Supporting Digital Production, Product Lifecycle and Supply Chain Management in Industry 4.0 by the Arrowhead Framework – a Survey

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***Abstract*—While Industry 4.0 targets are theoretically set from various aspects, the approaches for covering some of its key areas are heterogeneous. The main pillars for Productive4.0 – a European research initiative with the industrial drive – are Digital Production, Product Lifecycle Management and Supply Chain Management. These are also key areas for Industry 4.0, and so far handled with heterogeneous approaches, toolsets – and success, indeed.**

This paper has two aims. First, to provide an overview of the state-of-the-art concepts regarding these three areas, filtered through the actual industrial requirements. Second, to survey the Arrowhead Framework concerning these areas, and suggest a homogeneous approach that can support not only the main vision of these three domains but the actual design-time and operational-time tasks needed to make the vision of Industry 4.0 reality.

***Keywords*—Digital Production, Supply Chain Management, Product Lifecycle Management, Productive 4.0, Industry 4.0**

I. Introduction

The recent technological advancements of communication systems, Cyber-Physical Systems (CPS), and information processing technologies enable to fulfil the requirements of the fourth industrial revolution.

The real-life practice, however, shows, that the complexity of the application domains as well as the multi-stakeholder requirements makes it especially hard even for the specialists working in the same field to discuss concepts (which is an interoperability issue), and get tangible results. Moreover, all three key areas targeted within this paper – Digital Production (DP), Product Lifecycle Management (PLM), and Supply Chain Management (SCM) – contain various engineering domains, which has experts talking in different *terminus technici*. This requires further efforts to get any end-to-end Industry 4.0 process (e.g., DP, PLM, SCM) planned, designed, developed, integrated, configured, deployed, and maintained.

Furthermore, besides the digital twin and digital footprint concepts, non-technical processes need to be taken care of – these are the domains of law and economics. In reality, if we wish to grab full control, the *digital quadruplets* need to be synchronised: the *physical* world, the *cyber* domain, the territories of *law*, and the area of *economics*. There is, however a current concern in the engineering domains. They argue that the obstacles for realising of certain – otherwise useful and morally right – abstract procedures and products are there due to the reasons of capabilities within law and economics domains, rather than physics or engineering. The solution of this challenge urges meaningful cross-domain discussion among the experts of these fields.

Nevertheless, there are still a lot of current issues to clarify within the engineering domains themselves, concerning Industry 4.0. Although the DP, SCM and PLM areas have working solutions at a certain level, these are not *digitised*, *automated*, and the information processing and presenting methods are not *harmonised* in these fields. Among other initiatives, the European project Productive4.0 – with its 108 partners from the industry and academia – aims precisely this. The project is briefly outlined in the next chapter. Chapters III, IV and V provide a homogeneous vision of PLM, SCM, and DP, respectively, based on the state-of-the-art. Chapter VI reveals how the Arrowhead Framework [1] proposes to deal with the primary, burning issues, and Chapter VII concludes the paper.

II. Productive 4.0

Productive 4.0 [2] is a lighthouse research initiative of the EU, which aims at realising Industry 4.0 ideas and technologies to improve the manufacturing related processes, such as design, production and distribution. The full title of the project, ”electronics and ICT as an enabler for the digital industry and optimised supply chain management covering the entire product lifecycle” reveals its main focus areas.

Productive 4.0 deals with theories and solutions that are relevant in the sphere of Industry 4.0 – also known as Digital or Smart Industry. To achieve the Industry 4.0 requirements, the research and development are grouped around three dimensions in an industrial manufacturing point of view: Digital manufacturing, Supply Chain Management and Product Life cycle Management [3]. The defined pillars are influencing and interacting with each other.

The space that is defined by these dimensions on Figure 1 can be considered as a coordinate system where the points accurately determine the current maturity of a product in time.

