An Engineering Process model for managing a digitalised life-cycle of products in the Industry 4.0

Gianvito Urgese[1], Paolo Azzoni[2], Jan van Deventer[3], Jerker Delsing[3] and Enrico Macii[1]

Abstract— **The Internet of Things (IoT), and more specifically the industrial IoT, is revolutionising industry. This technology has catalyzed the fourth industrial revolution and inspired movements such as Industry 4.0, the Industrial Internet Consortium and Society 5.0. Morphing an industrial process or assembly line to aggregate Internet-connected devices and systems does not complete the picture. The concept penetrates all aspects of the engineering process (EP) which encompasses the full life-cycle of the product/solution. Phases of the EP traditionally tended to be sequential but, with the IoT, can now evolve and influence other phases throughout the product/solution life-cycle. The EU-funded Arrowhead Tools project aims to promote a service-oriented architecture (SOA) to allow tools within each phase of the engineering process to interact with each other. This paper, applies the proposed EP model to a real value chain composed of multiple stakeholders adopting different EPs for the life-cycle management of a Smart Boiler System.**

I. INTRODUCTION

This paper addresses product life-cycle management and the associated engineering process (EP) for the automation of digitalisation solutions oriented toward smart production. An EP model and ontology is proposed. The main objective is the efficient management of the product life-cycle, supporting automation of native and legacy production based on Internet of Things (IoT) and System of Systems (SoS) technologies. This EP will thus address both design-time and run-time automation/digitalisation engineering solutions.

The EP model proposed here is in the development phase under the ECSEL Arrowhead Tools project [1]. The Arrowhead Tools project aims to provide digitalisation and automation solutions for European industry to close gaps that hinder integration of information and operation technologies (IT/OT) by introducing new technologies in an open-source platform for the design- and run-time engineering of production facilities that embrace IoT and SoS.

The EP makes use of a service oriented architecture (SOA) for both automation design and integration of engineering tools. It is supported by the Arrowhead Framework [2], which is a framework to build SoS-based automation and digitalisation solutions. It also provides an architecture that supports the multiple ontologies and semantics currently used in industry. Examples include IEC 10303, STEP-based anthologies and Building Information Model (BIM).

[1]Politecnico di Torino, 10138, Torino (TO), ITALY gianvito.urgese@polito.it
[2]EUROTECH S.p.A., 33020, Amaro (UD), ITALY paolo.azzoni@eurotech.com
[3]Luleå University of Technology, 97187 Luleå, SWEDEN, jan.van.deventer@ltu.se

Since the designed Engineering Process model is under development in the Arrowhead Tools project, we refer to it from now on with the acronym AHT-EP.

The design of the AHT-EP and of its ontology are based on a gap analysis, which identifies the needed features and a suitable structure to define an engineering process model, that can support both EP digitalisation and automation, improving flexibility and configurability across different vertical domains and related value chains. In this paper, we start with a gap analysis to identify needs and features to be matched by an EP. Then, we present our AHT-EP model with a focus on the main engineering phases and a description of the ontology that we defined to identify the interaction between the various components of our AHT-EP. In the last section we present a Smart Boiler System use case (UC) to illustrate the advantages of using our AHT-EP model and its ontology. In this UC, all the different stakeholders, involved in the product life-cycle, are connected to each other, highlighting aspects such as value/supply chain, adopted tool-chains and tools to be interfaced.

II. GAP ANALYSIS

In the industry and software engineering domains, several EP models have been developed and used to describe the life-cycle of product/solution (P/S) and services produced.

In general, an EP is described as a workflow: a sequential description of phases and activities, during which documents, information and tasks are passed from one phase to another for action, according to a set of procedural standardised rules [3]. EPs can have branching points that result in the execution of parallel tasks and decision-making points that can guide the execution path toward many alternatives. Currently, the trend is to define 3D reference models that integrate aspects such as factory hierarchy and business architecture layers with the life-cycle value stream. A short review of EPs in software and production industries offers a proper background for a multi-dimensional solution space.

