs that may be important to take into account [29]. One of the main challenges in manufacturing systems continues to be the development of scheduling solutions to deal with both the planning information and the unpredictable events that may occur [30]. These challenges may occur in the development phase, due to the systems' complexity of implementation but also in the design phase. Production scheduling aims to effectively allocate the parts to be processed to the available resources and accomplish a determined objective, since scheduling is a process of optimizing both work and time. While the main goal of a scheduling solution is to optimize an objective or group of objectives by assigning each product to a particular machine in a particular time in order to be processed, while conflicts

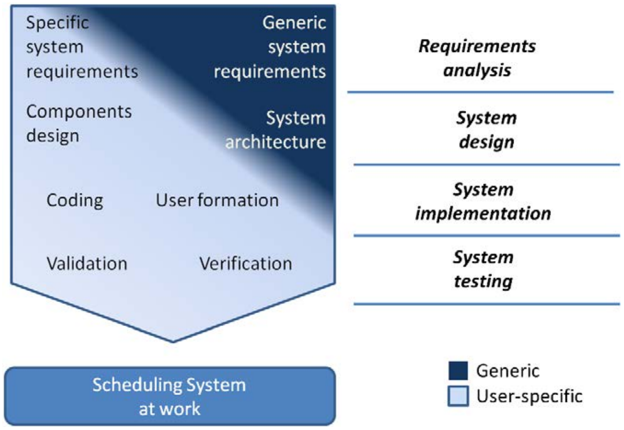

FIGURE 3. Scheduling generic and specific activities in the development of a manufacturing scheduling system [31].

between operations are avoided, in actual manufacturing systems it is common to only consider one objective, which does not reflect the dynamism and heterogeneity of smart manufacturing environments, where it is necessary to integrate different software and hardware components [2].

III. MANUFACTURING SCHEDULING IN THE CONTEXT OF RAMI 4.0

How can production scheduling be integrated in the RAMI4.0?

The RAMI 4.0 presents details about the concepts, standards, and interactions. However, details of implementation and application procedures are not specified. Also, it is not suggested a way to organize and find services and data that support machine discovery to perform the operations required by the products.

As identified earlier, little attention has been given to providing comprehensive guidelines to develop manufacturing scheduling architectures, which impacts the system design and implementation, and may help decreasing the development process times and costs [2]. Moreover, some scheduling systems may have common requirements, since all of them must have a number of common functionalities. The reuse of a validated architecture will shorten the development cycle, ensure the main functionalities of the system are appropriately covered, and allows the re-utilization for forthcoming systems of part of the developed code, as far as the architecture is designed in terms of independent blocks or function-specific modules [31]. The generic and specific activities are illustrated in Figure 3. Thus, both generic and specific activities should be considered when developing scheduling systems.

In this paper, a framework for implementing scheduling solutions based on RAMI4.0 is proposed. This framework for designing Smart Manufacturing scheduling solutions will be based on the non-functional requirements identified in [2]. Thus, this work will contribute with the guidelines to design a scheduling system in the context of Smart Manufacturing, focus on the main aspects of RAMI4.0. Consequently, the following aspects will be considered:

- Architectural layers: focusing on Functional, Information, Communication and Integration;
- Hierarchy Levels: focusing on Station field;
- Lifecycle & Value Stream: the guidelines for manufacturing scheduling will be concentrated in the Development stage of Type stage.

The smart scheduling system represented in the layers of the RAMI 4.0 framework consists of building a generic foundation for developing manufacturing scheduling systems for Smart Manufacturing, interconnecting the most high-level functions of scheduling to the shop-floor where are the physical assets that will execute the schedule.

Consequently, different features can be linked to each of the RAMI's Layers [32], [33].

- *Business*: business layer serves to mapping business models, ensuring integrity of functions in the value stream, modelling the rules the system has to follow, and link between different business processes.
- *Functional*: in this layer are represented the formal description of functions performed by the scheduling system, i.e. what the system is capable to do, for example perform scheduling operations, data analysis, simulation, data visualization and other features.
- *Information*: data from different scheduling components are stored in this layer. It can be rules description, data models, event's data, asset's data, provision of orders and so on. This layer should ensure the integrity of data.
- *Communication*: in communication layer are defined the protocols to establish a standard communication among the system, such as OPC-UA, HTTP, MQTT, bluetooth, etc.
- *Integration*: the integration layer will build the connection between the physical and the cyber levels. This layer works as a middleware that facilitates that connection, ensuring that the information is readable and compliant on both sides and provides information from the assets that can be computer-processed. Thus, it is composed by elements connected with IT, such as RFID readers, sensors, HMI, and so on. RAMI4.0 proposes the concept of Asset Administration Shell (AAS) which is used to transpose any asset into the digital world in a standardized way.
- *Asset*: in the asset level are present the physical components that constitute the scheduling system, such as raw materials, parts, products, axes, transport circuits, human workers, working stations, storage, relevant documents, and so on.

IV. FUNCTIONAL REQUIREMENTS FOR SMART MANUFACTURING SCHEDULING

Requirements play a crucial role when designing any kind of systems, as they are the basis to start developing anything from software to hardware. The purpose of a requirement is to influence the process of systems development and establish a basis for further steps, such as communication, system integration and maintenance, system architecture, benefits optimization, improving employee satisfaction and so on. Requirements may be differentiated in many types, but mainly in two big groups: Functional Requirements and Non-Functional Requirements. Functional requirements refer to the actions that a system has to perform automatically and the interactions between the system and other systems or human users. It is a requirement regarding a behaviour that shall be provided by a function or service. Non-functional requirements usually refer to every system's requirement that is not considered a functional requirement, and can be divided but not limited to System requirements, Technological requirements, Networking requirements, Quality of service requirements, Legal requirements and Constraints [34].