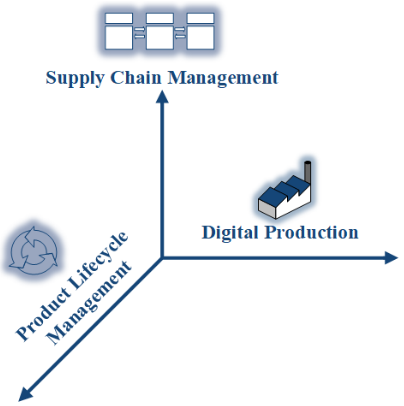

Fig. 1. Main pillars of Productive 4.0

The following sections will present the current needs and models of DP, SCM and PLM.

While this paper does not aim to unfold the various aspects and results of the project, it actually focuses on homogenising the views of these three pillars, and proposing one of the key elements of the project – the Arrowhead Framework – to be used for solving issues in these key areas conceptually, in a homogeneous manner.

III. Product Lifecycle Management 4.0

The effective development of IoT products will trigger several industries and manufacturers to improve their Product Lifecycle Management [4].

Although companies across all industrial fields are ramping up to meet the interest in this growing smart product market; generally, they face significant challenges in developing and manufacturing new and far more complex products. To regularly meet the industrial IoT requirements such as, amongst others real-time operation [1], high security [5], effective deployment and engineering [6], proactive maintenance [7], developers now must consider the capacity to entail connectivity and ubiquitous intelligence.

Current PLM providers are addressing and developing industry-specific IoT strategies and solutions. Throughout the plant layer, PLM suppliers are enabling consumers to help improve the next generation of smart factories. It is useful to architect and develop among others the production systems, their automated workstations and assembly lines. Here is the substance regarding the Industrial Internet of Things: solving not only interoperability, but the effective communication issues between smart products, machines, and systems and gathering as much information as it is possible.

When synthesising the state-of-the-art of the PLM field, there is a product lifecycle model starts emerging. This is depicted by Figure 2.

A. Beginning of Life

The Beginning of Life (BoL) is the starting point in a product's life cycle. It includes the phases from the innovation until the deployment of the product [8].

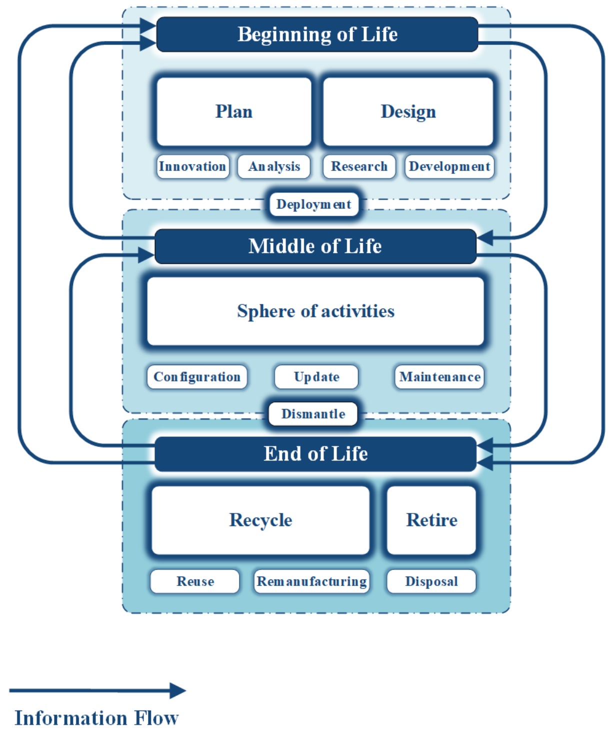

Fig. 2. The suggested perspective for the newly emerging PLM model

1) Plan: This is the initial phase that runs from idea to risk analysis.

- Innovation: This is the "trigger" of the Plan phase. Based on the previous experiences of an existing product or reacting to the ever-changing trends, new ideas are coming from which new products can be born.
- Analysis: There is a need for a forecast about the product. The importance of the phase is to answer, among other questions, e.g. whether the product meets market needs. Another important element is to assess user needs and analyse them.

