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Innovative end-to-end Management of Dynamic Manufacturing Networks

"Innovative end-to-end management of Dynamic Manufacturing Networks"

Deliverable D2.2.4

IMAGINE and IMAGINE Enlarged Platform Architecture, version 4

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Executive Summary

IMAGINE has introduced a novel business model (dynamic manufacturing networks and improved lifecycle support) to meet changing customer demand, provide advanced work environments, and reach new levels of sustainability.

IMAGINE is characterized by the fusion of automation and digitalization, resulting in more efficient integrated production methods, which increase efficiency along the entire production chain. IMAGINE architecture v3 integrates individual customer requirements for global planning and implements those requirements in local production by relying on service and complex event-processing technologies. Dynamic manufacturing networks in IMAGINE architecture v3 place focus on increasing efficiency in all aspects of manufacturing from the use of assets and resources to building agility and robustness into production systems, including supply networks, at global levels.

The incorporation of complex event processing and analytics functionality in the extended version of the i_platform provides the foundations for achieving synergy between execution and analytics applying core data analytics, modelling and simulation activities to manufacturing operations in a network. This results in the ability to seed smart behaviour in manufacturing networks for a better understanding of products, to drive more competitive products and manufacturing networks, optimize production processes, improve quality of the final product and lowering costs.

This deliverable illustrates how architecture v3 can become now a *knowledge enabled manufacturing architecture* enriched with smartness and visibility across the extended manufacturing network such that critical manufacturing operations are intercepted, analysed and executed proactively by applying the best manufacturing practices, information and services coupled with a wide range of performance metrics. The version 4 architecture model provides the ability to structure, categorise and inter-relate knowledge with respect to machinery and production lines and decreases the need for constant human intervention in manufacturing processes.

This deliverable offers architectural guidance and patterns for the analysis and selection of software components that address key concerns in manufacturing networks that exhibit smart functionality. Using the concepts discussed in this report as guidelines, developers and those organizations deploying their manufacturing solutions should have a fuller understanding of distributed manufacturing best practices and, as a result, realize the best value from their product development initiatives and technology investments. It also compares and associates the IMAGINE architecture v4 with current activities such as Industrie 4.0.

The deliverable also illustrates how industry domain-specific nuances and adjustments can be realized more quickly in the generic manufacturing architecture in v3 through a modular approach. It illustrates how to simply enable new variants in the generic manufacturing architecture by creating a manufacturing system that combines the best of two worlds: (i) a standard generic platform and the maintenance, and (ii) extensions and customisation of the standard generic platform with industry specific solutions allowing the best fit to the production process, according to the industry.

The reference architecture v4 in this document provides extendable interfaces with sufficient variation points so that it can address the demands of specific industry domains, such as for instance, engineering, aeronautics or automotive. Interface mechanisms are provided to enable extending and specialising core building blocks of the architecture with compatible functionality, replacing them with other more specialised building blocks or omitting them, if necessary. In addition, the blueprint

attributes and library can also be extended (or overridden) appropriately with additional characteristics to capture specific domain knowledge. To illustrate these points, detailed examples and discussion of specific extensions and specialised architectural support that was necessary for the automotive Living Lab is also presented.

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1 Introduction and Rationale

1.1 The Transition from Dynamic to Smart Manufacturing Networks

The dynamic manufacturing network espoused by IMAGINE allows manufacturing coalitions comprising production systems of geographically dispersed companies to collaborate in an ad-hoc manner in a shared value-chain and conduct joint manufacturing. In this way, a specialist factory can fill excess capacity by collaborating with other such like entities, increasing flexibility and reducing costs, whilst keeping manufacturing local to the products final destination, and also improving quality of product for the end consumer. The dynamic manufacturing network proposed by IMAGINE is an agile manufacturing model that allows for quick and scalable movement in modern manufacturing.

Dynamic manufacturing networks (DMNs) place focus on increasing efficiency in all aspects of manufacturing from the use of assets and resources to building agility and robustness into production systems, including supply networks, at global levels.

The IMAGINE architecture v3 (see deliverable D2.2.3) provided advanced functionality that allows dynamic monitoring of production and product quality. The introduction of complex event processing and analytics functionality in the in the extended version of the i_platform provided the foundations for achieving synergy between execution and analytics applying core data analytics, modelling and simulation activities to manufacturing operations. This results in the ability for DMN managers and product/quality engineers to take decisions based on production data traces. We observed through trials and experimentation at the Living Lab level that this advanced functionality eventually allows DMN managers, product designers, developers, and manufacturing teams to respond quicker to customer needs and possible disruptions in the market place. Therefore, the introduction of analytics in the IMAGINE architecture v3 gave us the opportunity to experiment with and develop a *knowledge enabled manufacturing model* enriched with smartness and visibility across the extended manufacturing network such that critical manufacturing operations are intercepted, analysed and executed proactively by applying the best manufacturing practices, information and services coupled with a wide range of performance metrics. This model provides the ability to structure, categorise and inter-relate knowledge with respect to machinery and production lines and decreases the need for constant human intervention in manufacturing processes.

The event processing and analytics features in the final version of the i_platform when combined with the knowledge-based structures of the blueprint model result in transforming DMNs into *smart manufacturing networks (SMNs).* SMN possesses the ability to adapt to changes - enabling real-time situational awareness - measured by increased responsiveness, agility and robustness. This is very much in line with current European initiatives in the manufacturing field such as Industrie 4.0 that are being driven by a number of leading industrial players and in particular forms one of 10 “Future Projects” identified by the German government as part of the German government’s High-Tech Strategy Action Plan 2020 [1].

In this deliverable we may define *manufacturing smartness* as gaining line of sight, optimizing use of dispersed resources and (human)-expertise, and planning a coordinated response to individual (partner) and collective manufacturing needs and response to changes in a collaborative manufacturing network. This propels the concept of smart manufacturing networks, which is the natural evolution of the original IMAGINE concept of DMN. The introduction of the smartness to the IMAGINE architecture v3 was the product of the advanced functionality achieved by the integration of WP-8 "Enlarged, Intelligent dynamic event monitoring activities" and its combination with the concept of blueprints in the original IMAGINE project.

The fundamental property of an SMN is the ability to gracefully adapt to manufacturing changes measured in real-time by traceability, responsiveness, and reduced margins of error. The manufacturing changes can be incidental such as internal or external disruptions or intentional changes such as product design changes. These changes must be met quickly and efficiently, across the manufacturing network to the shop floor – including outsourced capacity, which must adapt rapidly to change. To be able to adapt to such changes, SMNs should be a highly accessible, reconfigurable, integrated system equipped with knowledge-intensive production management abilities.

In addition to achieving connections between the manufacturing plant floor and the manufacturing supply chain (enterprise business systems, suppliers, and end customers) as was envisaged by IMAGINE architecture v2, the extended functionality achieved through the incorporation of complex event processing and analytics in architecture v3 has helped LLs improve their operational context by incorporating smart manufacturing functionality such as for instance:

- Self-monitoring manufacturing equipment that can report its own health and productivity status and react to changes (via appropriate KPIs) and communicate with maintenance staff requesting remedial action.
- The foundations for flexible and adaptable manufacturing resources that can respond to outages and consumer preferences.

Architecture v4 fills a gap in the manufacturing innovation infrastructure by identifying how novel manufacturing concepts and technologies based on the concept of manufacturing smartness can progress more smoothly from research to implementation in manufacturing and can solve a multitude of challenging manufacturing problems.

Architecture v4 highlights important functionality, advanced features and lessons learned when creating the necessary backdrop for a reference architecture for SMNs based on appropriate improvements and extensions of architecture v3.

1.2 Purpose and Scope of this Deliverable

In this deliverable we shall provide the fourth and final version of the IMAGINE architecture. In particular, this deliverable further refines and improves the third version of the IMAGINE architecture by taking into account adjustments from Living Lab trials and architectural decisions for simplifying release 3 of the i_platform.

The deliverable also illustrates how to seed smart functionality into architecture v3 by exploiting the concept of event-processing, analytics and combining these with the knowledge-structures provided by the powerful blueprint model. As with the third version of the architecture the fourth version is of generic nature but can be extended to cater for living lab specific requirements and needs. However, realizations of the generic platform may differ, depending on specific constraints and operational characteristics of the different living labs. To understand this powerful feature of architecture v4 examples will be given from the automotive Living Lab implementation.

1.3 Structure of the Deliverable

This deliverable is structured as follows. Section 1 provides a broad overview of the characteristics of dynamic manufacturing networks and discusses their transition to smart manufacturing networks, as well as appropriate characteristics that are necessary to support manufacturing smartness. Section-2 describes an innovative reference architecture that supports highly complex and inter-connected smart manufacturing networks. This reference architecture constitutes the basis for IMAGINE architecture v4. Section 3 provides a brief overview of Industrie 4.0 and compares its requirements with architecture v4. Section 4 introduces the reference architecture for smart manufacturing as espoused by IMAGINE and describes its seven architectural pillars. It also presents lessons learned from previous architecture versions and implementation releases for the i_platform. Section-5 presents the characteristics of customised implementations of the IMAGINE reference architecture for the various living labs, and gives examples and details from the automotive Living Lab. Finally, Section 6 presents our summary and conclusions.