A. *Engineering Process for Software Development*

One of the first engineering process models, introduced by Royce in 1970 [4], is the *Waterfall model*, which describes the steps to be implemented in a sorted list of consequential phases. Each phase of development proceeds in sequential order without any overlap; the result of the phase must be passed to the next phase in complete form, tested, and well documented after a predefined time period allocated for its development. Under the Waterfall model, the implementation of corrections of any defect found very late in the development of the product life-cycle is inefficient. However, its sequential nature promotes proper documentation of each phase to ensure formal information transfer between phases. The Waterfall life-cycle model can still be used in low-complexity projects with relatively smaller development and maintenance teams.

The *V-model* was introduced in the software engineering domain to improve some of the bottlenecks of the Waterfall model [5]. This structure allows developers and testers to work in parallel, with benefits for development time and costs. In the V-model, relationships between each phase of the development life-cycle and its associated phase of testing are explicit. This feature ensure that the result of each phase is properly checked and approved before moving forward to the next phase. Unlike the Waterfall, the V-Model involves tester teams in the requirement phase itself. It allows a certain level of flexibility since requirement changes are possible in any phase and can be satisfied with a small overhead [6]. The V-Model is mostly used in large companies as it requires a large number of resources to support reviews and updates of each development and associated testing stage.

The *Agile model* [7] aims to abstract the model and documentation of the product to be developed. This model does not have a fixed structure and can be customised for different application domains and products, making the integration of values, principles, and practices more flexible in the life-cycle description of a product. The Agile methodology requires an adaptive team that is able to respond to changing requirements even late in development. Working software is delivered frequently so that customers are satisfied by the rapid and continuous delivery of new software versions.

Comparison of these three life-cycle models reveals that unfortunately, there is not an easy recipe that can be applied to all UCs. Indeed, depending on the features of the project, one needs to choose which life-cycle model is best fit for purpose [8]. However, by analysing these frequently adopted EPs, one can note that the more the process is fixed and static, the more difficult it is to correct the project when requirements change. Small projects can be managed in a more flexible way with respect to large project. Therefore, ideally, it might be more convenient to partition a large project in several smaller parts, which can be developed in parallel by different teams (or different stakeholders) and integrated at the end to assemble the main product or service. This approach is particularly suited for the life-cycle management of the SoS, which can be partitioned into a collection of task-oriented or dedicated systems that pool their resources and capabilities together to create a more complex system that offers more functionalities than the sum of the single constituent systems [9].

B. Engineering Process in the Manufacturing Industry

The current state-of-the-art for engineering of a production process is based on the ISA 95 architecture [10] and engineering standards such as IEC 81346 [11], CAEX [12, 13], ISO 15926 [14] and IEC 62424 [15]. This has resulted in highly functional but very stiff and inflexible manufacturing automation architectures and solutions. Yet reliable flexibility has been difficult to provide in manufacturing up to now, due to the lack of engineering models capable to manage complex use cases based on heavily interconnected components from multi-stakeholders with different EPs (e.g. IoT).

Industry 4.0 digitalisation foresees the integration of stakeholders in ecosystems, e.g., a factory, an airport, or a bridge. Such integration requires data sharing among different local automation systems owned by different legal bodies, which are possibly located in different countries under their legal systems. The sharing of data enables the optimisation of productivity, raw material yield, energy and environmental footprint, etc., which is the basic motivation for automation.

Several reference architecture models are under development to improve the digitalisation level in the intelligent manufacturing domain by combining concepts, methodologies and technologies taken from the IoT, cyber-physical systems (CPSs), cloud computing, big data analytics (BDA), and information and communications technology (ICT) [16].

The smart manufacturing ecosystem developed by NIST [17], the Industrial Internet Reference Architecture (IIRA) [18], the IBM Industry 4.0 Architecture [19] and the Reference Architecture Model Industrie 4.0 (RAMI 4.0) that is one of the most eminent emerging architectures [20] that drive the manufacturing industry in the direction of a more connected and integrated development model for its automation [21].

