Engineering ICPS for Small and Medium Enterprises: A Novel DIN SPEC 91345 Compliant Digitalization Approach

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***Abstract*—An adequate and sound baseline for engineering Industrial Cyber-Physical Systems is given by the Industry 4.0 digitalization principles, in combination with the application of the Asset Administration Shell (AAS) Technology. On the one side, all essential aspects related to the digitalization of any industrial eco-system are comprehensively formalized by the DIN Specification 91345 RAMI4.0 (Reference Architecture Model for Industry 4.0), which combined with the use and application of the Asset Administration Shell Technology, provide a proper background for digitalizing any industrial eco-system. On the other side, by analyzing latest reported results and using lessons learned in practical experiences done by actively participating in digitalizing real industrial use cases, it has been possible for the authors to identify a lack on a technologically feasible and conceptually understandable digitalization approach for small and medium enterprises (SMEs) that do not have the required accessibility to adequate methodologies, technologies and tools. In this context, this manuscript summarizes a conceptually accessible approach to support the engineering of Industrial Cyber-Physical Systems with focus on the digitalization process of SMEs. This conceptual accessibility is provided by a novel structured procedure precisely grounded on the RAMI 4.0, that covers the digitalization process from the early stages of the adequate requirements compilation, through the specifications and developments along the Life-Cycle of Assets and processes, and thus establishing a solid foundation to achieve an economically and technically plausible implementation accepted by all involved stakeholders of the value chain.**

***Index Terms*—Digitalization, digitalized value chain, industrial cyber-physical systems, industry 4.0, RAMI 4.0, small and medium enterprises.**

I. Introduction

When it comes to specifying and implementing the digitalization process of Industrial Cyber-Physical Systems based on Industry 4.0 principles, an analysis of latest reported results allows identifying a gap related to a well-grounded and comprehensive scientific and technically feasible engineering approach covering the whole process from the early stages of the appropriate requirements compilation, through the specifications and developments along the Life-Cycle of Assets and processes, and thus establishing a solid foundation to achieve an economically and technically plausible implementation accepted by all involved stakeholders of the value chain.

In the context of Industry 4.0, although different reference architectures such as the Reference Architecture Model Industry 4.0 (RAMI 4.0) [1] and Industrial Internet Reference Architecture (IIRA) [2] and associated standards are available, the correct way to approach them can be very diverse, depending on many factors and prior considerations that must be taken into account. There is also the possibility of approaching it incorrectly and drawing conclusions that are not useful for the digital business, including an adequate compilation of the requirements and needs for the associated use case.

Small and medium enterprises (SMEs), in the search for new business and digitalization processes that benefit them, find some impediments to successfully carry out the digitalization process based on the concepts of Industry 4.0. For this reason and with the proposal of a detailed procedure that is considered novel, it is intended to lay the foundations to make clear that Industry 4.0 can be applied to all organizations, regardless of size, country and / or amount of resources available (physical and non-physical). Thus, by applying Industry 4.0 in this type of organizations, new types of business can be established between them through services added values. Those organizations involved in the value chain will find and will be able to make available valuable information that will allow them to improve the decision-making process throughout the Life-Cycle of the different Assets (things) of the company and thus obtain multiple benefits (not only economic).

With the procedure that will be developed in the following sections, stakeholders belonging to the category of Small and Medium Enterprises, as well as any other enterprise type, will find valuable information that will allow them to efficiently approach the different stages of a digitalization process using the RAMI 4.0 as a reference model and the standards and digitalization and networking technologies on which this industrial specification is based.

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By initially understanding the knowledge background about (I) the major "principles of Industrial Cyber-Physical Systems and Industry 4.0-compliant digitalization" described in Sections I and II, and (II) the most essential requirements from SMEs for getting "digitalized" systems and processes as described in Section III, the reader will learn in Section IV "how to apply and introduce Industry 4.0-compliant methods and technology, including added-value services based businesses, in eco-systems of SMEs". Finally, Section V teach how to replicate and apply the engineering approach by means of three exemplary use cases.

This paper is structured as follows: Section II discusses the main principles that should be taken into account when applying an Industry 4.0-compliant digitalization process. Following the Section III, which elaborates a comprehensive description of requirements for digitalizing Small and Medium Enterprises, the Section IV introduces the major features of an approach to engineering Industrial Cyber-Physical Systems considering this kind of enterprises and the proposed approach to cover the digitalization process. Section V shows the results of the application of the proposed procedure considering selected used cases. Finally, Section VI concludes the paper highlighting the final conclusions, possible further works and outlooks.

II. Industry 4.0-Compliant Digitalization

A. The Concept of Industry 4.0

The Industry 4.0 proposes an approach based on the digitalization and communication (through its networking) of the different Assets that belong to organization. An Asset is understood as any component, whether physical or not, that adds value directly or indirectly to the organization, interacting with different partners of the value chain. In the context of this paper Assets and "Things" will be synonyms (term commonly used within the context of Industrial Internet of Things (IIoT) and the IIRA Reference architecture [2]). Industry 4.0 seeks to open the way for information interaction in order to take new benefits of defined businesses (and improve the existing ones). It does not seek to automatize a process (that was already covered by the previous industrial revolutions), although it can support enhancing automation solutions. The aim is to harmonize the flow of available information, interconnecting different types of Assets, to improve some decision-making process. Clearly, Industry 4.0 will benefit greatly from high-tech processes, but the latter is not strictly required.

B. DIN SPEC 91345: Reference Architecture Model for Industry 4.0 (RAMI 4.0)

To cover the digitalization process, the RAMI 4.0 will be used as a reference architecture (Fig. 1).

The reference architecture model for Industry 4.0 (RAMI 4.0) provides the required scientific and technical background, that will set the basis to address the digitalization of Assets and processes in industrial eco-systems. To do the previous, the DIN SPEC 91345 uses the concept of Industry 4.0 Components (I4.0-Components) [1].

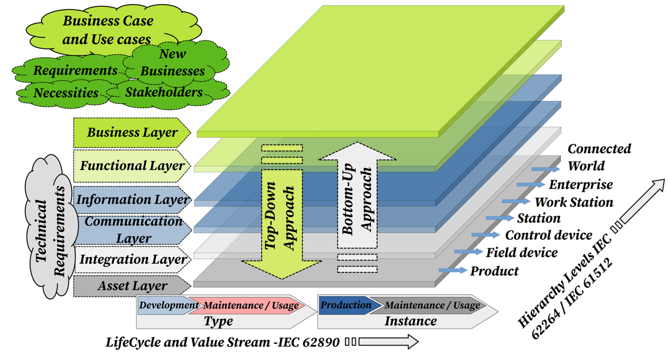

Fig. 1. RAMI 4.0 and possible digitalization approaches: Bottom-Up and Top-Down.

The first axis is related to the Life-Cycle of an Asset, the second is related to the position that it occupies in the hierarchy within the organisation where it performs its functions, and the third vertical axis is divided into 6 layers that address the digitalization and networking processes. Note: the characteristics and properties associated to those 3 axes are completely mapped into industrial standards as explicitly described and defined in Sections IV-E1 and IV-E2

To define an I4.0-Component, first, the concept of the communication and information presentation capabilities of an Asset and an Asset Administration Shell (AAS) should be properly understood.

1) Communication and Presentation Capabilities: According to [1], the communication and presentation capabilities of an Asset are strongly linked to Life-Cycle concepts, its technical functionality and the "world" to which the Asset belongs. The "world" is understood as the environment in which the Asset exists to fulfill a given functionality or role. These worlds can be the physical and the "virtual" or information world. For any defined Asset (physical or non-physical), its AAS will be defined in the information world and stored in a particular format defined in [3]. However, it is essential to clarify about the available ways in which an Asset presents and communicates its information. Depending on these attributes, the ways of approaching the creation or definition of the I4.0-Component, will be different and will require different implementation strategies.

The DIN SPEC 91345 assigns a CPXY code based on the grid shown in the Fig. 2, to define these attributes (see page 18 of [1]). The code is based on the composition of the "C Class" and "P Class" attributes. CP indicates that reference is made to this classification, X the corresponding classification for communication capabilities ("C Class") and Y for presentation capabilities ("P Class"). The specifications of each of the attributes for the different capabilities are detailed in the referenced standard.