The following keywords were adopted as described to express the necessity of each requirement:

- ''Shall'' - Legally binding. It determines that it is mandatory to fulfill the requirement.
- ''Should'' - Not legally binding. It expresses an intention to implement the requirement under certain circumstances but it does not need to be implemented.

The identified Functional Requirements are described as a tree format, where there is a main requirement that is split in different ones.

- FR1 Develop a dynamic scheduling system able to deal with several targets and specific production requirements in smart manufacturing environments: the main requirement identified in this work is to develop and provide a dynamic scheduling system that shall be able deal with several targets and requisites. These targets represent the production objectives, which may or may not be defined a priori and may change during the process. On the other hand, the requisites define the working boundaries of the manufacturing system, necessary to achieve an efficient production, that may change according to the circumstances.
- FR1.1 The system shall be able to replicate the physical system into the logical system: the system using recent technologies shall receive and interpret information regarding the physical system and based on that create a logical replica that may be quickly accessible and ready to be tested with different purposes in a computational environment.
- FR1.1.1 A factory topology replica shall always be held in the logical system, independently of how the data are saved (ontology, datamodel, etc.)
- FR1.1.2 – The replica shall be updated every time the factory topology is changed.
- FR1.2 The system shall be able to interoperate with other systems that may provide relevant information and knowledge for scheduling (ERP, MES, Data Analytics tools, etc.): the interoperability among different systems will allow to develop more accurate and efficient solutions, that may be deployed faster.
- FR1.2.1 The system shall have the capability of integrating software tools independently of the technology in which those are developed. The technology adopted should not be an obstacle to an easy and quick integration of different tools. In the current context of smart manufacturing, it is crucial that different tools may be connected and exchange data between them.
- FR1.2.2 The sharing of data between the different tools shall be harmonized: In order to facilitate the exchange and interpretation of data, it is necessary to follow a common path, so the data sharing between tools shall be harmonized.
- FR1.2.3 The tools to be developed shall have the ability to work collaboratively: collaboration is a key requisite in current manufacturing paradigm in order to achieve success. Thus, it is essential that the new developed tools have the ability to work collaboratively with other tools, therefore information among the system may be exchanged faster and more effectively.
- FR1.3 The system shall be independent of the chosen KPIs and capable to deal with several combinations. Solutions not being KPI-dependent are of immense importance in smart systems where the surrounding conditions may change frequently. This will allow to deal with different objectives and restrictions in different times, giving more flexibility and adaptability to the scheduling system.
- FR1.3.1 KPIs description shall be uniform for all of them: In order to facilitate the system's understanding of KPIs, they need to be created uniformly, to avoid misinterpretations or reading errors.
- FR1.3.2 The KPIs list shall be updated as the objectives are updated: by updating the list of KPIs each time the objectives of the system change, it allows to always have the scheduling system working on up-to-date solutions.
- FR1.3.3 The system shall allow the possibility to assign priorities to KPIs: KPIs do not have all the same importance and impact in the system. With that fact in mind, it is important to differentiate and prioritize them to better execute optimization solutions.
- FR1.3.4 The system shall allow to choose which KPIs to use in each moment: During the production process, the user shall have the opportunity to choose which KPIs need to be considered in the next scheduling instance. This may vary according to the needs of the factory.
- FR1.4 The system shall have the capability to perform the rescheduling of operations in real-time. This means that, if there is the necessity to change plans during the execution, the system shall have the capability to adapt accordingly and suggest new schedules.
- FR1.4.1 Thresholds for deviations should be defined. In order to perform rescheduling as necessary, the system needs to know when the rescheduling needs to be executed. Thus, it is essential to define boundaries that tell the system when the current schedule is not valid anymore.

- FR1.4.2 The system shall have the ability to monitor its own performance in order to check for considerable deviations from the running scheduling. After knowing the defined thresholds, the system needs, in a consistent manner, to check how it is behaving itself and if the current execution is still within the boundaries or not.
- FR1.4.3 When new orders arrive to the system, and if they are urgent, the system shall be able to notice whether rescheduling is necessary (if there is a considerable deviation from execution) or whether orders can be inserted into the current scheduling. The arrival of new information may or may not affect the current production.
- FR1.4.4 When there are considerable deviations, the system shall be able to automatically recalculate a new schedule. This will limit the human intervention and, consequently, improving the overall performance of the system, leading to faster deliveries of finished products and expenses reduction.
- FR1.5 The system shall provide human-machine interfaces that allow a seamless interaction with the human operator. The interaction between the human and the system needs to be easy and practical for any operator, and do not consume more time than necessary for the human operator.
- FR1.5.1 The application of new schedules at the factory shall be validated by the production manager (or equivalent) before being deployed in the production line. After each new scheduling suggestion, the production manager will validate the schedule to make sure that it fits the current needs.
- FR1.5.2 The user should have the possibility to ask for new schedules at any time. If the user finds it necessary, he/she may ask the system to suggest new schedules.
- FR1.5.3 The Graphical User Interface (GUI) shall provide the choice of priorities and use of KPIs, as well as adding and removing KPIs. When an operator decides to ask for a new schedule, he/she needs to define what are the priorities for that particular schedule and what KPIs are supposed to be met. Additionally, it is important that new KPIs may be added or old ones removed, according to the process evolution.
- FR1.5.4 The system shall allow interaction with the operator to receive feedback from the executions. Thus, it is crucial that the human operators may give feedback about previous executions, which will allow to improve future suggestions.
- FR1.6 The system should have the capability to use different optimization approaches that allow the best system's performance. By allowing several optimization techniques, the system may find what the is the best approach for different scenarios.
- FR1.6.1 The system shall be able to optimize the scheduling process simultaneously for different KPIs and targets. This means that the system will be able to focus on different indicators that may be requested and not only in one specific factor.
- FR1.6.2 The system should make use of data from both production line and external systems in order to provide more precise and robust scheduling solutions. By receiving feedback from internal and external sources the system may adapt accordingly and improve the overall performance.
- FR1.6.3 The scheduling starting point shall be the current state of the physical system. Thus, the system is not supposed to make assumptions regarding scheduling process but shall consult the present state to use the correct necessary data.