2 Reference Architecture for Smart Manufacturing Networks

Innovative architecture and platforms are needed to support highly complex and inter-connected systems in an SMN. A key consideration is how to enable development and application of comprehensive architectural frameworks that provide a sound basis for knowledge-enabled, model-driven analytics functions. Other issues to be considered include what new platforms will be needed to effectively extract actionable information from manufacturing partner systems; and how to provide a robust integration framework to support interoperability concerns, and control/synchronization and data analytics requirements of complex SMNs.

The IMAGINE project addresses issues central to a wide set of manufacturing applications, as made evident from its trials and experimentation in the Living Labs. In a situation like this, to cater for the wide ranging requirements of these diverse applications in differing domains such aeronautics, automotive and furniture construction, the best approach is to design and define a Reference Architecture for multi-partner smart manufacturing networks, which has sufficiently generic structure to address applications in a variety of manufacturing domains. The purpose of this Reference Architecture, which corresponds to architecture v4, is to provide sufficient and clear directions for the implementation of actual frameworks and platforms that will realize multi-partner manufacturing networks for diverse applications, or their future extended versions. Extensions and customisations of this plug-and-play Reference Architecture can then cater for the needs of specific manufacturing domains.

A Manufacturing Reference Architecture (MRA) - or the IMAGINE architecture v4 - is the fundamental organization of a manufacturing system, the relationships between its components and the environment, and the principles governing its design and evolution [2]. The MRA provides product developers with a framework for optimizing their technical resources in support of their business and product development requirements. For example, it assists with how to seed manufacturing lifecycle support, data analytics and monitoring facilities and management of critical events into a manufacturing network. An MRA for IMAGINE is an extensible architecture which reflects all the components and building blocks in IMAGINE architecture v4. Validation and proof of this MRA is based on reference implementations and prototyping, which were part of i_platform release 3 and those conducted in the final version of the i_platform as well as in all deliverables associated with complex vent processing and analytics in WP-8. We shall henceforth refer to the MRA as the IMAGINE architecture v4.

Architecture v4 reflects the building blocks and functionality in IMAGINE. In this architecture, we have established a set of foundational capabilities ("architecture pillars") that address key needs for modern manufacturing as it shifts toward a more agile, knowledge-intensive organizational structure and becomes increasingly aware of partner arrangements and connections in manufacturing ecosystems.

But what should a production-oriented reference architecture look for in a more strategic, business-driven smart service manufacturing network as foreseen by IMAGINE? Based on our experience with IMAGINE architectures v1, v2, v3 and the associated i_platform releases we can surmise that we should seek a reference architecture that incorporates the following seven pillars.

1. Enablement of Human-Interaction and Role-based Insights

2. Support for Connectivity of the Manufacturing Network
3. Production Planning and Resource Integration Mechanisms
4. Support for a Manufacturing Network Lifecycle Management
5. Raising the Level of Manufacturing Abstraction through Knowledge Structures
6. Enablement of Manufacturing "Smartness" by Embedding Manufacturing Analytics
7. Leveraging Open Standards

The above architecture pillars are generic enough in that they provide the foundation for developing a wide variety of manufacturing applications in diverse domains, e.g., aeronautics, automotive manufacturing, etc, which involve multi-partner manufacturing networks. Figure 2.1 shows a schematic of how these architecture pillars are connected to each other. Each of these pillars will be briefly described and associated with previous and current versions of the IMAGINE architecture in section-4.

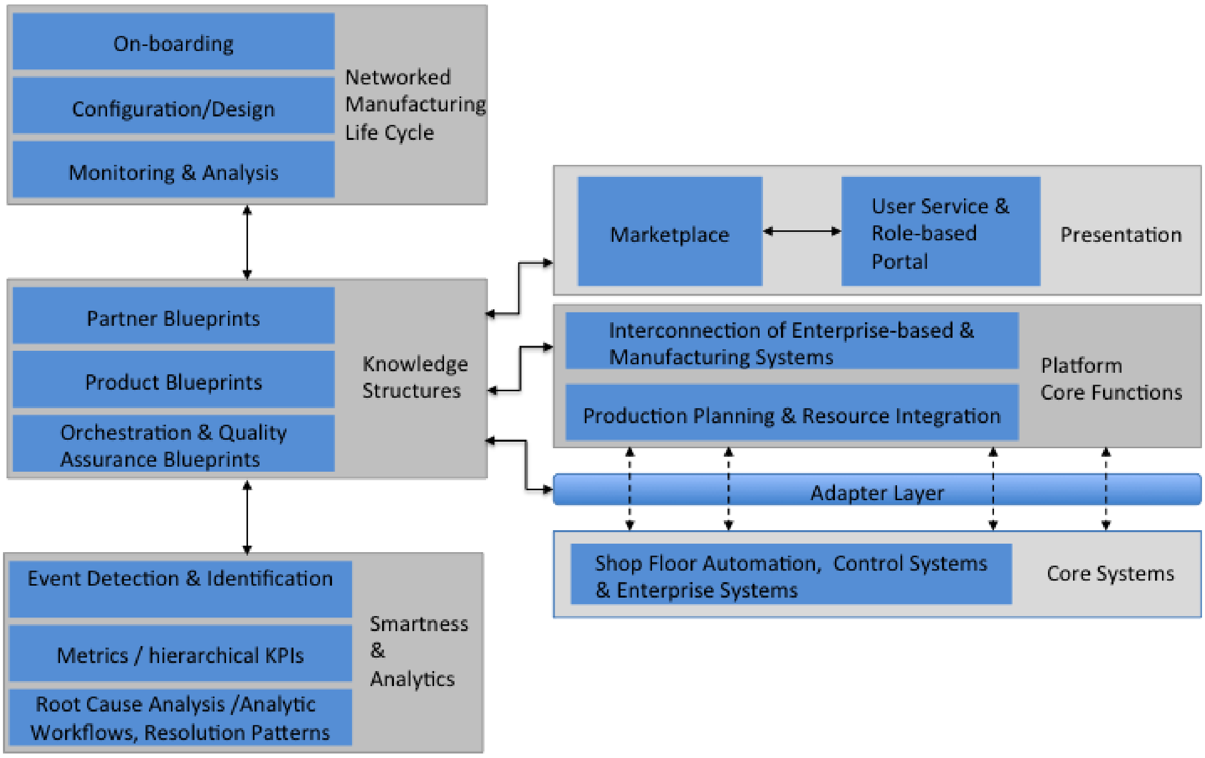

Figure 2-1 High-level view of generic Manufacturing Reference Architecture.

3 Brief Overview of Industrie 4.0

The 21st Century smart manufacturing enterprise will be data driven, knowledge enabled, and model rich. Separate automated manufacturing devices will be connected as part of a complete manufacturing process. These connected machines will operate alongside automated business processes that control materials flow and logistics. Connecting these intelligent factories to computer-aided design will allow the manufacturing flow to be changed as the product design is evolved or new products are introduced. Production flows and logistics might be varied based on demand and products might be customized to match customer specific orders and requests.

3.1 Industrie 4.0

The ideas summarised above constitute the foundations for Industrie 4.0, which is based on the premise that the introduction of the Internet of Things and Services into the manufacturing environment is ushering in a fourth industrial revolution [3]. In the future, businesses will establish global networks that incorporate their machinery, warehousing systems and production facilities in the shape of Cyber-Physical Systems (CPS) [4]. In the manufacturing environment, these Cyber-Physical Systems comprise smart machines, storage systems and production facilities capable of autonomously exchanging information, triggering actions and controlling each other independently. This facilitates fundamental improvements to the industrial processes involved in manufacturing, engineering, material usage and supply chain and life cycle management.