The Presentation Capabilities analyses how the data and information of an Asset is presented in the Digital World. In turn, the Communication Capabilities are referred to the communication of the data using digital communication Systems. Physical Assets carry information of the Physical World that need to be communicated in the network using different Technologies. Then, by defining these attributes individually, at the

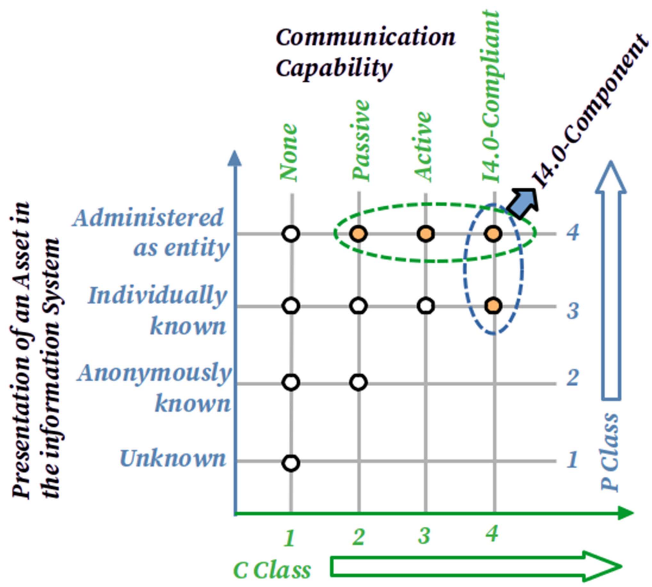

Fig. 2. Classification of Assets in terms of presentation and communication capability. Based on [1].

end the information is composed in the "CP Class" assignment according to the aforementioned CPXY code.

2) The Asset Administration Shell: According to [3], an AAS can be defined as a "Standardized digital representation of the Asset, corner stone of the interoperability between the applications managing the manufacturing systems".

The AAS is the basic requirement to obtain and create an I4.0-Component. According to [1], it includes information to represent the Asset and its Technical Functionality, as well as its Internet/Ethernet-based networking capabilities. Technical Functionality is defined [3] as "Functionality of the Administration Shell that is exposed by an application programming interface (API) and that is creating added value to the respective Assets(s)".

The concepts of Digital Twin can be combined with the definitions of the elements that are part of the AAS and corresponds to the contents of the Information Layer according to the RAMI 4.0 specification. Basically, the Submodels of the AAS (Objects that are part of the AAS) allow by-the-fact the implementation of the Digital Twin. The reference [4] on page 19 shows how the AAS support the definition and modeling of Digital Twins covering different required aspects to create them (Data, Models and Services).

3) Requirements of the "Industrial Asset Administration Shell": In the Industry field, there is a great deal of dynamism and sources of information from different Assets or Things, sectors, etc., of the organization. For example, a machine is a set of devices in which each part, is fulfilling a specific function. Thus, each specific function is combined to obtain a group of functions that give origin to the functionality of the machine. Each component has a supplier (that could be the same or not), has associated drawings, technical data, sensors, other Assets, etc. Particularly, the information to be exposed by the AAS will depend on the type and/or instance of the Life-Cycle and within the partner of the value chain where the Asset is located and "Living". Generally speaking and considering an Asset as e.g. an instance in the Life-Cycle phase "Use/Maintenance" (See reference [5] pages from 14 to 15), both static and dynamic data is available.

From the implementation point of view, it is important to consider the frequency of the data, before starting an implementation of an AAS in an industrial environment. In many cases, it is convenient to "fragment" the AAS into different parts (one for static data and another for dynamic data) and each of them with a different implementation approach (but always linked to the same AAS). For the creation of these parts, different Submodels and strategies during the implementation, can be used to fragment the corresponding information. Considering also the reference [6], different distributed service participants can host fragments of one AAS.

4) The I4.0 - Component: According to [1] on page 24, an I4.0-Component is an Asset that can be individually identified with the corresponding AAS with a digital connection within an I4.0 compatible infrastructure. Assets with different communication capabilities can be implemented as Industry 4.0 components. However, an Asset is not always an I4.0-Component. Some minimum requirements are needed for such an Asset to become an I4.0-Component. For this, concepts and considerations about the presentation and communication capabilities that were exposed in Section II-B1 and the reference [1] are required.

In accordance with the previous reference and the Fig. 2 an I4.0-Component should have at least passive communication (horizontal circle) and should be uniquely identifiable within the network (vertical circle).

5) Requirements for an I4.0-Component Based on the RAMI 4.0: In companies (industrial or not) there are Assets that have a high technological networking degree. It means that, there are Assets that will present and communicate the information in a different fashion within the world of information. The idea behind Industry 4.0 is to create, among others, a compatible ecosystem, in which all Assets can communicate with each other by offering and consuming services in a common and fully understood language [7], [8], [9] and directives.

According to the Section II-B1, it is then necessary to analyse how to integrate the Asset into the compliant structure. Each group of presentation and communication capability will require more complex implementation strategies and structures, as Assets move further away from being an I4.0-Component (Fig. 2). For example, if there is a heating tank that has no data (nameplate), and no way to extract the information from its parameters, an initial effort must be made in order to have the data available (i.e. Integration layer according to the RAMI 4.0).

C. The Industrial Cyber-Physical Systems

Industrial Cyber Physical System (ICPS) are related with I4.0-Components, if the latter is linked with the concepts and definitions of a service-oriented architecture. According to [10] Cyber Physical Systems (CPS) are: "Smart systems that include engineered interacting networks of physical and computational components". Also the reference define a CPS as a complex system that could be composed by different subsystems. Depending the degree of complexity, this complexity has a high relative importance and is involved in some decision-making process. Based on the previous, the following definitions will be highlighted:

- CPS are frequently systems of systems (SoS) [11] that perform critical applications;
- CPS should be characterized by well-defined components;
- CPS should support application and domain flexibility;
- Data exchange is a prominent dimension of CPS operation;
- CPS should have an appropriate level of awareness of physical location and time;
- CPS architectures should support legacy component integration and migration.

The Asset(s) representing ICPS can be seen as a "black box" offering a defined response (outputs) depending on the inputs it receives, and on it role/s it can/must play in the digitalized ecosystem. This functional element will be coupled or decoupled with other existing elements within the same ecosystem to achieve a given objective based on some directive. This is the concept of a Service-Oriented Architecture (SOA) [12]. These systems are conformed in different ways according to the functionalities exposed by each one of them. These functionalities can be combined to obtain new functions that result from a functional "Orchestration". Such aspects and concepts can be extrapolated to the industrial field, and particularly can be applied to any digitalized Assets. Then, through their different Digital Twins (i.e., different sets of digitalized data and information), these Assets, together with their AASs, can expose functions within a SOA and thus be orchestrated to meet particular requirements of different use cases. For this reason, the concepts of Asset, AAS and I4.0-Components, are compatible with the concepts and definitions of ICPS.

For performing this functions composition and/or orchestration, it is required that Asset, or CPS, possesses an orchestration engine. This engine has the capability to orchestrate and to expose the results as services in the I4.0 Network. [13], [14]. Note: The reader can get more details from an Industry 4.0, and AAS-compliant orchestration solution, deployed using low-cost technology, from the reference [15].

III. Digitalization Engineering in Small and Medium Enterprises

A. Current Situation and Context of Small and Medium Enterprises

It is important to note that companies are being requested to be active part of the digital transformation that is penetrating all aspects of the society and its economy. A digitalized and networked industrial environment has technologically associated a Digital Thread supporting with Added-Value Services the supply chains, the collaborative networks, the value-streams, and the innovation HUBs to which the companies belong to [16], [17], [18], [19], [20].

In [21], a study has been made which concludes that one of the most important issues for the implementation of Industry 4.0 is to fill the lack of knowledge. This applies particularly to SMEs, where the missing innovation infrastructures and the day-to-day market evolution are dictating the state-of-the-art knowledge. This aspects are reinforced by the results of the analysis provided in the articles [22], [23], identifying the lack of capital and the lack of knowledge, as drawbacks for supporting a fast digitalization process.