2) Design: The design follows the planning phase. If the analysis was successful and there is a need for the product it shall be designed.

- Research: First the construction of the product must be clarified. In this phase, the input-requirements and product-specific parameters are defined.
- Development: When the architectural design is finished, the development can start. Under this sub-phase, the hardware and software elements of the product will be created.

B. Middle of Life

After the BoL, the product comes to life, and it will be deployed and integrated depending on the purpose of usage.

1) Sphere Of Activities: Where the device is alive. Probably this is the longest stage, where the product is monitored all the time, and according to the current statement can be configured, updated or even under maintenance.

- Configuration: In this event, the software of the device does not change; only a configuration setting is done. In a smart ecosystem, the devices can have multiple roles, and according to the current work assignment, the device can be configured accordingly.
- Update: Updates make it possible for the device to complete its tasks with a different skill set or improved capabilities. Within the life of most IoT devices, sooner or later, their internal setup will change, for example, a firmware update or some bug fixes required. This can be handled through scheduled or ad-hoc updates. These often enhance and improve the capabilities of the product.
- Maintenance: From the operators point of view, maintenance is also one of the most important processes. Without this, the chance of malfunction increases and it may lead earlier shutdowns than the allotted service lifetime or cause more serious failures in the factory, which also raise unnecessary expenditures.

C. End of Life

After the MoL the product could be dismantled where two scenarios are possible; the device will be recycled or entirely disposed.

1) Recycle: The number of IoT devices is growing at an unprecedented rate. The market offers more and more options; the tools are exchanged more often, which in many cases causes damage considering, e.g. natural aspects. One of the important things is that these tools are properly managed in EoL, i.e. in that case if it is needed they must be completely disposed, or if there is a chance they should be recovered.

- Reuse: After the end of service time, a device may still be usable, but it will be replaced, as there is already another device that is more suited to performing expanding tasks considering current trends. At that time, there is still the opportunity to use the replaced device for a completely different purpose with the necessary software update.
- Remanufacturing: This is similar to reuse but in this case, the software update is not enough, and some hardware improvements are also needed.

2) Retire: : Practically this is the phase from where the device will certainly not get back into the life-circulation. Since this phase is usually the end of a long life cycle, it can provide useful information for the earlier, major life cycle phases.

- Disposal: There can be various reasons behind retiring a device, including a complete replacement – because the device cannot meet the expectations –, or simply the service life has ended. Still, the main reasons for retirement are partial or full damage due to incorrigible failures, inadequate maintenance or ageing.

IV. Supply Chain Management 4.0

Based on the theoretical definition, SCM is an activity that involves key processes from the supplier to the end user, creating valuable products, services or information [9], [10]. Three main groups of the supply chain have been identified on Figure 3: Supplier, Company and Customer.

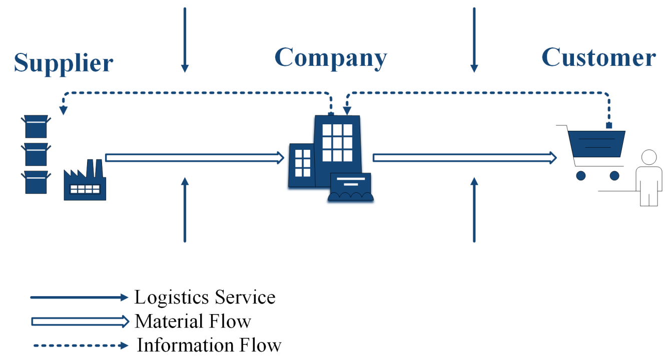

Fig. 3. Basic Supply Chain Model

The terminology of SCM was specified in many ways, and if we are looking at the definitions, it can be concluded that they are organised around collaboration, process integration, cooperation and coordination [11]. Responding to the identified challenges [12], the Arrowhead Framework offers a solution, primarily focusing on production supporting processes. Considering these points and challenges, in our point of view [13], these terminologies can be formulated into three major groups for aiming Industry 4.0 expectations in the SCM: *Collaboration, Combination and Control* (CCC). The main sub-elements of CCC:

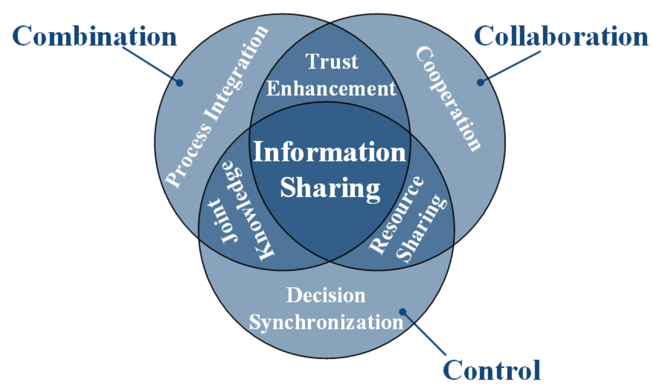

Fig. 4. Supply Chain Management 4.0 framework

- **Process Integration**: It forces the integration of global processes into the production between the participants.
- **Cooperation**: Meaning, that every participant is working to achieve the primary goal together with its benefits.
- **Resource Sharing**: Makes resources available among participants that would otherwise not be available for each other.
- **Decision Synchronisation**: It refers to the decision-making process between participants during the production processes in the aspect of the presented product life cycle stages.

- **Incentive Alignment**: The hidden actions and information can lead to incentive misalignment. The goal of the incentive alignment is to equitably distribute the risks, costs, and results of the business within the chain.
- **Trust Enhancement**: There is no effective collaboration without trust, but trust does not come from one action, so it needs to be continuously enhanced and improved. To reach this, the assurance of safety and security is a must.
- **Information Sharing**: This is the urge for strategic and tactical data to be unconditionally available to the appropriate members of the supply chain. Without this, automated and digital production is not feasible.

V. Digital Production

Through utilising the conceptual elements of Digital Production (DP) [14] the manufacturers can expand their enterprise processes, raise the production efficiency and can minimise resource waste and unnecessary task executions, as well.

Basically, the DP is a set of technologies for reducing product development duration and cost as well as for addressing the need for customisation, increased product quality, and faster response to the market. The procedures of production have accelerated, which means the development and also the deployment becomes faster. Besides, the quality should be increased, and the cost of the whole manufacturing process should be reduced which is a big challenge for the manufacturers – but with DP the following benefits can be achieved [15], i.e. shorter development time, fast feedback during the production, faster react on unexpected events, faster time to market, lower costs, improved quality, enhanced information sharing, fewer errors, flexibility and scalability.

In the DP era, automated and scalable production models, intelligent workflow execution and communication processes can be realised. The support of dynamic and automated production is also a significant field of Industry 4.0, but this is not an entirely solved part so far.

VI. The Arrowhead Framework to fulfil the requirements of Industry 4.0 key domains

A. Requirements

The primary challenge is to support the three dimensions described above from the industrial point of view. The current state-of-the-art is to address these areas by separate models, methodologies and tools. This confinement of the conceptual solutions of DP, PLM and SCM is hopefully a temporal state. This is mostly due to the burden of inter-domain communication issues among the experts of the *digital quadruplets*. This means that mechanical and electrical engineers, computer scientists have to work together with experts of the law and the economics domain in order to provide an optimal path to have a harmonised, converged Industry 4.0 playground – not only in the engineering levels but all the four areas of the digital quadruplets.

Even when staying within the engineering domains, the optimal, homogeneous solution requires a framework that can dynamically automate processes while taking into account various issues, including the

- creation of new System-of-Systems [16],
- integration of brand new as well as legacy elements [17],
- dynamic interoperability between elements [17], [18],
- seamlessly scalable information sharing among participants – even within different stakeholder domains and security levels [19],
- real-time requirements [1],
- reliability and scalability issues [20],
- Quality of Service issues [21],
- status handling of – or even the control over – resources [22], [23],
- ease of engineering processes – in design-time, deployment-time and operational-time [24],
- safety and security issues [25], [19].