RAMI 4.0 is a 3D map showing the most important aspects of manufacturing in the Industry 4.0 domain. Its adoption ensures that all participants involved share a common perspective and develop a common understanding. The model is described on three axes [22]: i) *Hierarchy Levels:* horizontal axis based on the IEC 62264 Enterprise control system integration. ii) *Life-Cycle and Value Stream:* axis representing the life-cycle of P/S, which is based on IEC 62890 Life-Cycle Management. iii) *Layers:* vertical axis describing the decomposition of P/S in such a way as to enable its virtual mapping across domains (Business, Functional, Information, Communication, Integration, and Asset).

However, these new reference architectures lack the ability to address some of the relevant key points that are useful for the SOA and SoS domains. Moghaddam et al. [23] recently interviewed a pool of experts, with the main aim of producing a critical review of the direction taken from the reference architectures designed to support the Industry 4.0 development and highlight the shortfalls of these models. In the following list, we report the major observations of this study coupled with the needs that we identified by analysing all the mentioned production engineering process models:

- None of the models expose the EP's available resources as fine-grade services; all are limited in that they provide only high-level macro services or even do not adopt an SOA model at all.
- RAMI 4.0 and IIRA are based on a slightly improved automation pyramid (IEC62264) that still presents challenges in terms of migration from a legacy control system to an SOA control system [24].

- The models do not specify how loosely coupled services, associated with EP resources, can be composed, shared, and utilized on-demand and throughout value networks of collaborating and competing stakeholders for supporting SoS UCs.
- Mechanisms for dynamic and decentralised mapping of EP resources onto micro-services have not been clearly addressed by any of the current reference architectures.
- None of the models and architectures reviewed specify how humans interact with emerging manufacturing systems and environments (i.e., human-machine symbiosis). We have to realise that this new technology requires training of people with new skills related to the understanding of the new platform, new tools and new architecture.
- None of these models support continuous engineering, making the interaction of different engineering processes from many stakeholders difficult.
- These models are not designed to explicitly support value chain and supply chain needed in the SoS domain.
- These models are mostly focused on the business-to-business UCs.
- Predictive maintenance is a significant enabler toward Industry 4.0. However, until now, it has not been considered within the framework of RAMI 4.0 to yield a unified predictive maintenance platform [25].
- None of the models address the bridging of legacy automation engineering and the new and emerging IoT and SoS platforms such that the integrated solutions can meet basic industrial requirements in terms of, e.g., real time, robustness, scalability, security, safety, and engineering simplicity.

Most importantly, all these models were conceived for a specific sector without considering the partnerships/alliances between the stakeholders involved in the product value chain and required, in the current industry panorama, to address the complexity that characterises products based on IoT and SoS technologies. Thus, to successfully develop those kinds of projects, companies need interdisciplinary teams of people with heterogeneous backgrounds, collaborating and interacting through integrated and automated EP based on ICT solutions.

III. THE AHT-EP MODEL

Current standards for automation engineering such as IEC 81346, IEC 62424 (CAEX), AutomationML, and IEC 62242 provide an EP model. However, common challenges must be addressed when applying these standards to complex systems with real industrial IoT-based scenarios. In particular, it is difficult to see how a general standard, described in generic terms for many types of products and industries, can be applied for a specific product, service, or installation. Moreover, documents describing the standard usually offer very few examples of how the standard can be applied to the many possible UCs within different vertical domains.

To fulfill the potential of production flexibility in Industry 4.0, automation and digitalisation solutions have to become more flexible. This requires engineering automation and its deployment at run-time. For this reason, the stiffness of today's automation implementation, based on standards such as the ISA-95 architecture, has to be significantly reduced. More recent architectures, such as RAMI4.0 and IIRA, consider this type of flexibility but don't support it when moving from pure automation to digitalisation and automation.

For this purpose, within the Arrowhead Tools project, we investigate and propose extensions to the current automation engineering standard IEC 81346 [26] by addressing and simplifying some of the common challenges. Referring to IEC 81346, it is obvious that throughout the process there are feedback and reiterations between the different engineering steps or phases. However, this remains insufficient to support the issues identified in the gap analysis. We added three supplementary phases to the original 81346-based EP. The first version of the enhanced AHT-EP is depicted in *Fig. 1.a*.