Moreover, the Digitalization of an industrial environment is often confused (i) with the process of automatization of that environment, (ii) with the need for the acquisition or use of expensive automation and control technology for its successful implementation. For example, in [24], the authors emphasise that the problems associated to the digitalization of SMEs are mainly (i) the understanding and use of new technologies such as artificial Intelligence (AI) and automation, (ii) the risk that humans are replaced by such technological solutions, and (iii) the necessity for high investment costs without enough compensation with visible benefits.

B. Characteristic of SMEs Creating Requirements for the Digitalization Process

For the proposal of the digitalization process, SMEs have been targeted, knowing that generally this type of companies have more restrictions or constrains than large companies. For this reason, if the proposed digitalization procedure is applied to SMEs, large companies will also be able to use it.

The following list, details the main attributes of SMEs in this context:

- Mainly no research and innovation departments, complemented with reduced innovation capabilities;
- Limited Knowledge transfer, what implies the necessity for training, education that should be Provided by third parties;
- Reduced market to a dedicated product and solution portfolios for a limited well identified market;
- Production and management processes mainly focused on day by day Businesses;
- Clear position in the value chain, with very well defined business with other stakeholders. Companies cannot exist by itself in isolation, it requires others organisations, resources, customers, etc. This makes it essential to consider different aspects of the Life-Cycle of products, machines, equipment, software, etc., and different partners and stakeholders that are involved. Each of them adds value to the product or uses it to achieve a well-defined organizational businesses objectives along the value stream;
- Very dependant businesses on the fluctuations of the Market;
- Rigid organizational structures very well defined with actors playing sometimes many roles;
- Not always state of the art Information and Communication Technology (ICT) infrastructure;
- Preference for the of use Low-Cost Technologies in order to reduce the amount of investments costs;
- Strong participation of Humans along the value stream and through different levels of management control and automation (if the SMEs has automation) hierarchy.

Something very important to highlight in this organizations, is that much of the specific know-how can be found in a distributed and non-digitalized form, usually in the mind of the owner or experienced employees. Decisions are also usually made by the owner or by the superior of the different sectors according to a certain hierarchy.

Functionalities are often grouped together, i.e. actors have to perform many different tasks. In other words, due to resources, there tends to be a lot of use of multi-skilled workers and not focused in specific activities. The same applies to any machinery and equipment that may exist.

The challenge of Industry 4.0 in SMEs is that the digitalization process can be very diverse and multifaceted. This is because many and varied sources of information can appear, such as spreadsheets, customised software, machines, equipment, etc.

In SMEs, a set of common requirements for digitalization of systems and processes can be defined. Naturally, each company will then have different ways for guaranty fulfilling the requirements. Nevertheless, common digitalization infrastructures and procedures, with slight modification according to the type of the SMEs and particularities of the business case can be applied for each of them.

Usually, requirements are based on data and information, no matter its source (digital or not). Particularly, within companies or organizations, data and information are available, because they need them to operate. What should be challenged is to find the data and information that are shared and made explicit among all participants (that are inside and outside of the organization). In this search for information, the company's Assets (physical and non-physical) appear, which are generally the ones that provide the required information in a specific form. Considering this, it is essential first to analyze the required information and then to identify the Assets that provide it.

C. Complementary Requirements for Applying the Digitalization Engineering Approach

The DIN Specification 91345 (RAMI 4.0) is basically a 3D-graphic representation of an industrial eco-system. A 3 dimensional space where each basis dimension is represented by one or more ISO-ISA-IEC industrial standards, alone or combined. On the one side, learning both, points in 3D-positions and inter-relations among those points, is a very essential and unavoidable requirement for any actor that want to digitalize based on RAMI 4.0. On the other side, to any of those points and with any of those inter-relations are always Humans structurally and/or functionally associated (see more details in Reference [25])

A very first requirement for doing digitalizing is "Learning which are the Industrial Assets (things) and their position within the 3-dimensional space". This is the first step of the engineering approach presented by the authors. The second requirement for doing digitalizing consist in "Learning navigating the 3D-Model and understanding all possible exchange of services among Assets (possible flow of digital data and information associated to the different phases of the Asset life-cycle), when the Assets are networked in an Internet/Ethernet based communication-information-infrastructure".

This set of technological steps composing the digitalization approach needs to be complemented with the identification and definition of a novel set of new service-based businesses that the digitalized environment are able to provide. As a matter of fact, a digitalized industrial eco-system is able to provide added-value services within the whole digitalized and networked 3D environment, complementing the traditional state-of-the-art businesses for which this industrial system was created.

It is valid for any kind of companies/industries, that these requirements can only be fulfilled if adequate educational/training programs are provided to the staff. For big companies, this is mainly done by internal departments dedicated to training and specialization courses. However, for SMEs, it is essential to provide easily accessible and didactic material, if possible in open-access-mode, that will support the training of their staff and with minor financial investment. Although details on the didactics and the learning strategy for teaching the digitalization procedure to SMEs staff are out of the scope of this paper, the authors recommend to access the background knowledge provided by the references [26], [27]. Moreover, to support the definition of this kind of educational/training courses, a proposal from the point of view of what is required to be learned in terms of Industry 4.0 and how the education should be established in the engineering field, is detailed in [28], [29].

In the opinion of the authors, learning and understanding the position and roles of Humans in each of and between the 3 dimensions of RAMI 4.0, as being an essential part of the 3D industrial environment, or by navigating it, is the overarching requirements for supporting learning and applying the engineering approach presented in this manuscript.

D. Integration of SMEs into an Industry 4.0-Compliant Ecosystem

The digitalization procedure aims to obtain digitalized Assets that can be integrated into an Industry 4.0-compliant ecosystem. The objective is to create a truly digital and interconnected ecosystem in which multiple organizations, whether SMEs or not, can exchange data and information in form of "services".

In order to support the proposed procedure, the analysis of requirements of Sections III-B and III-C was initially required. Once the requirements have been defined, the technical specifications for building this digitalized ecosystem need to be analyzed. The authors compiled the common characteristics exhibited in the aforementioned sections, to define the following list, enhanced by [30], as a fundamental basis for the definition of the procedure:

- The Implementation should be cost-effective and energy-efficient;
- Need to integrate Dynamic and Static data between different Assets within the same organization and partners of the value chain;
- Need to display information to improve the decision-making process;
- Service-oriented architecture to integrate services of the different Assets;
- Incorporate the necessary abstraction of the services to facilitate the exchange of them;
- The information must be available to all the stakeholders in the value chain;
- Need for integration of heterogeneous Assets into the digital world (devices, equipment, machines, reports, personnel, etc.);

- The information must be structured in a standardized manner (e.g. the authors propose using the Asset Administration Shell);
- Need to integrate digitalized information in a common network. Flexibility of manipulation and creation.

On the basis of the previous points, an important aspect to highlight is the degree of influence of the available technology to address the digitalization through the proposed procedure. In the context of SMEs, the latest technological developments are not necessary for the development of their business, nor are information systems. The information systems are usually systems with simple functions and very focused on specific tasks or processes.

The degree of technology that must be added to the Assets to be digitalized is influenced by the communication and presentation capabilities of the information (exhibited in Section II-B1). On this basis, the authors emphasize that different devices, using Industrial-based Low-Cost technologies, can be added to provide the necessary capabilities for integration into the ecosystem [15]. Traditional Industrial solutions can naturally be implemented.

IV. Engineering Approach for ICPS

A. Top-Down and Bottom-Up Approach: Combining Alternatives to Address and Navigate the Vertical (Layer) Dimension of the RAMI 4.0

Throughout the digitalization process, there are two possible alternatives for approaching the vertical layers of RAMI 4.0, Top-Down and Bottom-Up (Fig. 1). The Top-Down approach implies starting from the Business Layer and reaches the Asset Layer of the reference. This approach is based on the definition of necessities and requirements of one or more organizations and different stakeholders to discover Assets to be digitalized. In turn, the Bottom-Up approach is based on considering the Assets and then discovering the requirements and needs of the various business organizations and stakeholders that can be fulfilled by the digitalized Assets.