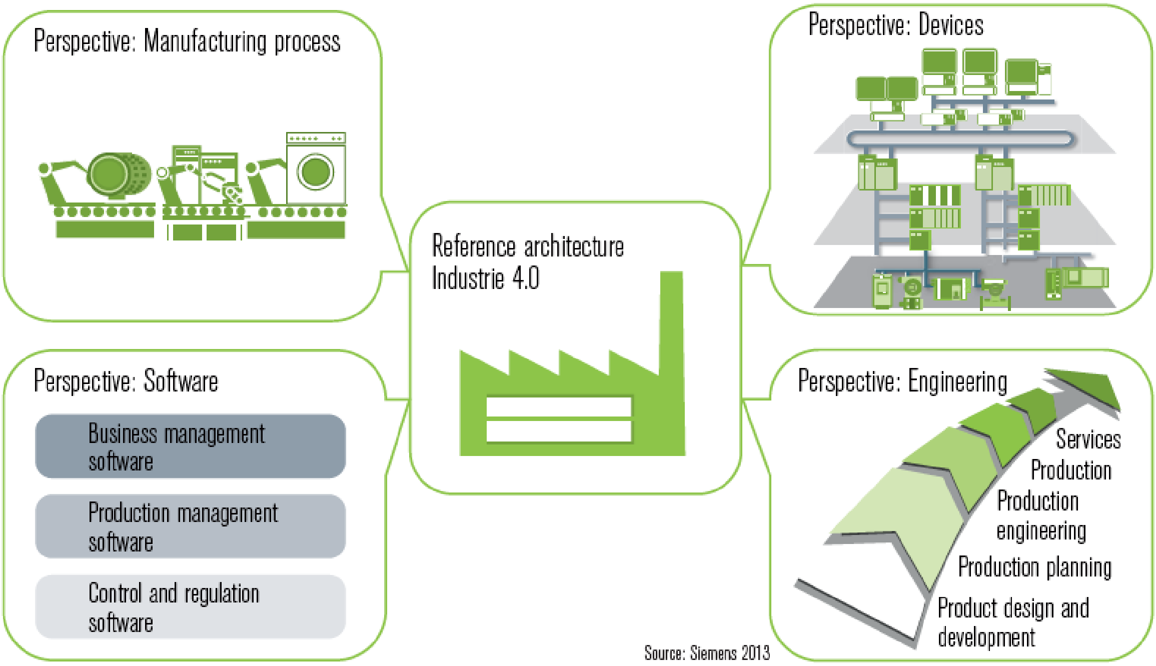

Figure 3-1 Industrie 4.0 reference architecture perspectives.

The functional pillars of Industrie 4.0 are Big Data, Internet of Things, Internet of Services and Data, and Integrated Industries. These four pillars can collapse into three main aspects: Technology, Collaboration and Processes.

In Industrie 4.0 efforts will focus on stipulating the cooperation mechanisms and the information that is to be exchanged in manufacturing set-ups [3]. The complete technical description and implementation of these provisions is referred to as the Industrie 4.0 reference architecture. This reference architecture is a general model that applies to the products and services of all the partner companies in a manufacturing network. It provides a framework for the structuring, development, integration and operation of the technological systems which are relevant to Industrie 4.0.

The sample reference architecture in Figure 3.1 encompasses the following four perspectives:

- The perspective of the manufacturing process in terms of processing and transport functions.
- The perspective of specific networked devices in a manufacturing system, such as (smart) automation devices, field devices, fieldbuses, programmable logic controllers, operating devices, mobile devices, servers, workstations, Web access devices, and so on.
- The perspective of the software applications used by one or more partners in a network, e.g. for business planning and management, inter-company logistics or supporting value networks, including the relevant interfaces and integration with the manufacturing environment.
- The engineering perspective in a manufacturing system (Product Lifecycle Management/PLM). This could involve using data derived from the manufacturing process to plan the necessary resources (in terms of both machinery and human resources) and optimise machines in terms of their mechanical, electrical and automation technology properties, right up to the point where the manufacturing system is set up and brought online, whilst also taking operation and maintenance into account.

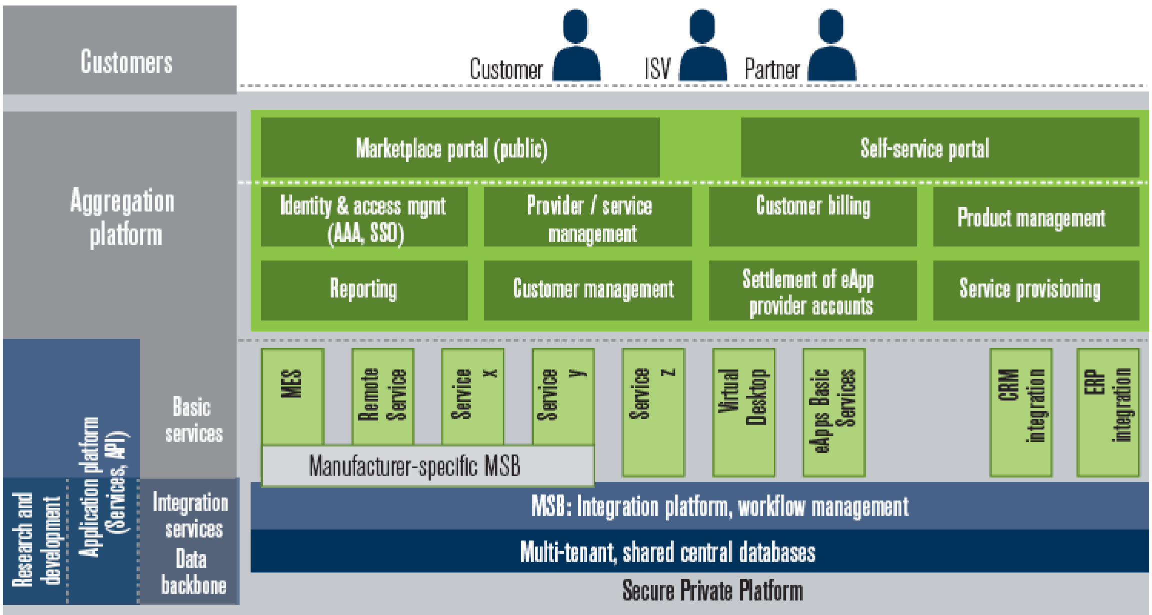

Figure 3-2 Sample reference architecture for a CPS manufacturing platform (source [3]).

Experts usually describe production in an Industrie 4.0 system as a marketplace in which machines offer their services and exchange information with products in real time. This is highlighted in Figure 3.2 which provides the building blocks of a sample manufacturing reference architecture for Cyber-Physical Systems as perceived by Industrie 4.0 [3].

The marketplace portal is an online service for purchasing manufacturing services and applications. The self-service portal is a web-based infrastructure that facilitates access to actionable networked data and services throughout the operation of the manufacturing enterprise. The aggregate platform provides such services as customer billing, product management, customer management, and single sign on. The basic services provide such systems as MES, CRM, and ERP, or integration services for integration of (MES, ERP, CRM) legacy systems, while a Manufacturing Service Bus (MSB) provides an integrated platform and coordination mechanisms for basic services via workflow management capabilities.

The Industrie 4.0 Working Group presented a comprehensive collection of medium- and long-term key priority areas for Industrie 4.0. These include:

- Standardisation and open standards for a reference architecture,
- Managing complex systems,
- Delivering a comprehensive broadband infrastructure,
- Safety and security as critical factors,
- Work organisation and work design,
- Training and continuing professional development,
- Regulatory framework, and
- Resource efficiency.

3.2 Comparison between the IMAGINE Architecture v4 (MRA) and Industrie 4.0

Several of the Industrie 4.0 requirements are in common and met by the IMAGINE reference architecture for Smart Manufacturing Networks reported in this deliverable. Table 3.1 provides a brief summary and comparison of features between IMAGINE architecture v4 and the reference architecture for Industrie 4.0.

It should be noted that Industrie 4.0 requirements are still largely in the phase of specification and amendments are expected, while IMAGINE architecture v4 features have been or are being implemented in the final i_platform for the IMAGINE project. Another major difference is that Industrie 4.0 places major emphasis on machine-to-machine (M2M) communication, which enables network-connected devices to exchange information and initiate actions and RFID signal exchange, while IMAGINE currently places no emphasis on such technologies.

Characteristics	Industrie 4.0	IMAGINE Architecture V4
Independence from manufacturer, sector, communication technology operating system, & programming language.	Industrie 4.0 is technologically sector-neutral, will run on different operating systems and can be implemented in a variety of languages.	Same considerations also apply in the case of IMAGINE.

Characteristics	Industrie 4.0	IMAGINE Architecture V4
End-to-end digital engineering.	Industrie 4.0 will digitize its design and engineering. It requires that the digital models available in computer-aided design or engineering systems be incorporated into a production planning system.	IMAGINE expects that all information from MBOMs and engineering systems is incorporated into product blueprints to drive production planning systems.
Marketplace-enabled infrastructure and operations.	Industrie 4.0 is described as a marketplace in which machines offer their services and exchange information with products in real time.	IMAGINE relies on a approach where manufacturing services, and information relating to products, expertise, partners, standard manufacturing processes and quality information is available from an on-line marketplace.
Top floor–shop floor integration.	Industrie 4.0 employs horizontal integration through value networks and vertically integrated networked manufacturing systems.	IMAGINE supports both horizontal and vertical integration of systems and resources in networked manufacturing systems.
Service-orientated (SOA) plug-and-play and event-based architecture.	Industrie 4.0 service-oriented architectures in the form of a scalable, platform-independent solution which responds to internal and external events with learned behaviour patterns.	IMAGINE also relies heavily on plug and play service-orientated (SOA) architecture and event-based techniques taken from standard event-driven architectures (EDA).
Support for the manufacturing network life-cycle.	No manufacturing network life-cycle support is currently provided.	IMAGINE relies heavily on automated support for the entire manufacturing network life-cycle ranging from planning and design to execution and monitoring.
Support for advanced abstraction mechanism and domain-specific languages for manufacturing.	Industrie 4.0 plans an initiative based on AutomationML with the aim of optimizing interoperability between engineering tools.	The overriding objective of IMAGINE is its reliance on a powerful linguistic environment that models, inter-relates and provides facilities for analysis of all aspects of manufacturing networks.
M2M communication via the "Internet of Things".	The foundation of cyber-physical systems in Industrie 4.0 will be machine-to-machine (M2M) communication, which enables network-connected devices to exchange information and initiate actions without requiring intervention by or assistance from people. Telemetry (aka of machine language) helps remote machines and sensors collect and send data to a	IMAGINE places no emphasis on M2M. However, the blueprint approach as well as event processing and service calls used in IMAGINE could be extended to include M2M communication and telemetry principles.