B. A brief overview of the main Arrowhead concepts

The Arrowhead Framework [17] has originally come to life to cover interoperability and integration issues for the IIoT world. It supports the collaboration of newly built as well as legacy CPS architectures based on the principles of Service-Oriented Architectures (SOA) through applying the System-of-Systems (SoS) approach. One part of the above listed issues are tackled through the Local Cloud concept [26] empowered by inter-cloud communication capabilities [27] [20]. The Arrowhead Framework defines mandatory core systems for the local clouds, which provide the necessary core systems. Further, supportive core systems provide general services that are often needed in System of Systems, so integrators do not have to implement their solutions for such common services. The Application Systems are distinct elements of the SoS, these provide (and in fact, consume) the various application services – in a discoverable, late-bound, loosely coupled way that is defined by the SOA. Figure 5 describes the current, main systems of the Arrowhead Framework.

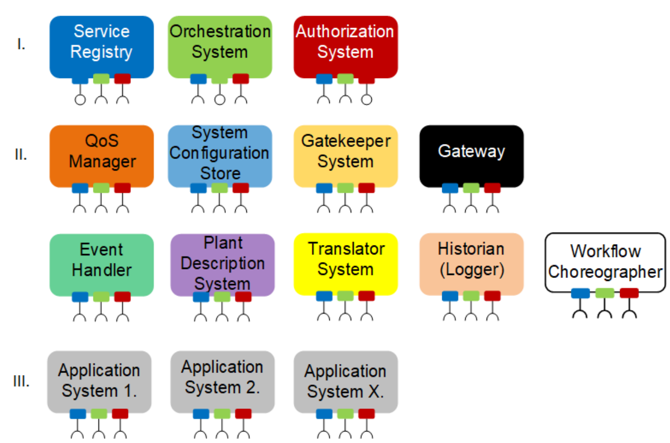

Fig. 5. Core Systems of the Arrowhead Framework

The mandatory core services [28], [29] are Orchestration System (mainly service discovery and late binding), Service Registry (so services providers can announce their active