Each method has its relative advantages and disadvantages. On the one hand, beginning the digitalization process from the Asset perspective (Bottom-Up), it is possible to satisfy businesses that do not meet the real needs or requirements. It can even confuse the digitalization procedure with a process of automation and control. On the other hand, starting from the Business perspective (Top-Down), it can require digitalization and networking of Assets that do not exist or even can not be digitalized yet.

The Bottom-Up and Top-Down approach, raises points of controversy about the adoption of one or the other. For this reason, it is decided that a combination of both points of view, is going to be performed in order to have a complete overview. The reference [23] shows a discussion of these two approach Bottom-Up and Top-Down in Sections II and V. Authors also consider a combination of both methods for application in a case study.

For the digitalization approach presented here, a Top-Down analysis is going to be performed, to begin the process with a clear idea of the businesses and their requirements, and then, to define the possible Assets that are available and that should be digitalized. After the definition of the Assets, a Bottom-Up approach is performed to identify data and information that are useful and match with the business, and other sectors within and outside the organisation.

It is important to highlight that, starting with a Top-Down approach, it does not imply a hierarchical structure within an organization or company. The objective of beginning with the Business layer and from a given point in the Life-Cycle, is to identify which Assets are more potential than others to cover the requirements. Digitalizing Assets for the sake of making data and information available requires time and investments that must be justified. This is much more evident in SMEs than in large companies. Naturally, once Assets are identified, it is expected that the information models must be supported by data from different stages of the Life-Cycle considering different stakeholders. This implies, once the Asset is identified and digitalized, it can serve different companies from different stakeholders.

B. Fundamentals of the Proposed Digitalization Procedure

A specific digitalization solution must be strongly linked to a specific business or use case(s), whose implementation needs digitalized data and information provided by one or more digitalized Assets in a network. Therefore, the Asset(s) to be digitalized will depend on an exhaustive analysis of the requirements and the information needed to perform those businesses. In this context, these Asset(s) provide(s) the required data for a defined digital business or use case. This suggests that the vertical layers of the RAMI 4.0 (Fig. 1) must be explored from top to bottom. From this perspective, the digitalization process starts specifying the Business Layer going in a Top-Down fashion until the Asset layer [29].

However, it is natural that in this process, questions arise as e.g., how to solve the intermediate layers, such as the Information, Communication and Integration layers. The information layer can initially be fulfilled with the information generated by the iteration between the Business layer, Functional Layer (mainly services and business processes) and Assets discovered in the Asset Layer. For the Integration and Communication layers, there can be a wide variety based on different hardware and software solutions. Being these two layers the two fundamental resources to convert any Asset into an I4.0-Component.

Low-cost industrial-based solutions are recommended to cover the processing needs required in the Integration and Communication layers. However, traditional industrial solutions can also be used. It is important to note that the developed solutions must be compatible with an industrial environment. And if the solution does not exist, there is a potential new business opportunity. The definition of the most suitable devices is beyond the scope of this work, but different alternatives should be analysed based on the integration methods of the Assets, the communication protocols used and the services defined for the interaction with the network of AAS.

Once the Business and the required Functions have been defined, the required information must be analysed. Next, it should

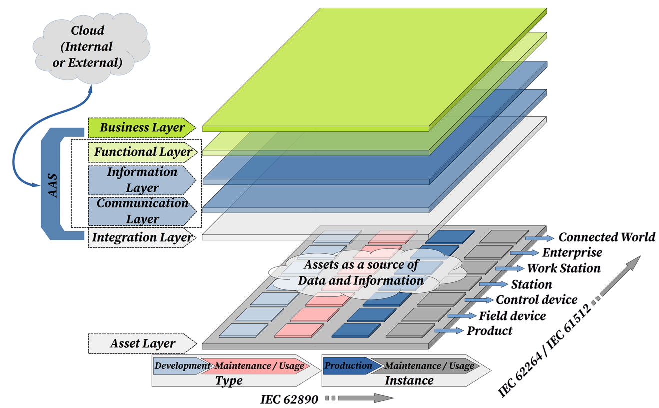

Fig. 3. Asset Layer of the RAMI 4.0. Bi-dimensional grid.

be examined which Asset(s) of the organization provide(s) that information and in which form. But perhaps the detected Assets, don't have the required communication and information presentation capabilities in order to meet the requirements (to be considered an I4.0-Component). Therefore, at this stage, it is necessary to center the Asset Layer and place the identified Asset (or a group of them) on the two-dimensional base shown in Fig. 3. In the referenced Figure, Assets are represented by small parallelepipeds only in this Asset layer in order to focus the bi-dimensional grid. It is known that each layer will have its corresponding grid. Note: On Fig. 3, only the Assets on layer 1 are represented by parallelepipeds. However, these grid representation has to be used in all layers of the RAMI 4.0 as depicted in Fig. 5.

The previous procedure, will allow to quickly focus on the Asset(s) in question. The two axes that compose the two-dimensional base, involve the Life-Cycle aspects of the Assets and the hierarchy that they occupy within the organization where they are being analysed. Remembering that the Business, Function and Information layers are already defined in the first step, the Integration and Communication layers are approached in the next one. This implies a mixed digitalization process in which the RAMI 4.0 is vertically navigated in different directions depending on the stage of the digitalization process. In fact, the definition of the Communication and Integration layers may require to redefine some functional and information related aspects defined in the previous layers.

As a matter of fact, with the adoption of RAMI 4.0, the Information layer of one Asset will store only the information of this Asset. If another Asset needs access to this information, in order to perform some function or business, it will search via the Communication or Functional layer. For this second Asset to access this information, it will be necessary to establish a relationship with first one Asset. That is, all Assets share the same physical means of communication, but the relationships are established by software.

Considering this, a RAMI 4.0-Compliant digitalized Asset will be correctly defined if the Asset, Integration, Communication, Information and Functional layers are very well defined. Finally, the Business layer will be able to consume the own necessary information and services as well as those provided by other(s) digitalized Asset(s) within the I4.0-Network to implementing the desired application. Remark: The RAMI 4.0-Compliant digitalized Asset is also able to provide data and information for desired applications implemented by the Business Layer of other(s) digitalized Asset(s) in the I4.0-Network.

C. Logic of the Digitalization Procedure

Following the Section IV-B, a logical procedure is going to be established to approach the digitalization process. This process is built on an adequate navigation of the 3D RAMI 4.0 and the correct definitions of Assets. This means the Assets, need to be positioned in the two-dimensional grid (See Fig. 3). Thus, the Asset will be completely defined in terms of its Life-Cycle and hierarchy levels within the organization. This placement will be shaped by the business and use case(s) that have been determined. After that, the subsequent process takes this base information and builds the subsequent vertical layers of the RAMI 4.0. This construction follows a pattern that can be generalized to different uses cases. This implies that generic solutions can be envisioned for the digitalization process of Assets, to "convert" them into I4.0-Components, so that it can be seamlessly integrated into a Service-Oriented Architecture. The Fig. 3, presents the RAMI 4.0 showing all the relevant information. In addition, information is added regarding the AAS, indicating the layers that it covers (Based on [6], page 12) for the generation of the I4.0-Component within a Cloud (internal or external) in the organization.

Since the Smart Grid Architecture Model (SGAM) [31] is a 3-dimensional reference model like the RAMI 4.0, and the service-based interactions among digitalized "Things" in the grid follow similar patterns as the Assets in the industrial environment are doing, the authors propose also considering the Use-Case-based method of the SGAM is providing, in order to support the application of the Top-Down approach as a first stage of the digitalization engineering procedure. Remark: In the context of Industrial Cyber-Physical Systems and Industry 4.0, Assets could be any "Thing" that can be digitalized and networked using Internet/Ethernet technology. Moreover, with few differences in the networking technologies and protocols, the SoA-based infrastructure in both kind of systems, i.e. Industry 4.0 and Smart Grid, is similar.

All the best practices acquired with the definition of use cases within the context of the SGAM are extremely useful to support the digitalization procedures using the RAMI 4.0 as a reference model. Note: The description and analysis of the SGAM is outside the scope of the present work. For more detailed information, the readers are recommended to see [31].