These requirements are important to build a manufacturing scheduling system, although such systems may not be limited to the ones identified in this document. Nevertheless, the authors believe that an important step is been giving by presenting these requirements in order to achieve harmonization and standardization in scheduling systems designing and development for manufacturing. These are also the baseline for the definition of the design principles explored in the next section.

V. DESIGN PRINCIPLES FOR SMART MANUFACTURING SCHEDULING

This section presents the design principles (DP) to support practitioners in developing scheduling systems for manufacturing environments.

The identified DP are based on an adaptation of the axiomatic design principles where each functional requirements is matched with one DP [35]. Thus, each of the presented DP is related with the FR previously defined. In Figure 4 is a summary of where each of the design principles fits in RAMI 4.0 layers axis. Note that, this work does not intend to depict business processes and value chain interactions, as so, the business layer is not covered in this document.

The first group of design principles refers to replication of the physical system into a cyber system, making it able to easily communicate with other systems and strive in smart manufacturing environments.

- DP1.1.1 A replica of the factory may be held in the logical system through the adoption of AAS, which is the Digital Twin applied to Industry 4.0. The AAS transforms the physical or intangible asset (entity) into a I4.0 Component, which is the way to describe thoroughly the properties of a CPS. By other words, the AAS is the digital representation of the real asset, containing all of its information and technical functionalities, and administering communications with other I4.0 Components. It is included in the Integration layer of RAMI 4.0.
- DP1.1.2 In order to achieve this updatability, two factors must be considered. First, needs to be defined how the data are accessed. For this, RAMI 4.0 provides standard communication protocols to link the Integration and

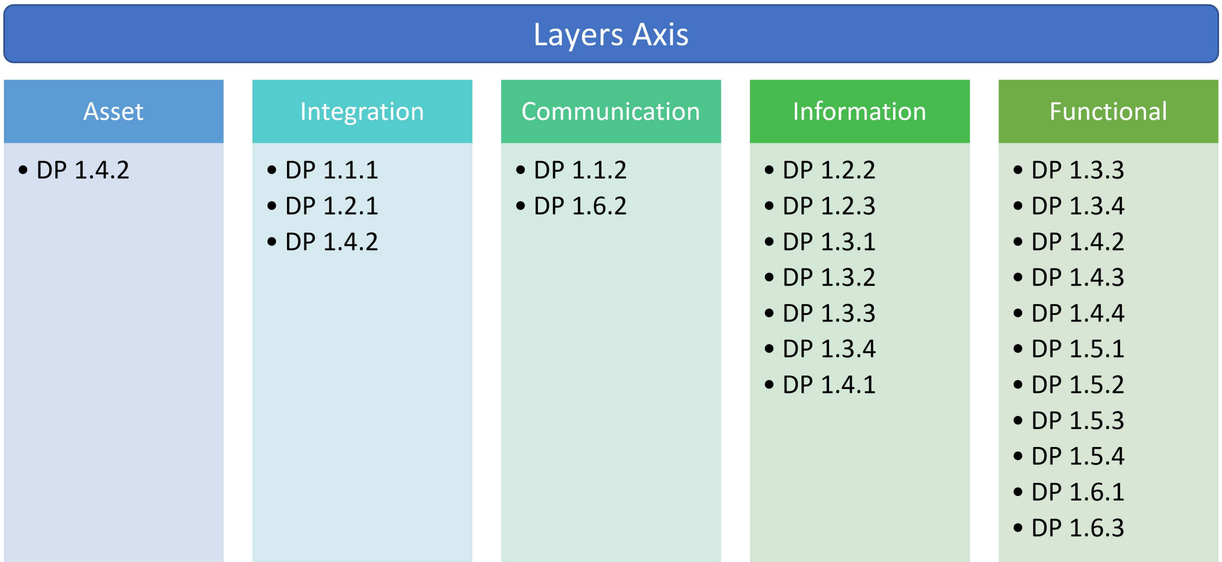

FIGURE 4. **Identification of design principles in each layer of RAMI 4.0.**

Information layers, such as HTTP, TCP-IP, MQTT, and OPC-UA protocols, which may depend on the device type and its capability to send data. Second, it is necessary to identify which parts of the asset will be available digitally and, consequently what data will be provided by the asset and stored in the Information layer. The Information layer will include the several data models that may describe the asset. By adopting generic data models to describe the assets it will be possible to the digital factory updated.

The second set refers to the interoperotion between the scheduling system and other systems relevant to it, such as ERP or MES. A seamless interoperability allows to develop more efficient systems.