In AHT-EP we add the engineering steps of system Maintenance, Decommissioning & Recycling, Evolution, and Training & Education, thus capturing the relevant needs for system maintenance, people training, evolution, and P/S end-of-life retirement during the lifetime of P/S. The impacts of this approach for the end users are as follows: i) Faster return on investments. ii) Reduced costs for maintenance due to the efficient engineering, validation and deployment of maintenance itself. iii) Reduced costs derived from continuous evolution (continuous engineering) of automation and digitalisation solutions targeting production.

A. The eight AHT-EP Phases

We designed the AHT-EP, shown in *Fig. 1.a*, as a flexible solution to support the intertwined EPs of UCs from several industrial sectors addressed in the Arrowhead Tools project. We provide a short description of the eight phases of the proposed AHT-EP below:

1) The **Requirements** elicitation phase is the practice of researching and discovering the requirements of a system from users, customers, and other stakeholders. The output of this phase is typically a list of requirements.
2) The **Functional design** phase consists of adopting the 'functional design' paradigm to simplify the design of P/S.
3) The **Procurement & Engineering** phase involves, first, the process of finding and agreeing to terms and acquiring from an external source the goods, services, or works required to engineer the P/S and construct/manufacture it. The engineering phase, in turn includes the design, development and testing of the P/S, generating a prototype of the P/S and, after some iterations the final version of the P/S (that will be deployed and commissioned).
4) The **Deployment & Commissioning** phase consists, first, of the installation/integration of the P/S in the final operative environment, while the commissioning phase is the process of assuring that the P/S is designed, installed, tested, operated, and maintained according to the operational requirements of the owner or final client.
5) The **Operations & Management** consist of operating and managing the P/S according to the operational specification of the P/S and requirements of the owner or final client.

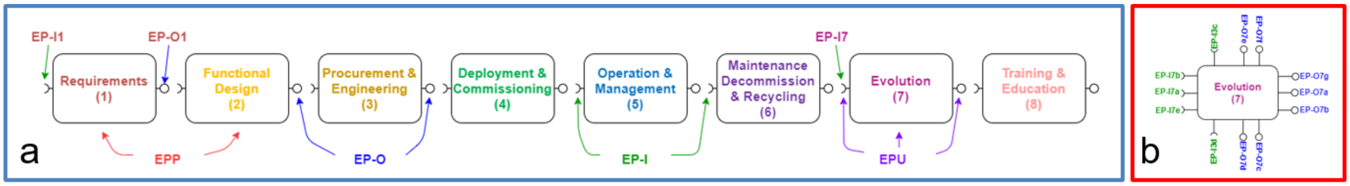

Fig. 1. **a)** Arrowhead Tools Engineering Process and Engineering Process Units. **b)** Rule for enumerating the multiple EP-I/EP-O of a single EPP.

6) **Maintenance, Decommissioning & Recycling** consists of identifying and establishing the requirements and tasks to be accomplished to achieve, restore, and maintain operational capability for the life of the P/S. In this phase, we also consider the decommissioning of the P/S at end-of-life and the responsible recycling to reduce the impact on the environment.
7) The **Evolution** phase deals with the inability to predict how user requirements, market and technology trends will evolve a priori. This phase must also ensure the continuous improvement of the P/S, always respecting the user requirements in an efficient, reliable and flexible way.
8) The **Training & Education** phase includes all the educational and professional training activities required by the engineering process, across the entire P/S life-cycle.

Other processes linked to the product life-cycle, such as Production, Marketing or Sales, that are not directly related to the EP can be eventually represented as black boxes, connected and interacting whit the AHT-EP.
Within the Arrowhead Tools project, we will support the adoption of the AHT-EP by using the Arrowhead Framework as a service oriented solution to manage and automate the phases of the EP, as proposed by Kozma et al. [27].

B. *The AHT-EP Ontology*

To manage the complexity of the engineering process of SoS, an ontology is presented to model and track the interactions between the engineering process's phases, toolchains and related tools, especially considering the EPs adopted in multi-stakeholders value chains.