The correct definition of use cases is a complex issue and is often strongly related to business and the definition of roles within stakeholders. In [32], page 20, there are definitions of different types of use cases, according to the level of hierarchy and degree of granularity (detail) of the use case. The definition of the use cases is very important because they are one of the starting points of the developed approach.

Finally, the proposed procedure consists on three steps that will be described in the following sections.

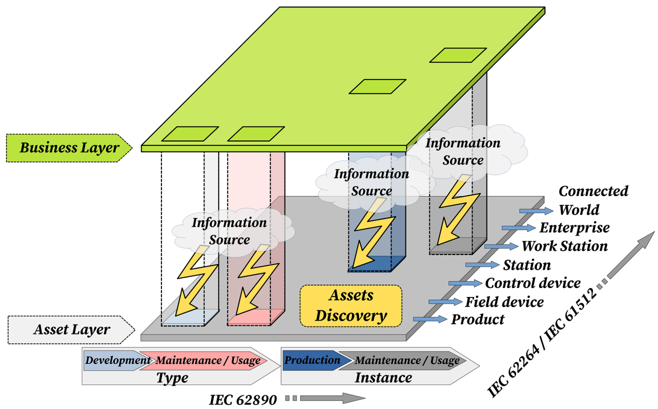

Fig. 4. Assets “Discovery” navigating the RAMI 4.0 in a Top-Down fashion.

D. First Step - Discovery

The First step is focused on the discovery of Assets that meet real organizational needs or requirements, avoiding as far as possible, that the digitalization process relies only on providing technological solutions. The First step is composed by the following sub-steps or stages:

1) Identify a potential business, a problem to be solved, a process to improve, a quality standard to ensure, etc. The final objective is to define needs and requirements.
2) Research as much as possible the know-how associated to that business. This aims to acquire the basic knowledge of the businesses being analyzed, which will help later identifying the Asset(s) that will provide the required data and/or information.
   a) This phase consists of gathering information from different sources, that must be as reliable as possible. Therefore, it is recommended to obtain information from specialists in the field, and personnel of the organizations where the digitalization process will be implemented;
   b) This step is going to generate the requirements that are going to be refined and/or modified when the know-how has matured and/or when the organizations and the different sources of information are studied in depth;
   c) If there are several businesses, it is suggested to see how to integrate them, or to propose different phases of implementation.
3) Identify possible Assets that provide useful and relevant information to cover the requirements (See Fig. 4).
4) Identify and select relevant information.
   a) Identify what information is available on the selected Asset(s). Data should be discriminated according to the origin or source, i.e. whether it is information provided by the Asset supplier, a related third party, the customer-user, etc. This step is greatly enhanced if there is the opportunity to consult experts and/or personnel of all the involved data/information stakeholders;
   b) Define and identify the process and scope where the Asset(s) develop their activities and mainly their functionalities. This implies, having knowledge about the interaction between Assets of the organization. For example, if Assets compose workstations, if they work by performing various functions, who loads information in the Asset, etc;
   c) Start asking which internal sectors of the organization could benefit from this information. Sectors are understood as the different functional groups within the organisation, e.g. purchasing, sales, production, engineering, etc. It can also be extrapolated outside of the company (involving external partners);
   d) Identify with which other Assets (physical or not) and information systems (digitalized or not), internal and external of the company, the Asset(s) exchange valuable information.

In a nutshell, the First step consists of gathering as much information as possible about the business and the involved Asset that are available. Naturally, this information may be subject to many modifications, as this is the initial stage of the digitalization process. This stage seeks to establish as solid for the requirements and specifications.

Generally, the digitalization process starts from scratch, and that is why in many cases, the intervention of different specialists is required. Considering different points of view, the gathered information is enhanced. For this reason, it is suggested that any digitalization process, should be integrated by an interdisciplinary group of professionals. They can be internal (from different sectors) and external (different partners of the value chain) of the organization.

E. Second Step - Details and Redefinition

The First step consists on confirming which are the Assets to be digitalized as well as which are the digital Businesses that can be effectively realized. The Second step is aimed at deepening and laying the foundations of the digital information and functions needed to support specific use cases for the digital businesses.

The next stages are complementing this First step, conducting to a solid positioning of the Assets within the two-dimensional basis of the RAMI 4.0 (Fig. 3).

1) Identification of the different component parts of the Assets that provide valuable information. It may be the case that an Asset itself provides useful information as an Asset as a whole, but there are information coming from components of these Assets, that are useful or necessary;
2) Interaction of Asset with other Assets located on the Information Technology (IT) systems as well on the Operational Technology levels (OT). This step is required to (i) identify relevant data and information that the Assets can or must provide within the company information-communication-control (ICT) infrastructure, (ii) identify potential stakeholders and customers of that data and information. It is important to reinforce here the fact that the positioning and interactions of the Asset(s) that result from this identification are considering the Assets in only one of the phases of its Life-Cycle (e.g. Instance: Usage/Maintenance);

3) The position of the Asset in the company infrastructure follows the standards IEC 62264 [33]/IEC 61512 [34], responding completely to the specifications of the hierarchy dimension provided by the RAMI 4.0. Detailed in Section IV-E1;
4) Taking into account the Value-Stream/Life-Cycle specified by the RAMI 4.0, IEC 62890 [5] it follows the identification of which data and information of which phase of the Life-Cycle of the Asset(s) will have to be digitalized. It is important to reinforce here the fact that the positioning and interactions of the Asset(s) that result from this identification are in this stage expanded to other phases of the its Life-Cycle (Type and or Instances). Detailed in Section IV-E2;
5) Position the Asset on the two-dimensional basis (Asset layer) of the RAMI 4.0 (Fig. 3). This will serve as foundation for the construction of the rest of the five (5) vertical layers;
6) Classify the Assets according to the communication and presentation capabilities, using the standard DIN SPEC 91345 [1]. Detailed in Section IV-E3;
7) Identify the relationships and how the different stakeholders of the value chain relate to each other. Mainly based on the standard DIN EN 62890 [5]. Emphasize the figures of "Component Producer", "System Producer" and "Operator/Customer" and identify different interrelationships;
8) Define the interaction of Assets with other Assets in the digital ecosystem. The scope of the digital ecosystem can be as broad as needed for a desired digital business and will be strongly influenced by the different stakeholder interrelationships;
9) Creation of the Asset Administration Shell. With all the collected data of the previous steps, the information has to be structured and matched with the different available objects of the AAS (Submodels, properties, etc.). To generate the AAS, different software tools can be used [35], [36].

In the following paragraphs the items regarding "Positioning the Asset in the Hierarchy levels of the RAMI 4.0", "Positioning the Asset within the Life-Cycle according to the specifications of the RAMI 4.0" and "Classification of Assets according to the communication and presentation capabilities" of the previous list will be detailed due to their importance.

1) Positioning the Asset Within the Hierarchy Levels of the RAMI 4.0: The hierarchical axis of RAMI 4.0 places the Asset "Structurally and Functionally" within the company in which it performs its tasks and services. Within an organization, particular hierarchical levels must be defined to specify the different functions. Traditionally in organizations, there is a hierarchy in the structuring of information and its functionalities through the definition of Sectors. One of the goals of the Industry 4.0 aims to harmonize and offer a more "horizontal" access, where there are no vertical levels in terms of data information. Organizational structures need to be maintained to keep the organizational roles defined. For a deeper understanding for the correct positioning of Assets considering this axis of the RAMI 4.0, it is recommended to read the standards [33], [34] based on the standards [37], [38], [39] for a detailed overview.

TABLE I
CLASSIFICATION AND DESCRIPTION OF ASSET LIFE-CYCLE PHASES

Asset	Life-Cycle Phase	Classification and Description
Type	Development	Refers to information relevant to the Asset's development
	Usage/ Maintenance	Asset information related to the maintenance or use of the Asset's functionalities as a type. This implies, information updates, user manuals, etc
Instance	Production	Necessary data for the instantiation of the product and generally associated with a transformation process
	Usage/ Maintenance	Considering the information that the Asset has available to it when it has already been produced and is being used fulfilling its function

This axis could be a bit confusing to apply for organizations (not only SMEs), and particularly, for Assets that do not have any degree of automation and control. Since the aforementioned standards are oriented to industries that do have these capabilities, when applying them to SMEs, attention should be paid to always look at the "Functional" point of view of the Asset, regardless of its technological level. Several of these conclusions have been obtained from the feedback of [40].