Characteristics	Industrie 4.0	IMAGINE Architecture V4
	central point for analysis and action by humans, computers, or other machines.	
RFID as the basis for parts tracking and "intelligent products"	Each workpiece in Industrie 4.0 carries an RFID tag containing the individual processing data. Materials to be processed will use RFID to inform machines which work steps have already been carried out and which are still out-standing.	IMAGINE places no emphasis on RFD technology. However, the blueprint approach could be extended to include similar principles to those used in Industrie 4.0.
Enhanced work environments	Industrie 4.0 intends to humanize production lines. Workers will be assigned to coordinate automated production processes and intervene when machines call for action.	IMAGINE includes humans in the loop as part of its monitoring and analytics approach as human-machine interaction involves humans as the partners or supervisors of the machines ("human-in-the-mesh") in a manufacturing network.

Table 3-1 Comparison between Industrie 4.0 and IMAGINE reference architecture.

4 Reference Architecture for Smart Manufacturing Networks

Key properties for effective management of smart manufacturing networks are: enhancing manufacturing network visibility, information sharing, manufacturing process integration and insights for making informed decisions so that the production line does not get hampered and the overall production runs according to plan and does not suffer. Each partner in the network produces one or more product part(s) assembled into final service-enhanced products under the control of joint production schedule, while keeping its own autonomy. Production schedules are monitored and improved collectively to accomplish a shared manufacturing goal.

Objective of the architecture v4 (depicted in Figure 2.1) is to lay the architectural groundwork for developing next generation smart manufacturing processes and equipment (self aware, self diagnosed, adaptive and optimized manufacturing operations), which enable cost effective and agile manufacturing of complex, technology-intensive, innovative, customized products and applications.

4.1 Pillars of the Manufacturing Reference Architecture

As mentioned in section 2, the pillars in architecture v4 provide the foundation and means to develop solutions for smart manufacturing networks. Building blocks can be "assembled" across the pillars and integrated with enterprise assets in a flexible manner to achieve a specific manufacturing solution. Assembling and deploying components on an as needed basis yields a manufacturing solution in less time than traditional approaches and enables a more dynamic and adaptive manufacturing network. In the following we examine the architecture v4 pillars, associate these with IMAGINE implementation releases, and report on implementation experiences and LL trials. We also identify future desirable features for SMNs that can be achieved by incorporating more advanced "smart" functionality.

4.1.1 Enablement of Human-Interaction and Role-Based Insights

Achieving effectively networked, cooperating, and human-interactive systems is an integral factor in the adoption of SMNs. Architecture v4 has characteristics that enable compositionality within dissimilar but connected systems, while also considering the integration of humans into systems with variable levels of autonomy. The i_platform user-centred portal in release 3 supports this feature. Human-machine interaction involves humans as the partners or supervisors of the machines ("human-in-the-mesh") in a manufacturing network. As emergent system behaviour begins to occur, humans will monitor and determine both its positive and negative effects on overall system operation.

The i_platform role-based user-centred portal provides end-users with a single dedicated, personalized point of access to relevant and authoritative information and manufacturing services. It provides personalized access to a variety of information, services and support built specifically for critical manufacturing functions that include production, planning and quality assurance. Personalised access to the i_platform resources is provided on the basis of access rights and business rules precisely defining their role and responsibilities. Doing so, the portal retains access information and acts as a controller were all security/privacy and resource access can be managed, with encapsulation of single-sign-on, and identity management.

To master complexity which was introduced in architecture v1 (see deliverable D2.2.1), the general consent between the Living Lab partners was to reduce the number of actors to four: Market Maker, DMN Manager, Partner and Client. This was accomplished in architecture v2 (see deliverable D2.2.1) where DMN Manager collapses the roles of the Product Engineer, Quality Engineer, Production Planner, Plant/Process Manager into one. The current implementation of release v3 offers currently the four role-based capabilities for human users, which achieve collectively the following functions:

- Provide access to authorized users of manufacturing networks information and services across multiple organizations and a user-friendly role-based portal and makes it easy to find relevant information, partners and manufacturing processes.
- Give authorised users concise analysis and reporting capabilities against consolidated enterprise KPIs.

The role-based portal is depicted in Figure 4.1 where it is associated with the integration framework of architecture v4.

Future extensions of architecture v4 require explicit support for the following roles, which can be assisted by the automated monitoring, analytics and problem resolution tools offered by the current version of the i_platform.

- Product Engineers: These have the responsibility to design products and to apply manufacturing processes that turn raw materials to a new product. They identify and realize measures for product improvement, test optimization and product cost reduction.
- Production Planners: These help determine the sequence and schedule of a SMN's fabrication, assembly, and installation process. The SMN could enable mobile access to important KPIs for shop-floor and labour, inventory and order fulfilment status.
- Production Schedulers: The solution helps the human scheduler examine, resolve and re-schedule options by means of the human-interactive features of the IMAGINE portal for a customer order that has run into material availability issues.
- Quality Engineers: These make sure that products are delivered to the customer in an order–to-promise time with a specific QoS level and notify the appropriate stakeholders in the manufacturing value chain of defects which may lead to containment of errors by providing accurate time estimates which reduce downtime.

4.1.2 Support for Connectivity of the Manufacturing Network

The first tenet for a smarter manufacturing network is connectivity. The discrete systems and resources in a manufacturing network need to be connected so that product information and processes can flow alongside the raw materials. Developers in an SMN need to share information with partners and integrate their systems with external systems to ensure high levels of performance and functionality. Building an infrastructure foundation that is interoperable, contains open source and proprietary information in balance, and operates under common standards provides a starting point.

Architecture v4 provides the framework to integrate with the control and automation and with enterprise level systems, but also with the PLM software portfolio. The architecture offers the flexibility to adjust to the specific requirements of different industrial domains and manufacturing processes.

Connectivity issues were highlighted in architecture v1 (see deliverable D2.2.1) and implemented in release 2 and improved in release 3 by refining the functions of the adapters to external systems. The current implementation provides plug and play components, which can be used successfully to address the advanced requirements of smart manufacturing networks. Architecture v4 functionality provides complete vertical and horizontal integration as explained below and shown in Figure 4.1.

- *Vertical (intra-organization) integration and correlation of information and processes uniting the factory floor with enterprise-based systems and decision makers:* Service-based integration of shop-floor equipment, machines and personnel with enterprise systems, e.g., ERP or CRM, brings many benefits in terms of business automation, response time, and data quality. This is a fertile avenue for inter-linking business processes to achieve business goals, sharing information throughout the manufacturing network and providing a single unified view of product-related data and production processes. Seamless vertical integration of systems automates production control while at the same ensuring high flexibility with regard to order changes, variant combinations, and process modifications.
- *Horizontal (cross-organization) end-to-end integration of information and processes across the entire value chain, emphasizing customer focus:* This type of integration implies seamless communication among dispersed resources spanning network partners and effectively linking product parts and processes throughout manufacturing network partners to deliver a single unified product.

Future extensions of architecture v4 can be used to introduce smart device and Internet of Things functionality to IMAGINE, which is currently missing.