The structure of the AHT-EP (*Fig. 1.a*) is based on *Engineering Process Units (EPUs)*, which are classified as: i) *Engineering Process Phase (EPP)*; the eight phases detailed in the previous section. ii) The *Engineering Process Interface (EPI)*, that represent both the input/output connections between internal AHT-EPPs and the external links with other EPs controlled by different stakeholders that need to interact with the AHT-EP of the P/S. Moreover, we introduced the *Engineering Process Connection (EPC)* enumeration to assign a unique numeric identifier to each EP-I/EP-O connection (a pair of interfaces) involving many stockholders with complex EPs.

As an example, in *Fig. 1.a EP-I1* represents input for the Requirements while *EP-I7* represents input for the Evolution. The output are identified in the same way (*EP-O1* is the output of the Requirements and so on). Moreover, we defined a so-called *Engineering Process Mapping (EPM)* to identify the link between the tools and one or more EPUs.

To support the IoT and SoS UCs of different domains, the AHT-EP can be designed by connecting the EPPs in a customised flow, without necessarily following the sequential order illustrated in *Fig. 1.a*. Moreover, the EP-I and EP-O interfaces can be more than one for each EPP and can serve to connect each EPP with external Engineering Processes from other stakeholders that interact in the life-cycle of the P/S. In the following, we propose a rule for enumerating the multiple EP-I/EP-O of a single EPP. In the case of multiple EP-I we begin by assigning a letter to each interface in clockwise order, starting from the input on the left-bottom. In the case of EP-O we run the enumeration from the output of the EPP placed on the right-side-up of the block. As an example, the *Fig. 1.b* illustrates the representation of the Evolution EPP with multiple input/output interfaces enumerated with the proposed system.

To represent the connection graph of the AHT-EP, we can adopt a standardised tabular format for representing direct graphs [28]. In *Fig. 2*, we show an example that uses and connects two AHT-EPs and an unknown engineering process. The dashed lines represent connections external to the main AHT-EP. In this example, AHT-EP 1 is the main process that uses seven of the eight phases and is connected with two external engineering processes. AHT-EP 2 is composed of three EPPs, where two (EPP1 and EPP4) are connected with EPP2 and EPP3 of AHT-EP 1, respectively. The external EP receives inputs from EPP6 of AHT-EP1 and provides inputs in EPP3. It is the responsibility of the stakeholder, the owner of the EP, to implement and validate interfaces and connections belonging to its own perimeter. In the example, stakeholder 1 (StkH-1) is in charge to implement and validate all the connections enumerated from *c1* to *c12*, while StkH-2 is responsible for *c13* and *c14*.

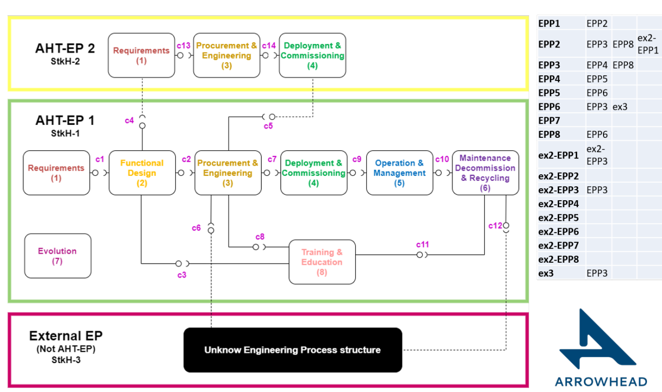

Fig. 2. Direct graph & tabular notations of two AHT-EP from different stakeholders connected with an unknown EP from a third stakeholder.