- DP1.2.1 In the context of Industry 4.0, an asset may be any entity, from a hardware device to a software application. Thus, the AAS will allow the integration of the asset in the digital world, which can be done through HMI, switches, or sensor readers. According to RAMI 4.0, the communication between different tools shall be done through data mapping to XML, JSON, OPC UA, AML, RDF. Nowadays, there are so many technologies being adopted to develop different or similar tools that it is vital to keep them interacting smoothly, thus the adoption of common interfaces will allow tools to interact with each other without being reprogramed each time a new tool is connected. In this way, the communication between different tools will be facilitated and technology independent.
- DP1.2.2 The transferring of data shall be harmonized through the use of a data model or ontology. The Information layer of RAMI 4.0 comprises not only the technical data of the assets, but also semantics as a common language, which means that the data models will be included in this layer. Consequently, by defining common data models or ontologies, the exchange of information will be harmonized, leading to faster and easier communication between different tools. As examples of data exchange formats recommended in RAMI 4.0 there are XML, JSON, or RDF [20].
- DP1.2.3 The adoption of standard communication protocols, as mentioned in DP1.1.2, and common I4.0-compliant interfaces and data models, will facilitate the collaboration between tools of different manufacturers. Thus, the infrastructure shall be designed to facilitate the integration between tools, which means tools shall be designed in a way to work together so they can provide functionalities that would not be able to by themselves. Consequently, data sharing and using needs to be uniformed between the different components.

Next are presented the design principles relevant for developing KPI-independent scheduling solutions. Different systems have different objectives and constrains, thus a generic scheduling solution cannot be dependent of what the KPIs are.

- DP1.3.1 KPIs description need to follow the same rules of creation in order to be uniform. This may be realized by the definition of several fields that need to be fulfilled, when creating the data model, either by adopting XML, AML, JSON, or other standard format. The KPIs description shall be part of the Information layer.
- DP1.3.2 Save system's objectives in Information layer (data model). KPIs can be updated by the user, that should have their own digital replica for user. Then, it will be easy to establish the communication between both parts through standard communication protocols. KPIs must be saved in a generic data model, which will facilitate the update by the user during the process,

if it is necessary to update the production objectives. These objectives may vary and comprise, for example, energetic consumption, waste reduction or throughput increase.

- DP1.3.3 An editable field, at the moment of KPI's creation or during the process, need to be available in order to assign or change KPI's priorities. This data will be stored in Information layer and updated if there are changes during the process.
- DP1.3.4 During the production process, and before starting a new schedule execution, the system shall provide the possibility to choose (through the GUI) which KPIs will be considered in the next execution, since not all of them may be relevant at each time. The user may then choose which KPIs are relevant for the next scheduling instantiation. This can be done through selection boxes, for instance.

The fourth group of design principles is related to the capability of the system to execute a rescheduling in real-time, if there is a plan changing during the production execution.

- DP1.4.1 Boundaries need to be specified when the KPIs/restrictions are defined. Thus, maximum and minimum levels of acceptability need to be identified. These boundaries shall be defined when the KPIs are created, i.e. when the associated asset is instantiated, and stored in the Information layer of RAMI 4.0, which is where the data models can be found. For example, if a working station can only manufacture products of type X, it shall be specified during the instantiation of the digital replica of that station. On the other hand, if the energy consumption of a work station must be below some threshold, the scheduling system may consider that KPI when allocating production tasks.
- DP1.4.2 Through the acquisition of real-time data from the shop-floor, the system needs to evaluate how the production process is evolving. These data can be acquired from working stations, human workers, digital readers, or other sources of information that are able to communicate with the digital world. This process can be done in different ways, for example, periodically (where the information is being verified in regular time intervals) or event-driven (where, each time there is a new event, i.e. a change in the system's state, that information is communicated to the higher layers). Then, an algorithm shall perform the calculations in order to verify if there are deviations that affect the current scheduling execution and, if necessary, suggest new alternatives.
- DP1.4.3 An algorithm should be implemented to verify if it is possible to fit the new order within the current schedule without going over the thresholds, for instance by placing new orders in idle time positions, or if it is necessary to perform a reschedule and change the actual production process.
- DP1.4.4 An algorithm should be implemented to automatically perform a rescheduling when there are significant deviations regarding the original schedule. It may or may not be the same algorithm that performs the initial scheduling, depending on the necessary conditions for each particular case.

A human-machine interface should be developed in order to ease the process between operators and the shop-floor. This HMI will make the link between the asset (human worker) and the digital world. The interface should be a friendly and intuitive GUI and contain all the necessary features for the worker to operate with scheduling system.

- DP1.5.1 The GUI should allow the production manager to analyze and validate the suggested schedule. Preferably, the interface will show all the important metrics that the responsible worker needs to analyze and, eventually, a graphical output of the schedule suggestion, such as a Gantt chart. Then, the user will be able to accept, refuse or ask for a new solution.
- DP1.5.2 The GUI should allow users to ask for new schedules in a simple way. Thus, new schedules may be generated not only when deviations occur, but also when the production manager considers it is necessary. As mentioned in DP1.3.4, this GUI should display the available KPIs to choose for the next schedule.
- DP1.5.3 The GUI needs to contain checkable boxes that allow to quickly choose which KPIs must be taken into account in the next scheduling generation, as well as which are the priorities for each KPI. Additionally, the GUI should allow the addition and removal of KPIs from the system.
- DP1.5.4 The GUI should support inputs from human workers, so feedback about previous executions may be registered and further analyzed. This can be done by allowing text insertion, which needs to be analyzed more carefully, or having predefined options that can be selected in order to identify recurrent situations. This may comprise, for example, production, maintenance, or process details.

Finally, in order for the system to have the capability to use different optimization techniques to find the best approach for different scenarios are presented the next design principles.

- DP1.6.1 Different optimization techniques should be implemented in order to reach a better performance of the system and, at the same time, allow to deal with multi-objectives problems. Heuristic optimization techniques are usually not optimal but more flexible and faster to find solutions. May be considered Genetic Algorithms, Particle Swarm Optimization, Ant Colony Optimization, Multi-agent Systems, among many other approaches.
- DP1.6.2 The scheduling system should be able to communicate with external systems to collect the necessary data to be used in the scheduling process. Thus, it will be able to adapt to the challenges in real-time. This can be done through the use of common interfaces and data models (DP1.2.3). Moreover, I4.0-compliant tools shall be wrapped in an AAS, hence the scheduling tool will be able to communicate easily with those tools.