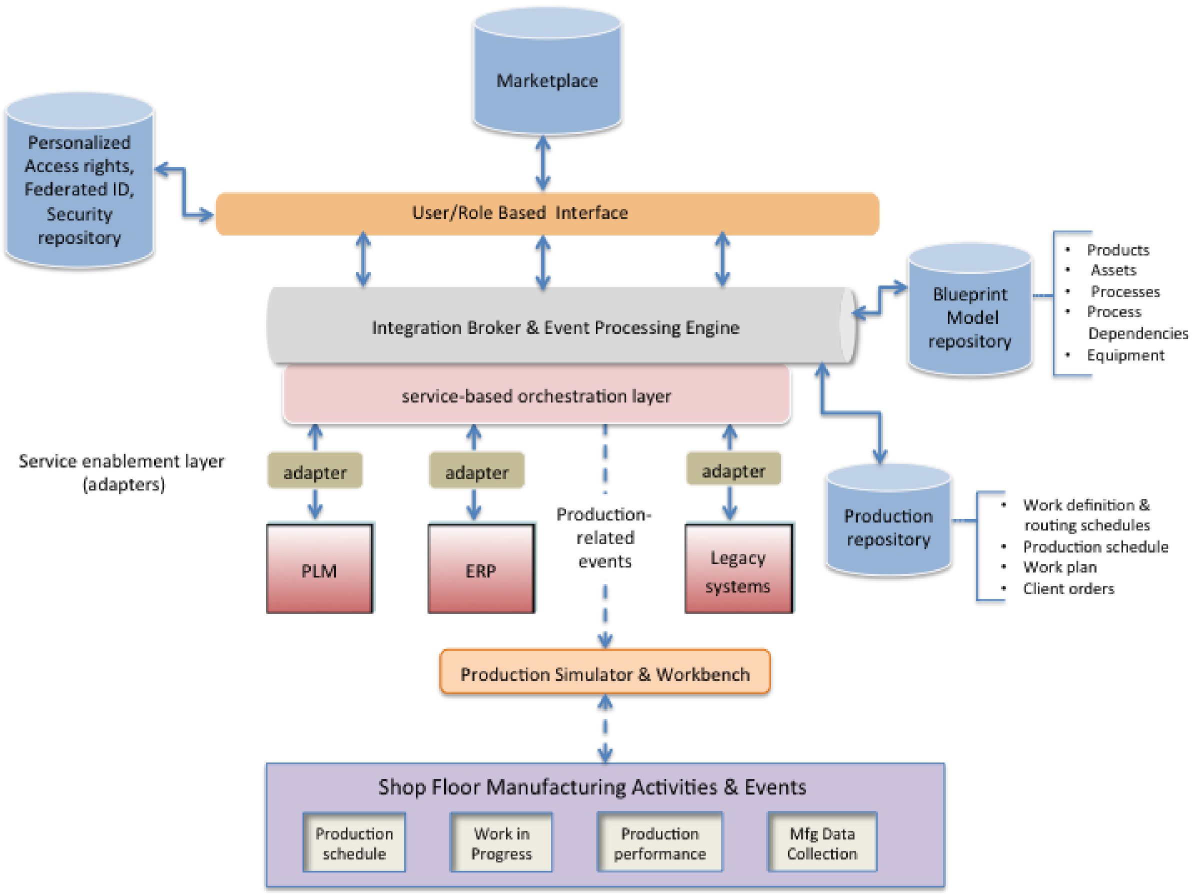

Figure 4-1 The connectivity and the integration framework of architecture v4.

4.1.3 Production Planning and Resource Integration Mechanisms

Production planning encompasses the production and machine schedules across multiple plants or production lines to meet orders or forecasted demand. Architecture v4 focuses on demand-oriented production in terms of a set of interconnected manufacturing resources that address in a coordinated and synchronized manner the manufacture of a particular product or a range of similar products demanded by a customer.

A production schedule is the central control instrument of production and contains information about needs to be produced and when it is going to be produced, such as a production plan. In it the individual steps of production are defined for each production article in the form of work sequences involving resources, humans, and operation-equipment combinations An important aspect of production planning and scheduling is selecting appropriate network partners (suppliers of all sorts) and forming manufacturing networks which can deliver product families based on product routings and available manufacturing resources (including human experts) and equipment required for production. This is depicted in the scheduler module of architecture v4 in Figure 4.2, which was implemented in releases 2 and 3.

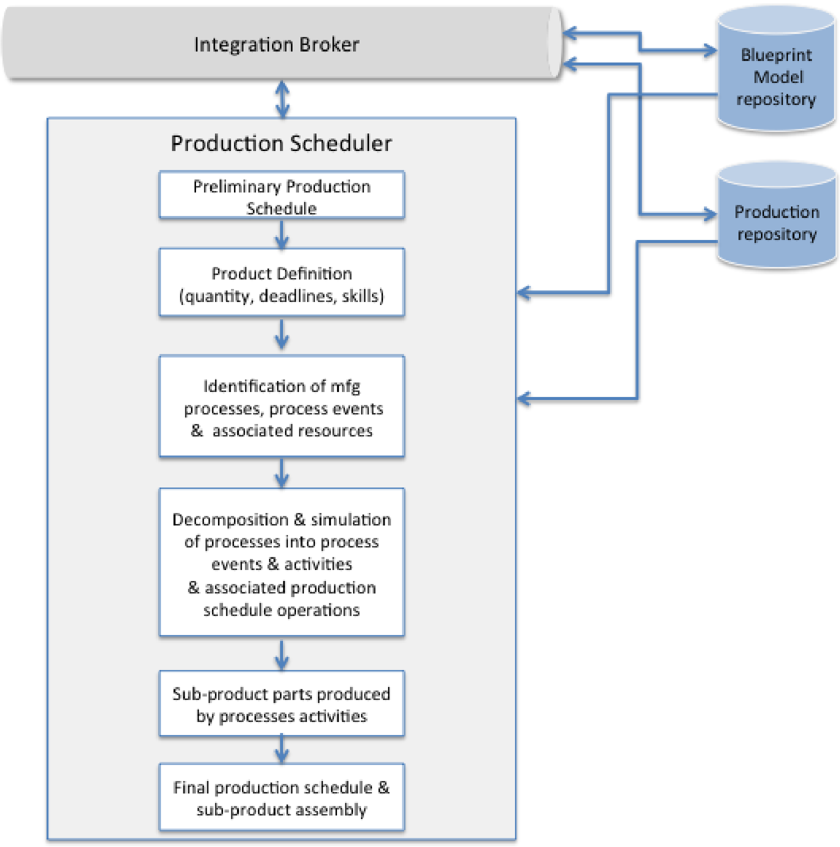

Figure 4-2 The scheduler module of architecture v4.

The scheduling pillar in Figure 4.2 provides the features for conducting decision support for production planning and scheduling across a multiple partners in a manufacturing network by means of a holistic view of manufacturing plans, associated resources and comprehensive demand, supply and capacity key performance indicators. The current version of the i_platform reviews metrics such as production capacity to plan appropriate production schedules, ensure raw material availability and make plant reallocation decisions when appropriate. Basic analysis includes status of plant utilization and trends in demand versus planned production runs.

The scheduling pillar also focuses on managing and controlling all manufacturing resources in a manufacturing network, such as partner equipment, materials and human resources. In this context, production flow-oriented design specifies the technical data mapping of the products (product definition) with the production flows (work plans) and all resources needed for production. In addition, production flow-oriented planning specifies the planning of the production process in the form of production orders (triggered by customers) and planning of required resources. Overall this component projects production schedules, plans material requirements, capacity requirements, and renditions of the final product, which signifies the end of the production course.

The above issues were first highlighted in architecture v1 (see deliverable D2.2.1) improved in architecture v3 (see deliverable D2.2.3) and implemented in releases 2 and 3.

Advanced analysis is necessary for future SMN extensions of architecture v4 by including activities such as hedging analysis on commodities used in production, forecasting of machine output and linear programming to optimize production resources.

4.1.4 Support for a Manufacturing Network Lifecycle Management

The digitization of manufacturing networks and products means that a manufacturing network, just like a product, takes on a full digital existence before it is built. The manufacturing network must also transit through a digital existence before it is put into operation and its operational features must improve if anomalies during the production are detected. An innovative feature of architecture v4 is a manufacturing network life-cycle management approach that improves the ability of the manufacturing network to make better and faster product- and network-related decisions. Architecture v4 constitutes a systematic approach to managing the series of changes a manufacturing network goes through - from its design and development to the fine-tine tuning of its entire operations repertoire. The central element in architecture v4 is an entire manufacturing network and its associated manufacturing processes as opposed to a product - in the case of the PLM lifecycle. The manufacturing lifecycle methodology in architecture v4 exhibits the following phases, which were introduced in architecture v1, v2 and improved in architecture v3:

- On-boarding: This phase involves the registering of partners in a Marketplace, where they can advertise their capabilities, capacity, product/services and availability in the form of partner, product and quality assurance knowledge carrying structures (blueprints) for eventual retrieval by interested parties when seeking to create a manufacturing network dynamically.
- Manufacturing Network Analysis and Configuration: This phase involves the planning of a manufacturing network (i.e. network of those service providers whose composition of manufacturing services delivers the final product) on the basis of a customer request and network available expertise and resources, including equipment, processes and products ensuring increased manufacturing flexibility, optimal manufacturing and market responsiveness.
- Design of Manufacturing Network: The design phase of the manufacturing network concentrates on streamlining manufacturing processes by modelling and mapping process

event flows to reveal optimal manufacturing paths from beginning to end. Analysing and measuring process performance on an end-to-end manner then follows this phase.

- Monitoring of Manufacturing Network: The purpose of this phase is the actual deployment of a manufacturing network and the subsequent monitoring of its execution, e.g., detection of abnormal conditions, machine failures or KPI deviations, and its consistent adaptation to changing consumer demands. Aim is to monitor production processes and either automatically correct or provide decision-support facilities to human specialists for correcting and improving process activities.