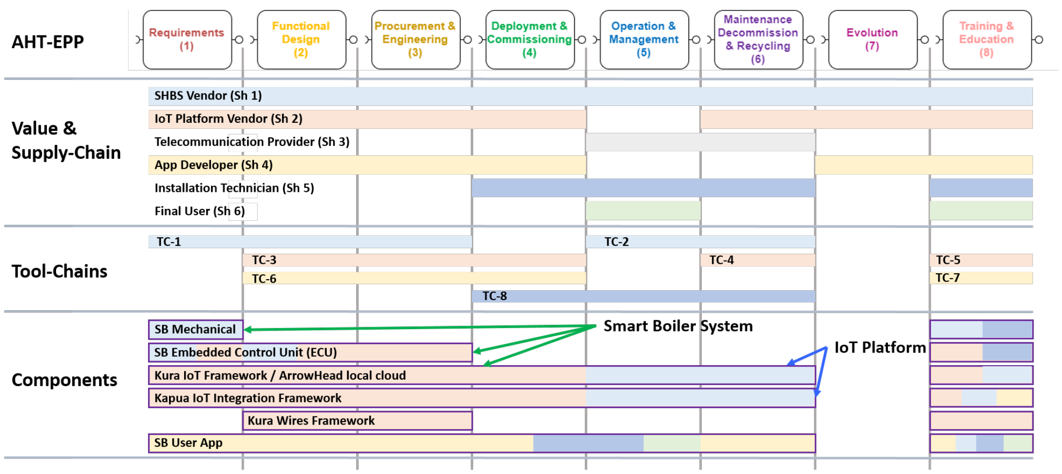

Fig. 3. VCEP-map of the Smart Boiler System representing the interaction of four layers: **AHT-EPP** AHT-EP Phases, **Value/Supply Chain** of Stakeholders (StkH) represented with the six colours, **Tool-Chains** design, methods, & tools (each tool-chain has a Unique Identifier), and **Components** (frameworks).

C. *The AHT-EP Model Advantages*

The ontology described above addresses the four objectives associated with the digitalisation of the engineering process. i) The entire model allows feedback connections that provide inputs to previous phases and an Evolution phase intended to provide feedback for future enhancements of the P/S. This ensures continuous engineering. ii) The shift from single to integrated multi-stakeholder automation and digitalisation can be achieved by connecting the AHT-EP of the P/S with external EPs adopted from one or more stakeholders. AHT-EP will support interfaces that can be customised and used for this purpose. iii) The handling of an increased number of I/Os due to much more fine-grained automation will be guaranteed by the capability of the AHT-EP to handle multiple I/O interfaces for each EPP. iv) The Digital learning and training activities as an integral part of the engineering cycle will be supported by the inclusion in the AHT-EP of the Training & Education phase.
All these combined advantages makes the model flexible and adaptable to support a wide spectrum of vertical UCs that goes from semiconductor engineering, to mining, finance etc.

IV. RESULTS & DISCUSSION

The Arrowhead Tools project aims to develop a seamless tool chain to empower European industry to move towards digitalisation. The use cases of the project adopt the previously proposed ontology to reveal similarities between the different domains and develop general and interoperable tools. A good example to illustrate these concepts is related to smart cities and more specifically to smart heating systems. These systems are currently required to reduce the environmental footprint while ensuring improved comfort for the end user. The digitalisation of heating systems makes them complex SoS, wtih a value chain composed of several stakeholders, adopting different EPs to manage the life-cycle of the components of the system.

A Smart Boiler System (SBS) is an end-to-end solution for the consumer market, intended to extend a standard boiler for home usage with connectivity and smart functionalities, integrate it into an IoT infrastructure and provide added-value services for the manufacturer, installer, user, etc. For the manufacturer, this solution simplifies, improves and optimizes the management of a fleet of boilers; it allows for improvement of the quality of the P/S, reduction of maintenance costs, an increase in the return on investment, etc. It also simplifies the everyday activities of maintenance operators and improves the quality and safety of their job. Eventually, for the final user, this system improves the boiler safety through continuous remote monitoring by qualified personnel, and it increases users comfort level while reducing energy consumption and the carbon footprint. The smart boiler system is a very good example to illustrate the complex ecosystem that supports an apparently simple consumer application.