2) Positioning the Asset Within the Life-Cycle and Value Stream Dimension of the RAMI 4.0: The main idea is to classify data and information associated to Assets according to four (4) major phases of their Life-Cycle. In this context the RAMI 4.0 provides one axis classifying Assets into two major categories within their Life-Cycle, as shown in Table I (Complement definitions with [3]):

The purpose of these categories is to group all the information that is collected by an Asset throughout its Life-Cycle (from its purchase order to its commissioning, use and disposal). Therefore, the standard DIN EN 62890 [5] must be used as a reference to deepen the concepts. This must be complemented with the contents of the aforementioned standard DIN SPEC 91345 and the reference documents [3]. In this context, it is important to differentiate the origin of the information, since an Asset groups information from different partners in the value chain, which must be correctly classified to avoid confusion.

Since the digitalization approach considers the digitalization of Assets along all phases of their Life-Cycle, one mayor result is the creation of the so-called Digital Thread [41]. As a matter of facts Digitalized Assets can now participate in new Digital Businesses, with digital Type-data as well as digital Instance-data. Those data will often be provided by different stakeholders for the Type and the Instance. The digital Business can be done by any of those stakeholders when they have access to the Digital Thread of the Asset.

The amount of possible Businesses associated to one digitalized Asset is big along its own Life-Cycle, but bigger (huge) when the interactions are done with the Digital Thread of all other digitalized Assets in the I4.0-Ecosystem.

The following simple example should help the reader to better understand the big impact of this digitalization approach for a value chain: Recycling in Business Layer for a digitalized Electrical Motor. A first set of digitalized data should be associated to the motor instance Life-Cycle phase "End of life (Recycling)". In this case, data of the Life-Cycle phase specification of the motor Type will be very useful. If the motor is having screws, digitalized data of the motor specification Life-Cycle phase (BOM of the motor), specific digitalized data about material of the screws will provided by another company (Screws Provider), this company will be stakeholder of digitalized data of the Type of the screws (in this case, for the digital Business is important the interaction between the two Digital Threads if there exists, from the motor and from the screws).

3) Classification of Assets According to the Communication and Presentation Capabilities: The presentation and communication capabilities defines, from a technological point of view, which steps will be necessary to obtain an I4.0-Component. It may also be the case that there is no need for in-depth technological development, but rather to adapt or try to harmonize what already exists with the requirements. In the context of SMEs, it is essential to analyze this because, the different possibilities of integration, with other Assets, systems and implementation, basically depend on how the Asset exchanges data and information and interact with their environment. To define the presentation and communication capabilities the standard DIN SPEC 91345 details the necessary steps to follow and the corresponding codification. Initially, each Asset will have a specific ability on which different alternatives must be analyzed and defined in order to present and communicate its data and information in the digital world.

Remark: This is a disruptive point for SMEs, since the addition of the necessary technology to transform any Asset into an I4.0-Component is often costly, and needs dedicated investments and associated know-how.

F. Third Step - Proposal for Implementation

The third step, defines the proposal and elaboration of prototypes (software and hardware) that allow to address all what has been previously researched and developed.

Initially, a preliminary study and a concrete proposal must be performed. This is because an initial investment will be required. Afterwards, the prototypes will be refined during the implementation. In this stage, enough data and information are available to define the specifications that an I4.0-Component must meet to be compatible in a Service-Oriented Architecture [30].

Once the Asset has been correctly positioned in the two-dimensional base (see Fig. 3), and the communication and presentation capabilities of the Asset have been classified according to [1], the required devices (Hardware) and Software developments can be addressed. Considering the Fig. 5 the major targeted layers of the RAMI 4.0 in this Third step are the Communication and Integration Layers.

Considering now the Top-Down and Bottom-Up approach addressed before, partial conclusions are obtained that are very useful to address the digitalization process during this Third step:

- The Business and Asset layer are initially defined or approximated, with all the information that has been collected for the correct positioning of the Asset in the two-dimensional grid. But, some of the elements of the Functional layer are also already available. This is because basically, the required functionalities for the business are provided by, one or a set of Assets together.

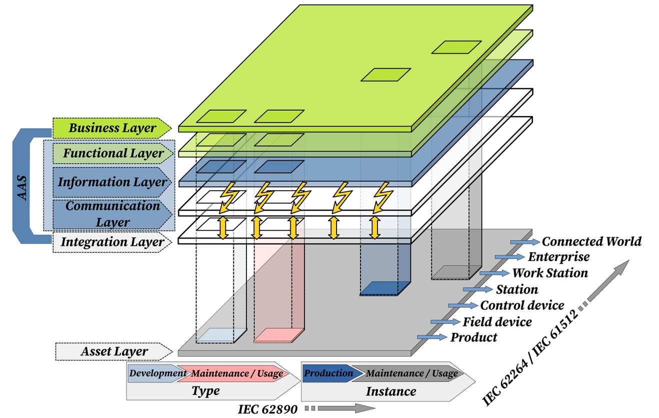

Fig. 5. Strategy of iterating on the integration and communication layers of the RAMI 4.0 based on the information available from the remaining layers.

- After the analysis of the Life-Cycle and positioning of the Asset in the hierarchy axis, combined with the analysis of the interaction of the Asset with other Assets in its digital environment, the Information layer should be defined Section II-B2. Note: The contents of the Information layer and the relationship of those contents with (i) the AAS (Submodels) and (ii) the definition of Digital Twins, are specifically explained in reference [4].

One of the principal challenges of the digitalization approach relies largely on how the Integration and Communication layers of Asset(s) can be specified and implemented. This is because they are highly dependently on: The kind of Asset (existing or not existing communication and presentation capabilities of the Asset and of the ICT infrastructure where the Assets is integrated), digitalization of data and information from Type- or Instance-phase of the Assets Life-Cycle. As a matter of facts, once the specification challenge has been solved, the technological implementation of both, communication and integration layer, follows well defined standards. Remark: The proposed digitalization approach does not refer to a specific standard to be followed. The final selection should be done by the company and stakeholders.

Concerning the specifications of both addressed digitalization Layers, it is possible to classify the Asset(s) based on the following aspects, supplementing the classification proposed in [1]:

- *Low or no communication and information presentation capabilities:* In the case that the Assets do not have any capacity to communicate and present data within the information world, some investment must be made to acquire different types of devices or software to cover mainly the integration, communication and information layers;
- *Intermediate communication and information presentation capabilities:* If the Assets have any existing technology, the solutions to be proposed must be adapted, for example, to existing protocols and connections with information and implementation structures already established beforehand. In this scenario, the solution would be added to the existing one, only to provide new functionalities;
- *High communication and information presentation capabilities:* In which only a few developments are necessary to adapt and process the available resources.

TABLE II
DESCRIPTION OF THE REQUIREMENTS AND USE CASES

Industry sector	Description	Use Case
Dairy Industry	Minimising differences in volume and composition between the dairy and the dairy industry, to establish the relevant corrective actions	Product losses
	Improving decision making in the planning of the dairy's production processes, based on advance knowledge of milk quality at the production stage	Quality of the product
Wine Industry	Improve the early detection of anomalies and their correction, definition of the correct use of the elements, having a traceable history of the Asset, and the facilitation of chemical and organoleptic controls performed and to be performed	Quality of the product
	Improve the bottling stage. Ensuring the manufacturing process of the product rather than focusing on the product	Maintenance of Assets
Beer Industry	Quantify beer production times. Improve delivery times to the customer, personnel provision, provision of equipment maintenance personnel and plant sanitation.	Production optimization and traceability
	Since Beer is a food product, quality assurance parameters are needed. Many of the stages of the process that affect product quality depend mainly on the time variable	Quality of the product

TABLE III
LIST OF ASSETS AFTER APPLICATION OF THE PROPOSED DIGITALIZATION PROCEDURE

Industry sector	Asset	Description
Dairy Industry	Dairy tank delivery note	Document delivered by the industry to the transporter prior to each milk collection round
	Tank recollection unit	Device in charge of sensing the flow rate and temperature of the raw milk loaded on the truck in each tank. It can also have other additional sub-devices such as PH meters, GPS, Milk Analyser, among others. It generates a ticket with important information for the industry for each dairy and summarises the information of the entire route
	Scale	Device in charge of weighing the milk truck at the receipt of the industry
	Milk Analyser	Device in charge of analysing the composition of samples taken at each milking farm, and/or general samples of the raw milk in the truck. Also analyses, the different samples characterising the product. It obtains different data such as PH, temperature, fat, density, lactose, salts, among others parameters
	Thermal tank for milk transport	In this tank, the milk must be preserved and covers the period in which, it is collected from the milking farm and delivered to the dairy company
Wine Industry	Wine aging barrel	Particularizing the Asset in the aging state of the wine
	Mobile Bottle Filler	As mentioned above, this Asset performs the function of the final bottling of the product and performs the following operations: rinsing, filling, capped, encapsulated, labelled and packaged
Beer Industry	Heating Tank	This Asset has the function of heating the pre-maceration water, to a specific temperature and volume defined by the recipe, in order to start the mashing process.