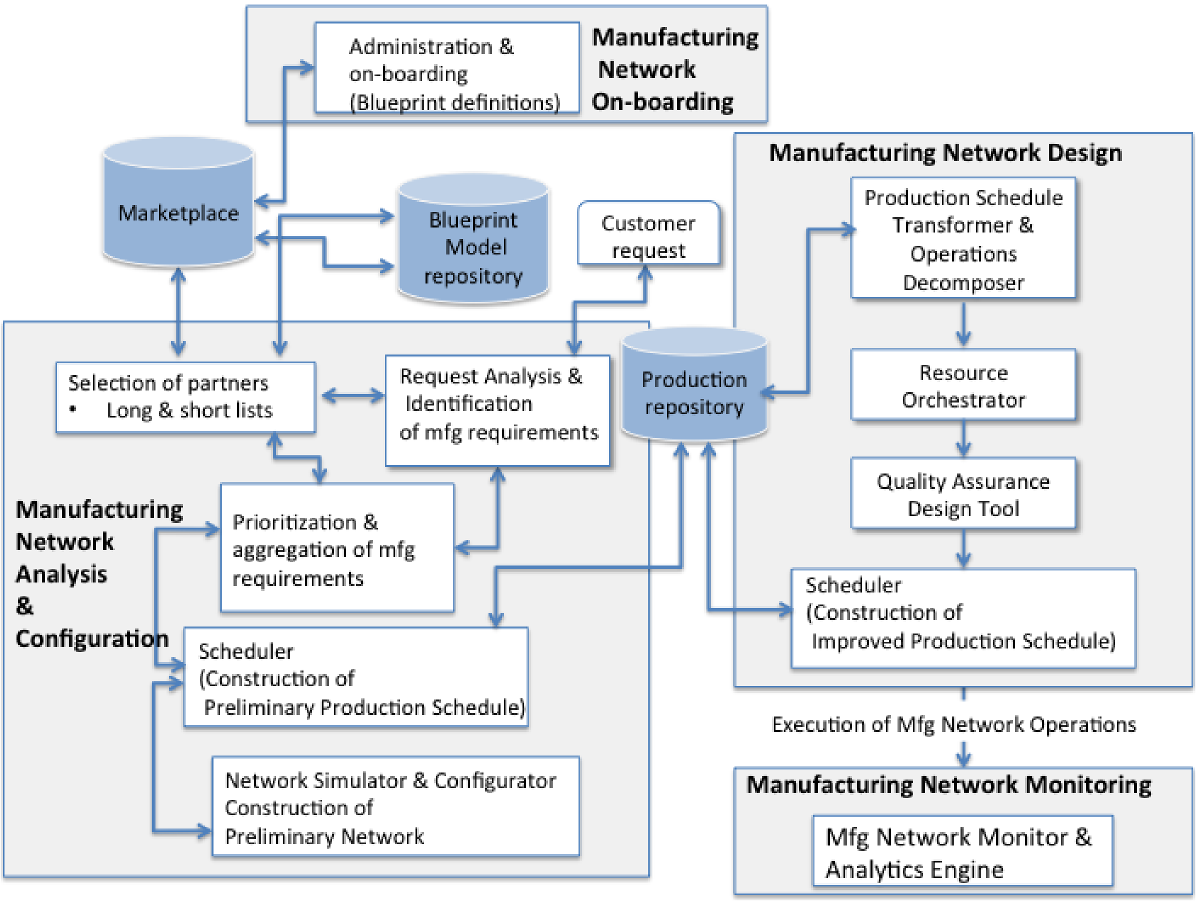

Figure 4-3 Manufacturing lifecycle support in architecture v4.

The modules supporting the manufacturing lifecycle methodology DMNs and eventually for SMNs is depicted in Figure 4.3.

4.1.5 Raising the Level of Manufacturing Abstraction through Knowledge Structures

Aim of the IMAGINE architecture v4 is to establish a unique manufacturing network comprising partners and their resources that can collectively respond to and service customer requests successfully. A fundamental aspect of the IMAGINE architecture is its reliance on Knowledge-intensive structures to integrate the industrial value chain, including aspects of production planning, production engineering, production execution and monitoring which were hitherto implemented separately. This results in improving manufacturing responsiveness by getting more transparency into manufacturing operations, and raising individual productivity through knowledge sharing across organizations involved in a manufacturing network.

Architecture v4 utilizes and associates expressive units of abstractions that encapsulate multiple manufacturing aspects (e.g., functional, behavioural, timing, quality of service, control) to achieve more visibility into and better management of manufacturing assets thereby improving decision making and production efficiency. For instance, production improvements can be introduced if a production can have current information about the status and capability of the deployed resources. Manufacturing knowledge in architecture v4 is packaged into a set of four knowledge-structures known as blueprints:

- The partner blueprint is intended to provide business and technical information to facilitate choosing partners in a manufacturing network by a specific contractor, e.g., an OEM.
- The product blueprint summarises all the attributes necessary for producing a standard or configurable product, such as machines, tools, personnel skills, materials, other equipment, and other entities that are necessary to start and complete manufacturing work. It is used to provide valuable product information for all the Manufacturing Network Lifecycle phases.
- The end-to-end process (renamed orchestration) blueprint ties together the events of discrete processes associated with all aspects of product development while providing the ability to adapt to changing conditions and environments. This blueprint defines how actions are executed and where responsibility is handed off between overall manufacturing functions and individual partner capabilities. This blueprint is used during the design as well as the execution management and monitoring phases of the Manufacturing Network Lifecycle.
- The Quality Assurance blueprint is used to structure data collections as regards metrics for operations analytics and associates these with end-to-end manufacturing processes. It is used mainly in the design and execution management and monitoring phases of the Manufacturing Network Lifecycle. It helps enforce end-to-end process metrics for manufacturing operations and measure and control production status and performance across supply relationships between and within individual partners.

The blueprint environment is illustrated in Figure 4.4. This figure shows that the blueprints distil and encapsulate manufacturing knowledge from diverse sources: partner profiles and capabilities, production repository, request schedules and deadlines, product, equipment and resource descriptions, process and critical manufacturing event descriptions, desired product quality characteristics, and so on.

The blueprint model is a full-fledged manufacturing environment which provides a definition and an operation framework. The definition framework specifies the characteristics of the various blueprints, while the operation framework operates on blueprint definitions to yield interconnected blueprints which provide a concise description of an entire manufacturing network. Blueprints can be *extended and specialised* according to domain-specific needs. Operations such as definition and composition operate on blueprints, which they store in a blueprint repository and eventually in a manufacturing network marketplace – if necessary. Operations like authentication, query/retrieval, publication and so on, operate on blueprints already stored in a marketplace or store blueprint into the marketplace.

The knowledge carried in blueprints when associated with event processing and analytics functionality associated in architecture v3 leads to the introduction of manufacturing smartness which forms the foundation for architecture v4.

The blueprint functionality was originally implemented in release 2 and improved in release 3 by the LL tests and experiments. Blueprints were also integrated with event processing mechanisms and event orchestration properties in deliverable D8.3 (Editor for modelling and management).

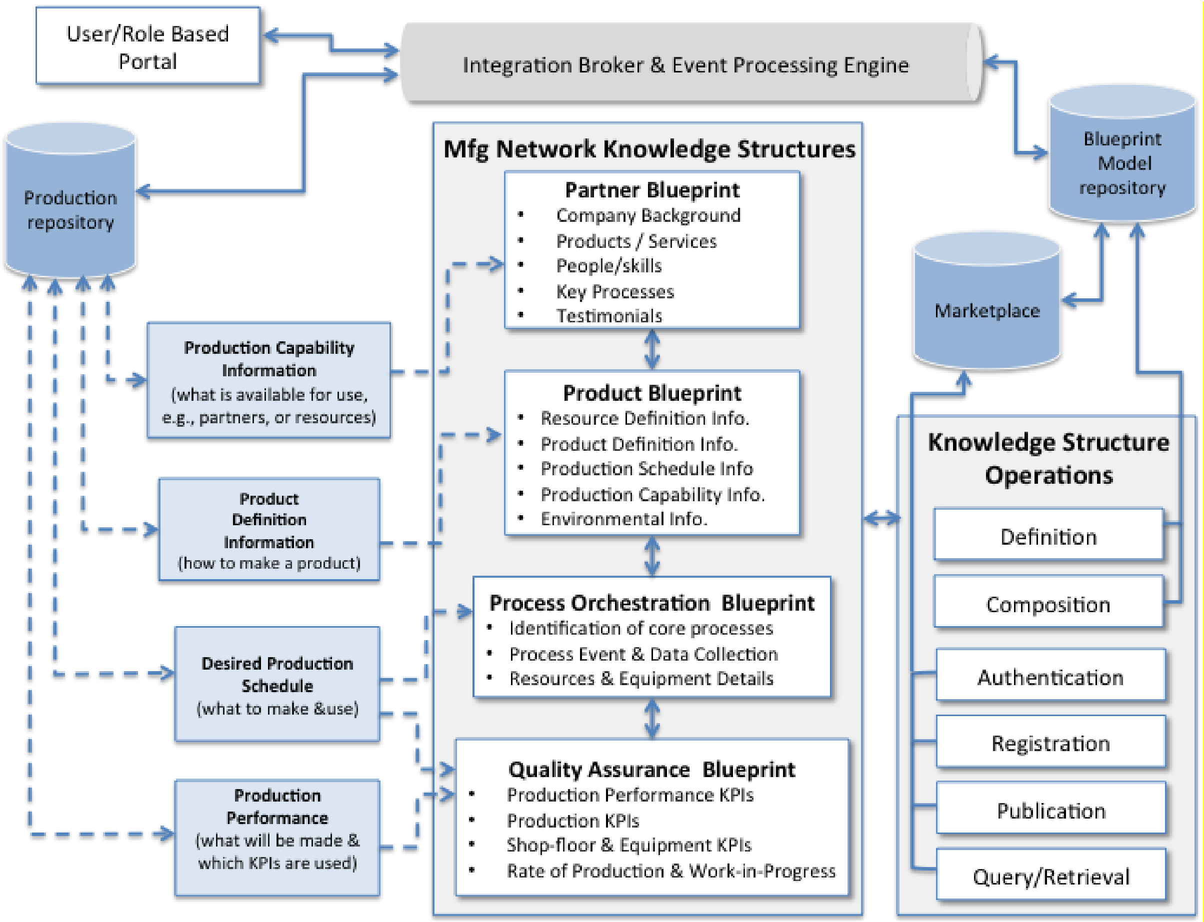

Figure 4-4 The knowledge structures and operations framework in architecture v4.