Design Principle	Impact for scheduling	Design Principle	Impact for scheduling
DP 1.1.1	High	DP 1.4.2	High
DP 1.1.2	High	DP 1.4.3	High
DP 1.2.1	High	DP 1.4.4	Medium
DP 1.2.2	High	DP 1.5.1	Medium
DP 1.2.3	Medium	DP 1.5.2	Low
DP 1.3.1	High	DP 1.5.3	Low
DP 1.3.2	High	DP 1.5.4	Low
DP 1.3.3	Medium	DP 1.6.1	High
DP 1.3.4	Low	DP 1.6.2	Medium
DP 1.4.1	High	DP 1.6.3	Low

FIGURE 5. Impact of each design principle for smart manufacturing scheduling (Low/Medium/High).

- DP1.6.3 Unless otherwise stated, the starting point for a new scheduling generation shall be the current state of the physical system, but never before the current state. Exceptions may occur if the schedule is supposed to start in a posterior defined date. Consequently, the scheduling system needs to be up to date.

In Figure 5 is represented the impact of each DP for the design and development of generic scheduling solutions for smart manufacturing environments, depending on how much each one should be considered. Naturally, some DP may vary and assume different importance degrees for specific use cases. However, the authors assume the impact may be High, which means the solution may not be successfully implemented without those principles; Low, meaning the solution will not be affected if the DP is not implemented, although it can facilitate the development and using processes; and Medium, as an intermediate stage between the previous two, that are not critical but should not be disregarded.

VI. SCHEDULING FRAMEWORK TARGETING SMART MANUFACTURING

The presented framework main goal is to ease the asset modelling, targeting scheduling systems designing and development for smart manufacturing environments. Therefore, the framework targets not only the acquisition of data at different granularity levels, as well as the asset modelling and asset allocation optimization through the execution of scheduling approaches. This optimization process outputs possible scheduling solutions to be deployed in the factory. With the help of a monitoring module, it is possible to get feedback from the shop-floor in real-time and perform data analytics techniques to monitor critical parameters and trigger self-adjustment mechanisms, if necessary. Thus, the framework is divided in three fundamental parts, as demonstrated in Figure 6:

- Physical and software components integration - The cyber-physical connection is a driving force for smart manufacturing environments that want to stay competitive in modern market conditions. The emergence of CPPS is allowing different entities in the shop-floor to be virtualized and connected together, which in turn facilitates the real-time monitoring of the shop-floor components as well as the controlling of those components in the production line. Consequently, is possible to integrate external tools regarding supply chain and data analysis with the shop-floor. Based on the concept of RAMI's Industry 4.0 Component, this part of the framework aims to connect the different hardware and software entities among the system. Namely, within the factory it is important to represent, virtually, entities such as machines and working stations, parts and products going through the factory, human workers, and general information about the factory as working hours, shifts, and any other relevant information. Furthermore, it is crucial to register the orders coming from higher level. All these assets, either physical or not, must be modeled, so they can be represented in an uniform and standard way, allowing an easy understanding and integration with other elements and even external assets. To conclude, all the previous information can be stored in a database, where it can be easily accessed by any module, such as production optimization and shop-floor monitoring.
- Production optimization - This is a core part of this framework. Here is where the production scheduling is performed. The scheduling tool needs to gathering all the necessary data from the shop-floor in order to allocate the orders accordingly. Here different approaches may be adopted, although the final goal is to optimize the production processes in the most convenient and needed way. This can be to reduce the overall execution time, reduce average idle the of working stations, balancing human workers effort, finish the products just in time, or any other relevant metric for each specific use case. In order to achieve these objectives, optimization techniques need to be adopted, which will be completely independent from the framework itself, and use case-oriented. Last, the final result should be delivered, to whom it may concern, in an easy to understand way, preferably through a visual output.
- Monitoring - The monitoring module will allow to monitor in real-time what is happening in the factory. The emergence of smart working stations and sensors in recent years has allowed to have more data collected from the shop-floor. The adoption of data analytics techniques will allow to understand these data and turn them into useful knowledge for the company. By defining KPIs to trace the working conditions, it is possible to verify how well the objectives are being achieved. If critical deviations are verified, a feedback may be send to the scheduling execution in order to adapt accordingly.

A possible architecture for the presented framework is identified in Figure 7.

The architecture is composed by the shop-floor layer and the applications layer, which are connected through a middleware that guarantees a smooth integration and communication between both parts. The shop-floor layer consists on the