In summary, technology facilitates and helps the digitalization process and with this, the generation of an I4.0-Component. The reference [42] highlights the fact that Assets, to some extent and especially in the shop floor, must have the ability to communicate and process information, in addition to having a unique identification. Based on the previous, it is expected that in this Third step the Technical Requirements will be defined through different specifications on how to implement the Functional, Communication and Integration layers. Data of the Information layer can be specified and processed using different available software tools [35], [36] to generate and store all the gathered information based on the analysis performed so far and according to the specifications of the AAS [3], [43].

The Communication layer can be addressed using the following specifications of OPC UA [44] and MQTT [45]. This definitions should be complemented with the specifications of the DIN SPEC 16591-1 [46] to properly understand, how to foster the

TABLE IV
INFORMATION AVAILABLE AFTER THE EXECUTION OF THE STAGES 3, 4, 5 AND 6

Parameters	Dairy Industry	Wine Industry	Beer Industry
Use Case	Product Losses and Row Product Quality	Product Quality and Traceability	Production Optimization and Product Quality
Asset	Milk Analyzer	Aging Barrel	Heating Tank
Main Function	Analyze Milk after collection	Aging Wine	Heating Water before macerating
Life-Cycle Axis RAMI 4.0	Instance in Usage/Maintenance	Instance in Usage/Maintenance	Instance in Usage/Maintenance
Hierarchy Axis RAMI 4.0	Field device	Station	Station
CP Class	CP33	CP11	CP11
Particularities	The equipment is capable of communicating with a computer. Database available	AAS must be deployed on the Asset. Independent power supply	Devices must be added to the Asset to extract real-time data
Proposed data integration resources and strategies	Creation of the AAS from the data provided by the device for each measurement	Sensor incorporation to the Asset and independence of power supply (batteries)	Replacement of components (mainly valves) and incorporation of sensors and actuators
Limitations	Access to device information may not be possible (use of proprietary protocol)	Low consumption technologies should be used to extract and communicate the data	Some devices need to be replaced and sensors incorporated

TABLE V
RESULTS OF THE APPLICATION OF THE STAGES 7 AND 8 OF THE SECOND STEP

Step	Description
Stage 7. Businesses between stakeholders	As the selected Asset is the heating tank, the information provided by the Asset will be very useful for the tank manufacturer. To verify design parameters (maximum pressure, maximum temperature, material type, etc.), this supplier can use real-time data of its product in use from the customer (Instance). This information will help to improve their products significantly.
Stage 8. Interaction between Assets	The Asset heating tank can be related to other Assets such as: Mash Rank, Fermenter Tank, Boil Tank, Malt Mill, Reverse Osmosis Equipment, The Operator, The SCADA system (if applicable), among others.

communication, interoperability, cooperation and collaboration between I4.0-Components within a SOA.

V. USE CASES APPLICATION AND APPROACH VALIDATION

In order to validate the requirements of the Section III and to show the results of the application of the three steps of the engineering approach described in Section IV, three Use Cases are selected. They belong to SMEs [40], in the sectors Brewing, Dairy and Wine industries. In this section only the final results of the application of the three steps proposed to approach the digitization process will be shown, displaying partial results only when it is necessary.

A. Requirements, Use Cases and Assets Definition - First and Second Step

As a result of the First step of the procedure described in Section IV-D of the procedure, the list of requirements and use cases, shown in the Table II, is generated.

At the end of the First step, it is expected to have the preliminary list of Assets to be digitalized. Nevertheless, adding the

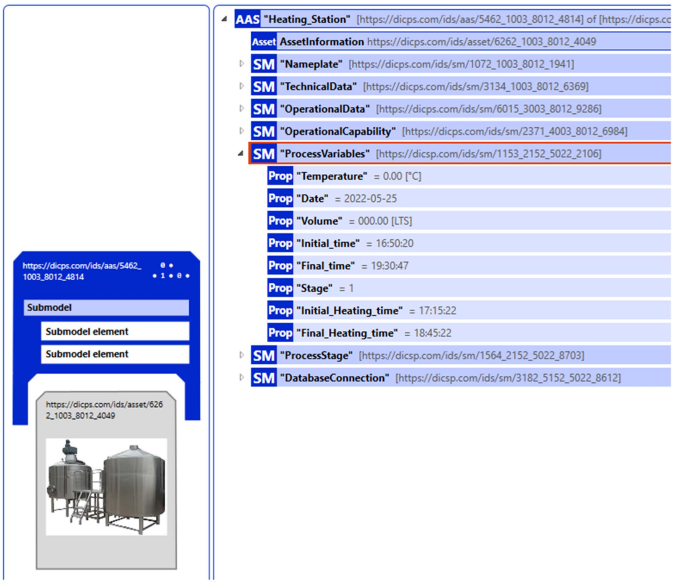

Fig. 6. AAS specifications with the corresponding information of one Asset using the AASX Package Explorer tool.

Second step (Section IV-E) of the procedure, the list is enhanced. The results are exposed in Table III.

Following the procedure, the next stage must be performed (Interaction of Asset with IT/OT systems). To define the different interactions, simple questions can be formulated in order to easily identify sources of data and information. Taken into account Brewery company and its Use case, possible questions for the Enterprise Resource Planning (ERP) are; What kind of Beer could we produce with this tank? or What type of tank and auxiliary equipment do we need to buy according to our process? Possible questions for the Supervisory control and data acquisition (SCADA) System are; What information do we need in real time? Temperature vs time? Hours of operation and shutdowns? What are the critical equipment to be maintained, What kind of maintenance do we need to reduce the heating process failures?

As it can be seen, this step seeks to define the interactions of this Asset with others that may require and provide relevant information for performing the desired digital business.

B. Implementation Proposal - Second and Third Step

To start defining the implementation proposal, the second step must be completed. The Table IV, show the results of the stages 3, 4, 5, and 6, including additional information.

In order to show the results of applying the stages 7, 8, and 9 of the Second step, the use case of the Brewery company will be selected. Table V shows the results of the stages 7 and 8. Fig. 6 shows the generated AAS of the Asset of this particular use case (stage 9).

To generate the information of the the AAS the AASX Package Explorer [35] tool is used. A typical output of the AASX Package Explorer shows on the left side of the Fig. 6 a picture of the digitalized Asset together with the generic schema of the AAS [1], as well as the "Unique Identifier" of the Asset and of the AAS. On the right side of the Fig. 6 the AAS developer becomes from the tool the "Unique Identifier" of the AAS and the Submodels including their properties [3], in this case of the heating tank. Remark: The proposed digitalization procedure is flexible enough to use different approach for structuring the AAS. For example, the different Submodels proposed by IDTA [47] could be included within the definition of the information models of the AAS.

Once the Second step is completed, the Third step will define specific information taking into account technical considerations of how to approach the Communication and Integration layer as discussed in Section IV-F. Particularly, some of the sections to be taken into account in this approach have been defined in Table IV under the names "Particularities", "Proposed data integration resources and strategies" and "Limitations" for each use case. As the Third step demands very specific and detailed information, such as the definition of sensors, communication protocols and definition of implementation structures, its specific details are beyond the scope of the present manuscript. Note: This approach should be used to redefine the steps of the First and Second steps if required.