4.1.6 Enablement of Manufacturing "Smartness" by Embedding Manufacturing Analytics

As explained in the previous subsection, the manufacturing blueprint model is a source of knowledge that makes creative use of manufacturing "intelligence" gathered from every point of the manufacturing network. This knowledge may range from product information and consumer preferences through manufacturing, production and delivery mechanisms and can be used to improve decision-making and product portfolio management thus leading to shrinking development times and better quality for products. When combined with analytics and complex event processing functionality the manufacturing blueprint model acts as a source of smartness for the manufacturing network as it turns data and information to useful knowledge and actionable choices that drive manufacturing operations and yields more informed business decisions.

The purpose of analytics and event processing support module in architecture v4 is to make sense of large sets of heterogeneous data originating from information technology systems, sensors, computerized controls, production management software, and the like, to manage each specific stage or operation of a manufacturing process.

In automated manufacturing, data analytics can help reduce defects and control costs of products. By tracking every detail about every part that goes into a product, from its original manufacturer, to where it was stored, to when it was installed, lets manufacturers retrace problems for better resolution. Monitoring defect ratios and on-time delivery can help with supplier selection and performance assessment.

The production analysis module in Figure 4.5 is an integrated set of manufacturing "intelligence" tools and components which serve as the basis for the IMAGINE architecture v3 and the design of the subsequent platform release. It enables both production line and plant benchmarking, and can help manufacturing network managers to understand where improvement measures might be necessary, and can help streamline and organize production capacity across plants.

The purpose of the production analysis and monitoring module is to monitor all relevant processes and events against the specified KPIs, intercept critical events, analyse root causes, and recommend remedial action. Examples include elements of cost, productivity, quality, energy, environment, and other factors. Objectives are:

- Manage optimised production allocation across the manufacturing network and quickly adjust to changing demand.
- Track production completion, material usage, and quality metrics during execution.
- Gain visibility into work in process, real-time quality, and production notifications.

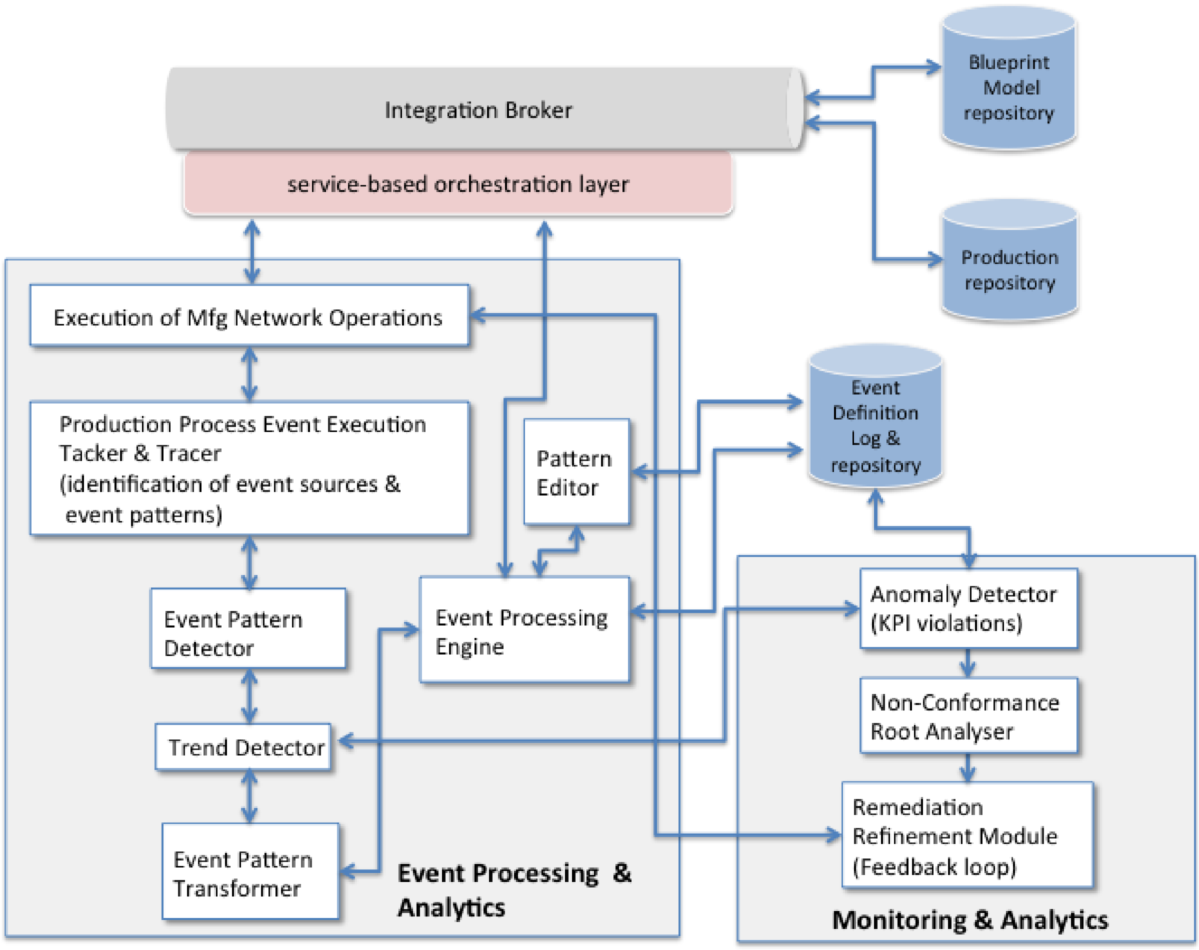

Figure 4-5 Event processing, analytics and monitoring capabilities in architecture v4.

In architecture v3 if an alert is triggered during the monitoring process, a monitoring module forwards all relevant alert data to a trouble-shooting building block, which provides the end-user with the possible alternatives to solve the issue at hand. The production analysis monitoring tool drills down to the specific details of an alert and suggests resolution to a human expert by proposing appropriate actions, such as assigning alternate resources, rescheduling job operations, placing problematic jobs on hold, erroneous material movements, etc.

The event processing, analytics and monitoring capabilities in architecture v4, in Figure 4.5 can - due to their modular structure - be easily extended to include "smarter" characteristics and functionality, such as adapting to external market conditions and changing requirements with little user involvement. It is these features that change the manufacturing system from a deterministic one, where all planning is carried out off-line, to a dynamic one that can determine and reason about processes, plans, and operations.

4.1.7 Leveraging Open Standards

The final pillar in architecture v4 is the use of common manufacturing standards. The standards that can be used in the context of architecture v4 include the following.

4.1.7.1 ISA-95 Standard

SA-95 is the international standard for the integration of enterprise and control systems. ISA-95 consists of models and terminology. These can be used to determine which information, has to be exchanged between systems for sales, finance and logistics and systems for production, maintenance and quality. ISA 95 defines the content and context of the information required for the interfaces between enterprise activities and control activities and also shows activity models and data flows for manufacturing information that enables enterprise-control system integration. This information is structured in UML models, which are the basis for the development of standard interfaces between ERP and MES systems.

4.1.7.2 Product life cycle support standards

Product Life Cycle Support (PLCS) [5] is the domain of ISO STEP AP239. PLCS provides standardized representations for product configurations during various phases of a product lifecycle (e.g., as-designed, as-built, and as-maintained). It has an explicit connection to model-based systems engineering as espoused by IMAGINE with in-service support requirements, and related resources such as maintenance plans, schedules, job cards, and work request/orders. In fact, recent versions of PLCS are defined using UML/SysML.