Fig. 3 illustrates the Value Chain and Engineering Process map (VCEP-map) of a smart boiler system for the consumer market. With this new concept, we provide an overview of the ecosystem of stakeholders, technologies, design methods and tools involved in the engineering process of the smart boiler. A VCEP-map is a simple and effective way to provide, in a two-dimensional schema, a comprehensive overview of the value chain and of the engineering process associated with a specific vertical market; with its visual linearity, the VCEP-map is easier to understand than a RAMI 3D solution space, and it provides, in a single snapshot, richer information content. The map facilitates the identification of the relations between the stakeholders (colors in the bars always represent the stakeholder), their involvement in the various phases of the EP (AHT-EPP section), and the usage of Tool-Chains mapped on the EPPs (colors of the tool-chains match the stakeholders using them). For each component of the smart boiler system, the map specifies which tool-chain has been adopted for the engineering of the component and in which phases, which stakeholders have been involved, and in which phases of the smart boiler life-cycle the components are used and by whom.

The combination of the VCEP-map and of the AHT-EP ontology defines a network between the phases of the EP of each stakeholder. The smart boiler manufacturer stakeholder (StkH-1) leads the value chain and is involved in every phase of the EP, across the entire life-cycle of the product, from early design to retirement. The IoT platform provider (StkH-2) leads the digitalisation of the vertical application, the telecom operator (StkH-3) is a service provider, while the application developer (StkH-4), the maintenance operator (StkH-5) and the final user (StkH-6) use, at different levels, the services and functionalities offered by the SBS.

StkH-1 designs and develops the boiler and creates the requirements to be provided to StkH-2, which will develop the embedded control unit (ECU) that allows for the boiler's digitalisation. StkH-1 is involved in the deployment and commissioning of the smart boiler. In its remote monitoring during operations and maintenance, StkH-1 exploits the information collected from the smart boilers fleet to improve the product and guarantee its evolution. StkH-1 is also involved in the training of the maintenance operator and in the production of documentation for the other partners in the value chain. The IoT platform vendor (StkH-2) designs and develops the ECU, the IoT framework installed on the edge of the boiler ECU, and its counterpart, the IoT integration platform that manages the entire fleet of smart boilers. The IoT framework and integration platform provide services and APIs that allow the development of the application's business logic and integration at the enterprise level. The IT department of the smart boiler manufacturer can integrate the fleet of smart boilers in its industrial processes, providing remote control, preventive and predictive maintenance, and collecting precious information about the product life-cycle. The application developer adopts these services and APIs to develop final user applications intended for the maintenance operator and the consumer.

V. CONCLUSIONS

The engineering process that leads a production line or a product from concept and requirements to operation and maintenance used to be quite static and sequential. The digitalisation of industry is changing this approach, as it is exemplified by Industry 4.0 and one of its reference architecture models, RAMI 4.0. In this paper, we show that EPs with a dynamic nature need to be extended with new engineering phases that, not being anymore sequential, are active and interact with each other throughout the whole life-cycle of the product/solution. This non-sequentiality has consequences for the EP of each of the stakeholders, as their phases and associated tools become dependent on each other. To address this complexity, we introduced an ontology to depict and clarify the information flows and dependencies among the EPs of the different stakeholders, their phases and their tools. Finally, a smart boiler use case was presented to illustrate the concept.

ACKNOWLEDGMENT

This research work has been funded by the European Commission through the EU H2020 research and innovation programme, ECSEL Joint Undertaking, and National Funding Authorities from 18 countries under the Arrowhead Tools research project with Grant Agreement no. 826452.

REFERENCES

[1] *Arrowhead Tools*. URL: http://www.arrowhead.eu/arrowheadtools.

[2] J. Delsing. *Iot automation: Arrowhead framework*. CRC Press, 2017.

[3] Pouria Ghobadi-Bigvand. "An adaptive, context-sensitive, workflow support system for process and automation engineering of production plants". In: (2018).

[4] Winston W Royce. "Managing the development of large software systems: concepts and techniques". In: *ICSE*. IEEE Computer Society Press. 1987, pp. 328–338.

[5] Kevin Forsberg and Harold Mooz. "The relationship of system engineering to the project cycle". In: *INCOSE International Symposium*. Vol. 1. 1. Wiley Online Library. 1991, pp. 57–65.