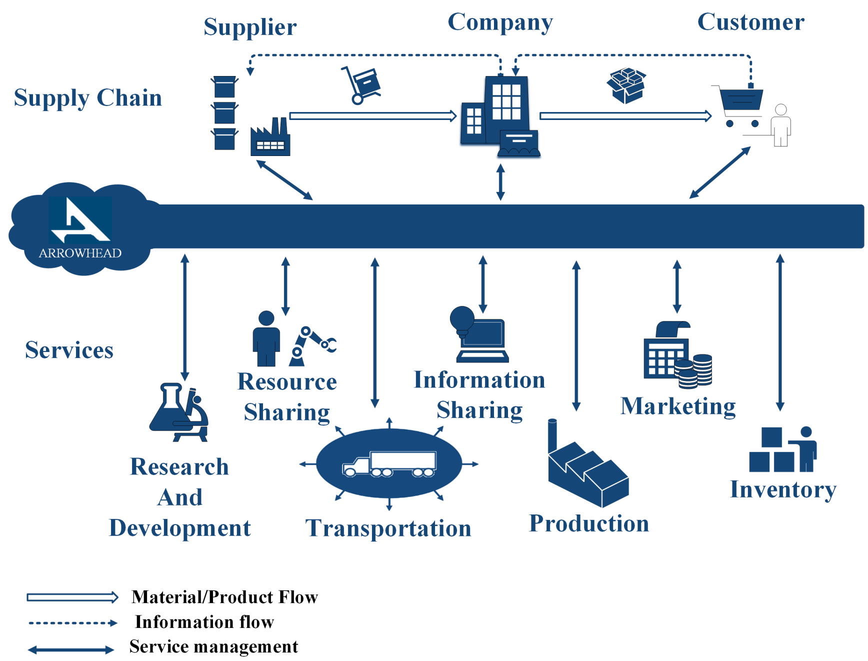

Fig. 6. SCM, PLM and DP managed by Arrowhead Framework

services), and Authorisation System (to provide Authorisation and Authentication). Further, supporting core services are provided by the Gateway [19] and Gatekeeper Systems [20] for inter-cloud communication (data and control plane, respectively), the Workflow Choreographer [30] (to trigger the next step in the process execution), the Event Handler [22] (to circulate status and event information), and the Plant Description System [6] (to keep track of SoS- or Plant-related meta-data), among others. Each stakeholder has their local cloud(s), working as an SoS, their systems implement either intra- or inter-cloud information sharing, as well as security- and other policies.

When taking a closer look at the above-listed requirements, the corresponding citations actually "hide" scientific papers related to Arrowhead Framework. These papers are not only requirement specifications, but original conceptual descriptions, and reports on implemented solutions.

C. The Arrowhead Framework to support DP

Digital Production is hidden in Figure 6 – these can be within the Supplier's premises or the Company's premises. Production is listed as one of the services in the figure (which is true for the SCM hierarchy), although there are many systems on the production floor that exchange services between each other – these could be, e.g., welding, screw-driving, cutting, painting, filling, etc. This infrastructure is by default supported through Arrowhead Framework; various application examples have been demonstrated already [6], [30], [31].

D. The Arrowhead Framework to support SCM

On the top of the Figure 6, the participants of the Supply Chain – Suppliers, Companies and Customers – are shown. They can operate their own Arrowhead Local Clouds, and they can exchange information (as services) among these local clouds by utilising the SOA-based, secure and scalable inter-cloud features of Arrowhead Framework. As a key SCM feature, information flows among the participants. Within their local clouds each participant gets information generated about their physical System-of-Systems (i.e., production floor elements, transportation and inventory systems, etc.), which is then shared among the rightful (i.e., trusted, authorised and subscribed) partner-systems. As Figure 6 shows, the flow of materials is physical; although it is also tracked by their digital (cyber) footprint. Both the tracking and feedback information can be shared among the eligible participants. Although it is not a material-, an energy-supply example for utilising Arrowhead in multi-stakeholder Supply Chains, [32] provides a powerful demonstration on such process-support.

E. The Arrowhead Framework to support PLM

The Arrowhead Framework offers the solution to the identified issues of the current PLM models [33], especially how to connect the main lifecycle stages. The newly emerging product lifecycle model – as shown by Figure 2 – has well-defined elements, which can be interpreted as stages (and phases). Similarly to the digital footprint in DP, digital records of life-stage events can be created and accumulated. Beside their timestamp, these can include meta-data on physical location, environment, configuration, maintenance log, as well as usage statistics. Such meta-data can also be shared with the help of the Arrowhead Framework, as part of Product Lifecycle Management – very similarly as it is done for the other management processes. All sorts of functions, participants and stakeholders can get important, decision-changing information based on these data – including R&D or Marketing departments, and tertiary users (e.g., used-device providers), as well.

VII. Conclusions

In this paper, we surveyed the capabilities of the Arrowhead Framework in relation to some key domains of Industry 4.0. These are the Digital Production, Supply Chain Management, and Product Lifecycle Management.

While the concept of "digital quadruplets" gets a novel introduction within this paper, its issues and solutions are not detailed here – merely the engineering aspects have been tackled, i.e., those related to the digital twins, and the DP, SCM and PLM. Information sharing is a key, central requirement of these domains, although the multi-stakeholder environment requires careful considerations regarding many (listed) aspects, especially security.

In short, the Arrowhead Framework is there to allow dynamic service discovery and loose coupling of service providers and consumers (e.g., information sharing). Furthermore, it is able to support DP, SCM and PLM processes – moreover, it is an enabler for making these processes efficient.

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