C. Evaluating the Impact of the Digitalization Engineering Approach in SMEs

The Table VI summarizes the most relevant characteristics of SMEs as described in Section III and provides a first evaluation of the impact of the contributions provided by the digitalization engineering approach.

VI. Conclusion and Outlooks

A. Conclusion

This manuscript summarizes a conceptually accessible approach to support the engineering of Industrial Cyber-Physical Systems with focus on the digitalization process of SMEs. This conceptual accessibility is provided by a novel structured engineering procedure precisely grounded on the RAMI 4.0. It covers the digitalization process from the early stages of the adequate requirements compilation, through the specifications and developments along the Life-Cycle of Assets and processes, and thus establishing a solid foundation to achieve an economically and technically plausible implementation accepted by all involved stakeholders of the value chain, with special focus on SMEs.

By initially presenting the knowledge background about (i) the major "principles of Industrial Cyber-Physical Systems and Industry 4.0-compliant digitalization", and (ii) the most essential requirements from SMEs for getting "digitalized" systems and processes, the manuscript described the major features of a novel digitalization engineering approach, including the results of its application to three exemplary industrial use cases. This allowed validating the most essential characteristics and requirements addressed in the Section III, in this case, in the three application scenarios. Following the information flow provided by the paper, the reader can learn "how to apply and introduce Industry 4.0-compliant methods and technology,

TABLE VI
IMPACT OF THE DIGITALIZATION ENGINEERING APPROACH IN SMEs

Characteristics of SMEs	Contributions of the digitalization engineering approach. Summary.
Mainly no research and innovation departments, complemented with reduced innovation capabilities	The implementation of the three steps addressed in sections IV-D, IV-E and IV-F requires multidisciplinary innovation teams.
Limited Knowledge transfer, what implies the necessity for training, education that should be Provided by third parties	The proposed approach teaches the main aspects of an Industry 4.0-compliant digitalization. The proposed procedure encourages teamwork and self-learning among the involved participants in the first step of the approach IV-D.
Reduced market to a dedicated product and solution portfolios for a limited well identified market	The introduction of digitalization following the approach guaranties the extension of the portfolios with new added-value services. By identifying new service-based digital business with different stakeholders, addressed in Section IV-E sub-step 7, companies can now extend their portfolios.
Clear position in the value chain, with very well defined business with other stakeholders	By adding the digital service-based businesses companies are having the possibilities to establish new relationships within existing or new value chains. This was addressed in section IV-E sub-step 7 and 8.
Rigid organizational structures very well defined with actors playing sometimes many roles	An Industry 4.0-compliant digitalized infrastructure is inherently distributed allowing dynamic relationships among the AASs. Moreover, businesses, functions and roles associated to Assets can be reconfigured supporting flexible organizational structures. Addressed in section IV-E sub-step 7, 8 and 9.
Not always state of the art Information and Communication Technology (ICT) infrastructure	The application of the proposed procedure requires minimal initial investment and by analyzing the communication and presentation capabilities of Assets, with the addition of different Low-Cost devices, the technology will be state of the art. Addressed in Section IV-E sub-step 6 and IV-F
The Implementation should be cost-effective and energy-efficient	The software tools used for the generation of the AAS are freely available, particularly under the Open Source philosophy. In turn, by making use of Low-Cost technologies, digitalization can be carried out inexpensively. Addressed in Section IV-E sub-step 9 using the software tool AASX Package Explorer and in Section IV-B.
Need to integrate and expose Dynamic and Static data between different Assets within the same organization and stakeholders of the value chain.	The fundamental resource generated with the proposed procedure to fulfill this requirement is the AAS. By obtaining the AAS based on requirements, its different objects, such as Submodels and properties, can represent static and/or dynamic data. Then, the implementation type will define how to manage each of those data types. Addressed combining the results of the sub-steps 6 and 9 of the Section IV-E and the analysis in IV-F
Need for integration of heterogeneous Assets into the digital world, using structured information in a common network	Similarly to the previous case, the way proposed by the I4.0 Platform to ensure this requirement is through the use of the AAS. By equipping each Asset with its corresponding AAS and making use of a Service Oriented Architecture, the integration of any type of Asset is ensured. This contribution is addressed by the creation of the AAS (using the AASX Package Explorer) with the sub-step 6 and 9 of Section IV-E and the and the analysis performed in IV-F regarding the alternatives to address the Communication and Integration Layer of the RAMI 4.0.

including added-value services based businesses, with emphasis in eco-systems of SMEs".

By defining and analyzing a representative set of different types of SMEs, a list of use cases based on real companies' businesses was obtained. These use cases were analyzed in the context of a training/education master course oriented to analyze different opportunities for the successful introduction of Industry 4.0 and ICPS in SMEs. A first major result from that course was the definition of a common procedure for allowing applying the digitalization engineering approach in an orderly, efficient and result-oriented manner in different kind of SMEs. The procedure was then enhanced with different tests performed in different contexts and applications [48] and supported by the authors' experience. One major outcome is the confirmation of the necessity to combine two different digitalization strategies in the context of the adopted reference model (RAMI 4.0), i.e., Top-Down and Bottom-Up navigation of the Layer dimension of the 3D model [23], [29].

As a matter of fact, after identifying new possible added-value-service-based businesses, the application of the Top-Down digitalization strategy guide the companies to define which functions and which digitalized data and information will be needed from which digitalized and networked Assets (Assets digitalized using AAS). However, any Asset digitalized using the Bottom-up strategy will have an associated AAS with different Submodels that will allow it to participate in many different added-value-service-based businesses. Remark: Assets should fulfill a specific function within the organization in which they perform. This involves performing a specific function for which the organization considers having those Assets available for the execution of its activity. The procedure aims to expose the Assets that offer valuable data and information to be digitalized.

Having validated the full set of specifications needed to proceed developing the RAMI 4.0-compliant digitalization of the Asset/s, the ICPS Engineering approach conduces into different forms of implementations of ICPS (I4.0-Component), as addressed, e.g. in other works of the authors [48].

B. Outlooks

The concept of Cyber-physical Production Systems (CPPS), can be associated with multi-agents in conjunction with a Service Oriented Architecture as another way to approach the proposed topic, based on the properties of these types of systems [49]: Flexibility/changeability, Reliability, Reconfigurability, Adaptability/agility and Dependability. Based on this, the developments associated to the third step of the digitalization engineering approach (Section IV-F) can be complemented and serving as a guide for the design of possible implementation structures.

Applying the Digitalization Engineering Approach, the current industrial eco-system is complemented with a Digitalized Data Infrastructure exposed as Services by the Asset Administration Shells in the Industry 4.0-compliant network. Using both reference architectures and models, i.e. the RAMI 4.0 and the IIRA [50], an extremely well-suited enhancement of the approach is the integration of Analytics that will appropriately support existing and/or new added-value services and associated business for the digitalized companies. And also the integration of those Analytics embedding them into the AAS-based infrastructure appears as a potentially high-impact outlook.

By digitalizing systems along their Life-Cycle and processes along the Value Stream, the digital data and information contained in the respective Digital Thread can effectively support the traceability of products, components and systems. One keyword is here "Digital Product Passport". According to the authors of [51], a digital product passports are currently one of the most promising technological approaches for improving information transparency along the value chain. This potential enhancement of the Digitalization Engineering Approach means new research and innovation challenges, among others those related to "interoperability, modelling semantic and syntactic of data", as well as the necessity for companies, along the value chain, to get digitalized avoiding being excluded of the new digital businesses associated, e.g. to the digital traceability of products and services [52].

The application of the digitalization engineering approach generate also complementary technical requirements, particularly those related to the definition of necessary initial investments for implementing AAS based on affordable solutions for SMEs, for example, the utilization of certified Industrial Low-Cost Technology, as initially proposed by the authors of [15], [53].

To address the digitalization procedure different implementation structures on which to consume and serve data and information in form of services will be required. Different solutions will also be required to implement/store the AASs (Cloud or Embedded). The implementation structures will require different Hardware and Software solutions that should be I4.0-Compliant. They should be in line with the communication and presentation capabilities of data and information as discussed in Section IV-F.

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