[6] Sonali Mathur and Shaily Malik. "Advancements in the V-Model". In: *IJCA* 1.12 (2010), pp. 29–34.

[7] Alistair Cockburn. *Agile software development: the cooperative game*. Pearson Education, 2006.

[8] S Balaji and M Sundararajan Murugaiyan. "Waterfall vs. V-Model vs. Agile: A comparative study on SDLC". In: *JITBM* 2.1 (2012), pp. 26–30.

[9] Steven W Popper et al. "System of systems symposium: Report on a summer conversation". In: *Potomac Institute for Policy Studies, Arlington, VA* 320 (2004).

[10] *ISA95, Enterprise-Control System Integration*. ISA.

[11] *ISO/IEC 81346-1:2009, Industrial systems, installations and equipment and industrial products Structuring principles and reference designations*. ISO/IEC.

[12] M. Schleipen, R. Drath, and O. Sauer. "The system-independent data exchange format CAEX for supporting an automatic configuration of a production monitoring and control system". In: *ISIE*. June 2008, pp. 1786–1791.

[13] M. Schleipen and M. Okon. "The CAEX tool suite - User assistance for the use of standardized plant engineering data exchange". In: *ETFA*. 2010, pp. 1–7.

[14] *ISO 15926 Industrial automation systems and integration-Integration of life-cycle data for process plants including oil and gas production facilities*. ISO.

[15] *IEC 62424: Representation of process control engineering - Requests in P&I diagrams and data exchange between P&ID tools and PCE-CAE tools*. IEC.

[16] Ray Y Zhong et al. "Intelligent manufacturing in the context of industry 4.0: a review". In: *Engineering* 3.5 (2017), pp. 616–630.

[17] Yan Lu, Katherine C Morris, and Simon Frechette. "Current standards landscape for smart manufacturing systems". In: *National Institute of Standards and Technology, NISTIR* 8107 (2016), p. 39.

[18] SW Lin et al. "The industrial internet of things volume G1: reference architecture". In: *Industrial Internet Consortium* (2017), pp. 10–46.

[19] Serge Bonnaud, Christophe Didier, and Arndt Kohle. "Industry 4.0 and Cognitive Manufacturing - Architecture Patterns, Use Cases and IBM Solutions". In: *IBM* (2019), pp. 1–39.

[20] Peter Adolphs et.al. *Status report: RAMI4.0*. Tech. rep. VDI/VDE-Gesellshact Mess- und Automatisierungstechnik, June 2015.

[21] Peter Adolphs et al. "Reference architecture model industrie 4.0 (rami4. 0)". In: *ZVEI and VDI, Status report* (2015).

[22] Martin Hankel and Bosch Rexroth. "The reference architectural model industrie 4.0 (rami 4.0)". In: *ZVEI, April* (2015).

[23] Mohsen Moghaddam et al. "Reference architectures for smart manufacturing: A critical review". In: *Journal of manufacturing systems* 49 (2018), pp. 215–225.

[24] Oscar Carlsson et al. "Migration of industrial process control systems to service-oriented architectures". In: *International Journal of Computer Integrated Manufacturing* 31.2 (2018), pp. 175–198.

[25] Alexandros Bousdekis et al. "A RAMI 4.0 View of Predictive Maintenance: Software Architecture, Platform and Case Study in Steel Industry". In: *CAiSE*. Springer. 2019, pp. 95–106.

[26] International Electrotechnical Commission et al. "IEC 81346-1, Industrial systems, installations and equipment and industrial products – Structuring principles and reference designations – Part 1: Basic rules". In: *IEC Standard* 81346 (2009).

[27] Dániel Kozma, Pál Varga, and Gábor Soós. "Supporting Digital Production, Product Lifecycle and Supply Chain Management in Industry 4.0 by the Arrowhead Framework-a Survey". In: *IEEE 17th INDIN*. Vol. 7. 2019.

[28] Urgese Gianvito, Acquaviva Andrea, and van Deventer Jan. *Deliverable D2.1 "Procedure model"*. Arrowhead-Tools project, 2019.