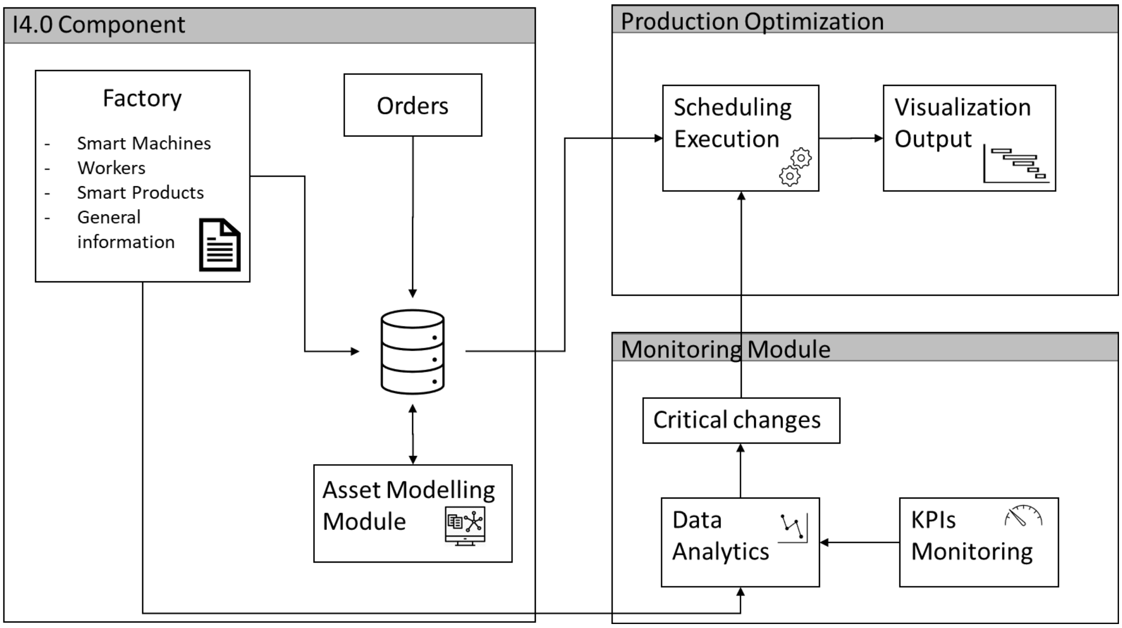

FIGURE 6. Manufacturing scheduling generic framework.

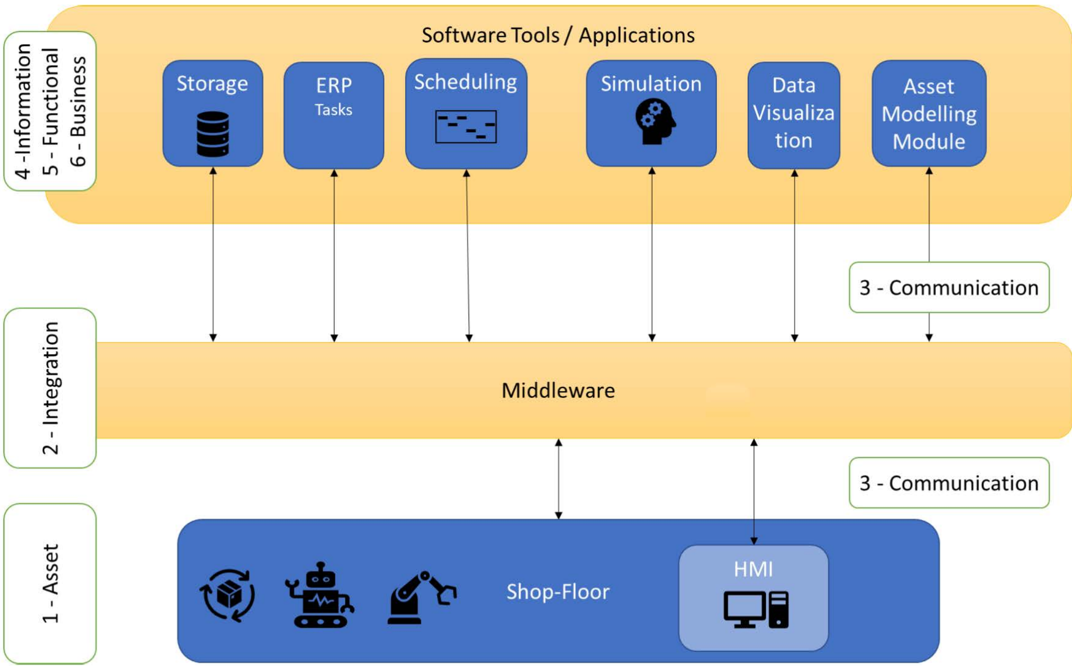

FIGURE 7. Manufacturing scheduling generic architecture.

factory itself, and is where all the hardware elements and processes are present. This layer can be associated to the Asset layer in RAMI4.0, and is where the entire production process is controlled. The middleware is the integration layer, and thus can be linked to the Integration layer in RAMI4.0. Middleware is responsible to ensure that the integration between high and low-level is flawless and all the components speak the same language. To do so, communication protocols must be defined in order to establish communication among all the components. In the higher level there are the software tools and applications. Those can be as varied as needed and can comprise databases, Enterprise Resource Planning (ERP) systems, Manufacturing Execution System (MES), scheduling tools, simulation tools, data analysis tools, data visualization frameworks or even the Asset Modelling Module which will allow to module each component in the system. This higher-level can be associated to the layers 4, 5 and 6 of RAMI4.0, since it is where the information and the requested functions are available, and from where the overall business in managed.

VII. PRACTICAL USE CASE

In [36] was presented an architecture to solve a task allocation problem, namely a Job-Shop Scheduling Problem, considering production and maintenance tasks, aiming to minimize the total execution time in the shop-floor. As final goal, these approaches should decrease delays and unexpected number of failures during the production process. This solution allows to reach more reliable schedules by considering the maintenance operations to be performed on the production stations. To solve this problem, a Genetic Algorithm solution was implemented where the goal is to optimize the task allocation based on the information provided about tasks and working stations. In this section, this work will be analysed to verify in each way it follows the guidelines of the framework and the generic architecture presented in this document and how it can be improved.

In Figure 8 is demonstrated the proposed architecture of the solution. Several tools interact with each other in order to gather the necessary data to generate the scheduling output solutions.

This architecture can easily be divided in two parts that match with the high and low layers in the architecture presented in this document.

One regarding the lower-level, i.e. the shop-floor, where the hardware assets are present. This includes available working stations, human workers, which will be decisive to allocate both production and maintenance tasks. A Graphical User Interface (GUI) is used to trigger new schedule orders by a human operator, which can also be done automatically by the system at predefined times. This is completely in accordance with the lower-level layer suggester in the architectures proposed in this work.

The second part is the higher-level, intended to host the software tools and applications. In this layer there is a management module, which can be an ERP, where are stored the orders from the customers to be processed. There is, also, a maintenance module, where the maintenance intervention are analysed and maintenance tasks may be triggered, and the shifts for maintenance teams may be defined. Furthermore, there is the scheduling module, corresponding to the main module in that study. The scheduling tool collects the necessary data, such as production and maintenance tasks to be executed, the factory topology (which gives information about the working stations, and the time horizon to execute the schedule and, through the implementation of a Genetic Algorithm, generates a collection of three types of schedules based on the gathered information. The adopted optimization technique allows to optimize the function cost, which in that case is to minimize the total production time of the entire shop-floor. The three types of schedules are a) allocate the tasks as soon as possible (which allows to free the machines sooner), b) allocate the tasks as late as possible (favoring a just-in-time production), and c) a hybrid approach which tries to maximize the distribution of the tasks and minimize the overall production time. To complement, there may be other software tools to complement the scheduling optimization. These tools may be used to perform data mining to explore the data coming from the shop-floor, data analysis searching for patterns or deviations that help to recalibrate the scheduling parameters, data visualization to present advanced output tools to help operators and decision-makers, and so on.

The approach in [36] is partially aligned with the framework presented in this work. The scheduling optimization module interacts with other modules to collect important data to be processed, namely a management module (equated to an ERP system) to receive production and maintenance orders, and external tools to gather additional data from data analysis, or to provide visualization outputs. Furthermore, there is the connection with the shop-floor to acquire data related to the working stations or human workers. All the information is stored in a database.

However, the components do not use a common middleware to communicate among them, instead they have point-to-point interactions, where each one interacts directly with other one. This fact, makes that more communication points are needed, which brings more complexity in terms of design and implementation, since the components do not use the same protocols to communicate.

VIII. FINAL REMARKS

A. DISCUSSION

The results of this work demonstrate how to apply relevant design principles in the development of manufacturing scheduling solutions, based on generic functional requirements identified. The document is divided in several stages. First, it brings together a set of functional requirements that will help designing and developing scheduling systems for smart manufacturing environments. The goal of a requirement is to influence the system development process and lay the groundwork for subsequent processes. As showed in 3, there are a significant part of Requirement Analysis and System Design phases that are generic and common across different manufacturing scheduling systems. Functional and non-functional requirements are the two basic types of requirements. The tasks that a system must perform automatically, as well as the interactions between the system and other systems or human users, are referred to as Functional Requirements. Non-functional requirements refer to any requirement in a system that isn't regarded a Functional Requirement. The identified Functional Requirements (see [2] for Non-functional Requirements) are based on real-world challenges that can be found in nowadays factories and are generic enough to be present in a lot of them. Secondly, this work provides a set of Design Principles to assist practitioners in the development of production scheduling systems. The identified DPs are based on an adaption of the

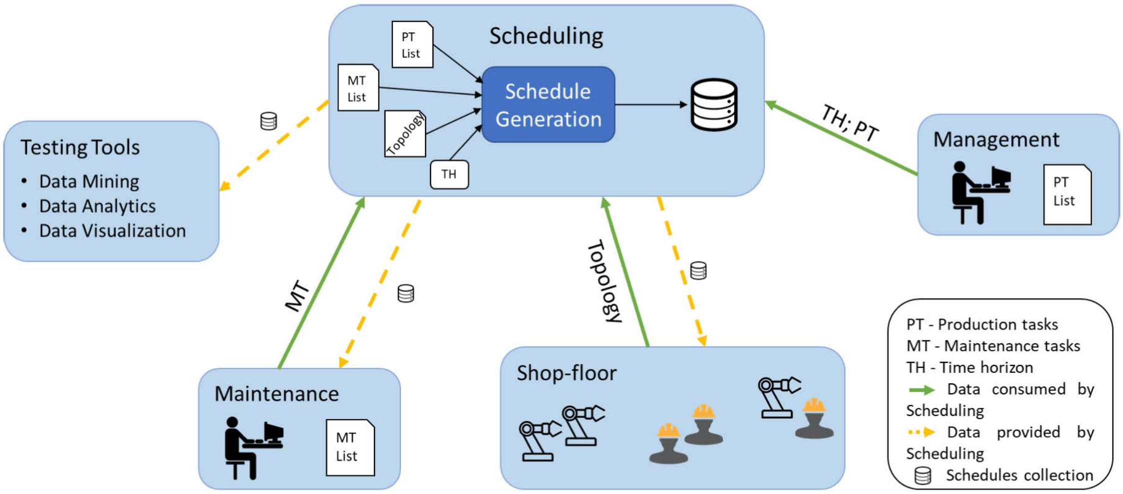

FIGURE 8. System interactions overview [36].

axiomatic design principles, in which each FR is matched with one DP. As a result, each of the DPs supplied is linked to the previously determined FR. This approach is deeply linked with Industry 4.0, mainly with RAMI4.0 reference architecture, where DPs are matched with RAMI4.0 Layers. Then, a generic framework is proposed, where the main goal is to guide the asset modelling, by identifying which assets are important for manufacturing scheduling solutions, and then facilitate its designing and development. Here, three fundamental parts were identified:

- Physical and software components integration, which aims to connect different hardware and software entities, such as machines, parts, human workers or production orders, among the system.
- The production optimization module is responsible to execute the scheduling. Consequently, the relevant data needs to be gathered from the shop-floor in order to allocate the orders accordingly.
- The monitoring module is an important complement that allows to monitor in real-time what is the status of the factory and evaluate how the schedule is performing, by defining KPIs previously.

This framework is complemented by a generic architecture composed by the low-level (the shop-floor layer) and the high-level (the applications layer), that are connected by a middle layer which guarantees a seamless integration between both parts. The different parts of the architecture are associated to the different layers of RAMI4.0, as it is a reference architecture that has been largely adopted, mainly in Europe, and may contribute to harmonize the development of scheduling solutions. Finally, a previous work on production and maintenance scheduling was compared to the proposed approach in order to evaluate how much it is aligned with the proposed guidelines. As a final remark, the main goal of this work is to propose a set of guidelines that help to develop scheduling architectures oriented to manufacturing, in a common and harmonized way, and filling the absence of a standard to develop manufacturing scheduling solutions. This will, naturally, impact the system's designing and implementation phases. Furthermore, the reuse of a validated architecture will shorten the development time, while ensuring that the main functionalities of the system are covered.

B. FUTURE WORK

As future work, it should be explained how to modelling the different scheduling-associated assets. This can be done using RAMI4.0's Asset Administration Shell, which is a concept of Industry 4.0 to provide information for the different assets in the system, namely it links any asset to the virtual world. Asset Administration Shell provides any component with capabilities to communicate and share information with the digital world. Furthermore, new application cases will be used to keep improving the Design Principles adopted.

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DUARTE ALEMÃO received the M.Sc. degree in electrical and computer engineering (genetic algorithms applied to task allocation) from the Nova University of Lisbon, in 2017. He is currently pursuing the Ph.D. degree with the Nova University of Lisbon focusing on production scheduling optimization. He is also a Researcher at the UNINOVA Institute. As a Researcher, he has been interested in topics, such as robotics and integrated manufacturing, smart manufacturing and cyber-physical production systems, with focus on process optimization. He has been involved in national and international projects, such as H2020 PERFoRM, H2020 GO0DMAN, H2020 AVANGARD, and P2020 CESME. His research interests include the design of production scheduling, cyber-physical production systems, and smart manufacturing solutions.

ANDRE DIONISIO ROCHA (Member, IEEE) received the M.Sc. and Ph.D. degrees in electrical and computer engineering from the NOVA University of Lisbon, Portugal, in 2013 and 2018, respectively. He is currently a Professor at the Department of Electrical Engineering, NOVA University of Lisbon, and a Senior Researcher at the Centre of Technology and Systems (CTS), UNINOVA Institute. He has participated in several research projects, most of them at the European level (e.g. H2020 Avangard, H2020 GO0DMAN, H2020 PERFoRM, or H2020 openMOS), involving different programs (FP7, QREN, H2020, or P2020). His research interests include the design and development of cyber-physical production systems as well as the study of smart manufacturing solutions using distributed control systems, modular production systems, and artificial intelligence based solutions to deliver more cost-effective and sustainable solutions. As result of the research activities, he published several scientific contributions in scientific journals and international conferences. He is highly involved and active in IEEE activities. He is a member of the IEEE-IES Technical Committee on Industrial Cyber-Physical Systems (TC-ICPS) and the IEEE-IES Technical Committee on Industrial Agents (TC-IA).

SANAZ NIKGHADAM-HOJJATI received the B.Sc. degree in mathematics from IAU, in 2005, the M.Sc. degree in information technology management (information resource management) from the Farabi Institute of Higher Education, in 2011, and the Ph.D. degree in information technology management (business intelligence) from IAU, Science and Research Branch, in 2017. She is currently a Postdoctoral Researcher in computational creativity at the Faculty of Science and Technology, New University of Lisbon-NOVA. She has also participated in several national ICT projects in Iran and worked as an University Invited Professor in several university, including IAU Tehran North Branch and Tehran Electronic Branch; the Farabi Institute of Higher Education; and the Informatics Non-Profit Institute of Higher Education. She has also been the Head of the Information Technology Management Department, Farabi Institute of Higher Education, and the Head of the Computer Programming Department, Informatics Non-Profit Institute of Higher Education. She has published several books and academic articles in a number of peer-reviewed journals and presented various academic papers in conferences. Her research interests include computational creativity, creativity support cyber-physical systems, digital creativity, and industry 4.0. She was an organizational chair, a co-technical chair, and a member of the technical committee in several conferences.

JOSÉ BARATA (Member, IEEE) received the Ph.D. degree in robotics and integrated manufacturing from the NOVA University of Lisbon, in 2004. He is currently a Professor with the Department of Electrical Engineering, NOVA University of Lisbon, and a Senior Researcher with the UNINOVA—Instituto de Desenvolvimento de Novas Tecnologias. He has participated in more than 15 international research projects involving different programs, including NMP, IST, ITEA, and ESPRIT. Since 2004, he has been leading the UNINOVA participation in EU projects, namely, EUPASS, self-learning, IDEAS, PRIME, RIVERWATCH, ROBO-PARTNER and PROSECO. In the last years, he has participated actively researching SOA-based approaches for the implementation of intelligent manufacturing devices, such as within the Inlife Project. He has authored or coauthored over 100 original papers in international journals and international conferences. His main research interest includes intelligent manufacturing, with an emphasis on complex adaptive systems, involving intelligent manufacturing devices. He is a member of the IEEE Technical Committee on Industrial Agents (IES), Self-Organization and Cybernetics for Informatics (SMC), and Education in Engineering and Industrial Technologies (IES). He is also a member of the IFAC Technical Committee 4.4 (Cost-Oriented Automation).