4.1.7.3 Exchange of product model data standards

The ISO 10303 STEP standard, which stands for "Standard for the Exchange of Product model data", is used to manage technical product data and serves as a foundation to define the data exchanges as regards the product blueprint. Since this standard is widely accepted by a large number of industries, reusing its constructs is beneficiary for interoperability purposes. Thus, by using STEP, it is easier to assess partners and see whether they respond to the preconditions and constraints set up by this blueprint.

The STEP standard contains several dozen separate documents. The purpose of STEP is to specify a form for the representation and unambiguous exchange of computer-interpretable product information throughout the life of a product. It also includes the related elements involved in the development of the product such as resources. STEP provides both broadly useful data modelling methods and data models focuses on specific industrial uses.

4.1.7.4 ISO 18435: Diagnostic, Capability Assessment, and Maintenance Applications Integration

ISO 18435 provides diagnostics and maintenance related activities which offer effective mechanisms for adapting maintenance strategies to various changes in manufacturing operations, such as changes in production requirements, changes in operational conditions and environment, and changes to continuously improve manufacturing assets during their lifecycle. For example, activities deal with the operational phase of maintenance task execution, which consists of maintenance task planning, involving asset inspection, monitoring and diagnostics, followed by treatment or repair if needed, and ends in the evaluation of maintenance results. These activities are mainly concerned with controlling routine maintenance tasks.

ISO 18435 also provides a combination of activities that focus on maintenance strategy planning that involves the selection of an approach for performing maintenance appropriate to each asset with options such as breakdown maintenance (BM), time-based maintenance (TBM) and condition-based maintenance (CBM) [6]. The maintenance strategies can be improved based on diagnostic capability assessment and maintenance histories.

5 Customised Implementations of the Reference Architecture

The architecture v4 depicted in Figure 2.1 is a standard architecture and associated manufacturing platform that manages the behaviour of generic manufacturing functions. By completing this platform with industry specific libraries, it is possible to create a system that combines the best of two worlds: (i) a standard generic platform and the maintenance, and (ii) extensions and customisation of the standard generic platform with industry specific solutions allowing the best fit to the production process, according to the industry.

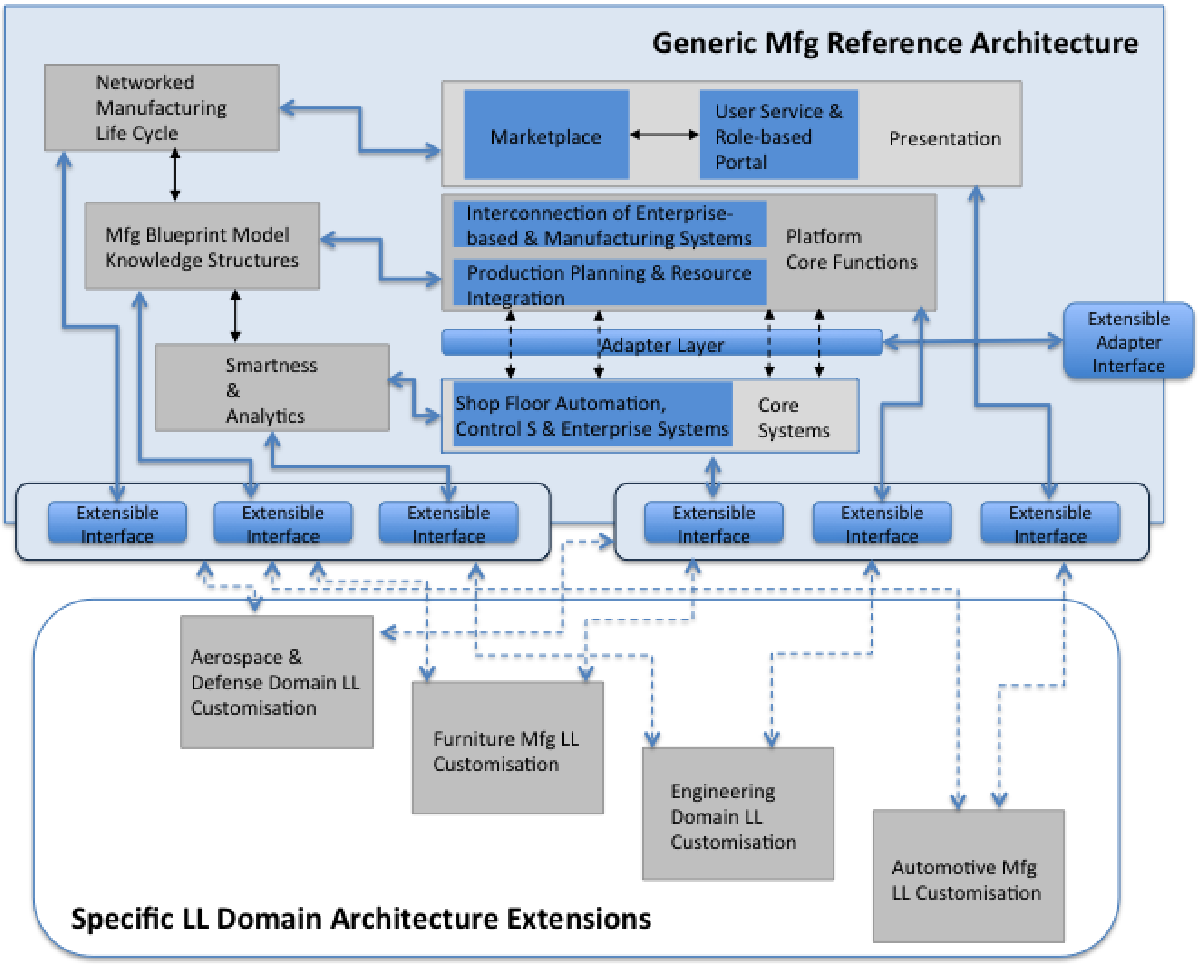

Figure 5-1 IMAGINE generic architecture and customisations.

The generic architecture v4 is based on the principle of openness to enable interchange-ability and internetworking between the components in a manufacturing network. The generic architecture v4 provides the architectural flexibility needed to meet specific domain characteristics or changing business requirements of modern manufacturing organisations. To cater for this important aspect, the architecture provides extendable interfaces with sufficient variation points so that it can address the demands of specific industry domains, such as for instance, engineering, aeronautics or automotive. Interface mechanisms are provided to enable extending and specialising core building blocks of the architecture with compatible functionality, replacing them with other more specialised building blocks or omitting them, if necessary. In addition, the blueprint attributes and library can also be extended (or overridden) appropriately with additional characteristics to capture specific domain knowledge. This is shown in Figure 5.1.

The architecture in Figure 5.1 has been created taking into account the generic architecture v3 as well as the architectural design principles, lifecycle phases, dedicated services and extensions for dynamic network management in Living Labs implementations (as described in the Living Lab Deliverable D4.1 Version 2) in order to be able to manage DMN collaboration all along the life cycle of manufacturing networks. Specific collaboration and interoperability requirements such as for instance, support for a secure environment, is not addressed by all LLs but is rather handled by the customization of specific LL platform variants – in this case of the aerospace and defence LL.

In this deliverable we shall present detailed examples and discuss specific extensions and specialised architectural support that was necessary for the automotive Living Lab. A similar approach was followed by all other LLs.

5.1 Automotive Domain Manufacturing Network

The automotive LL customisation of the generic IMAGINE architecture and i_platform delivers methods and protocols for unifying discipline-specific engineering information and integrating it with the generic building blocks and functionality found in architecture v4, which is depicted in Figure 2.1. The specific LL extensions and customisations of the generic architecture v4 are shown in Figure 5.2.

The Automotive living lab system customisation of the generic architecture is shown in Figure 5.2 to include three macro-components: the IMAGINE generic platform, hosted onto Reply's public cloud system, the Plant Simulation subsystem, housed inside the FIAT network together with the Tecnomatix-side AutoLL agent which is responsible of interfacing Tecnomatix with the third component, the Automotive living lab integration layer.

Identifying and dealing automatically with complex situations, devising and implementing recovery strategies have been the target of this LLs evaluation and experimentation with i_platform release 3 and now are candidates for further development and coupling with internal projects that are part of vehicle development.

5.1.1 Automotive Domain Customisation and Extensions of the i_Platform

For all automotive LL use cases and scenarios in the automotive domain which display disruptions in the automotive supply chain (see deliverable D4.4 v2), the IMAGINE Platform release 3 needs to interoperate automotive specific legacy systems. In particular, most of order-, product-, and partner data in the Blueprint repository require synchronization with the Tecnomatix Plant Simulation system, applying a poll-and-response web service method to retrieve such data.

The Automotive living lab integration layer integrates the needed IMAGINE functionalities with the Tecnomatix simulation tool via the provided web services and interfaces. In particular, it uses the following IMAGINE components:

- IMAGINE Blueprint Repository: every partner involved in the production chain is inserted in the Blueprint Repository so that the IMAGINE platform is aware of the available partners for the DMN;
- IMAGINE Partner Search Component: this component is used during the Reconfiguration Phase to retrieve the partners that respond to the new requirements and production

problems. For this reason this component is essential for the purposes of the Automotive Living Lab.

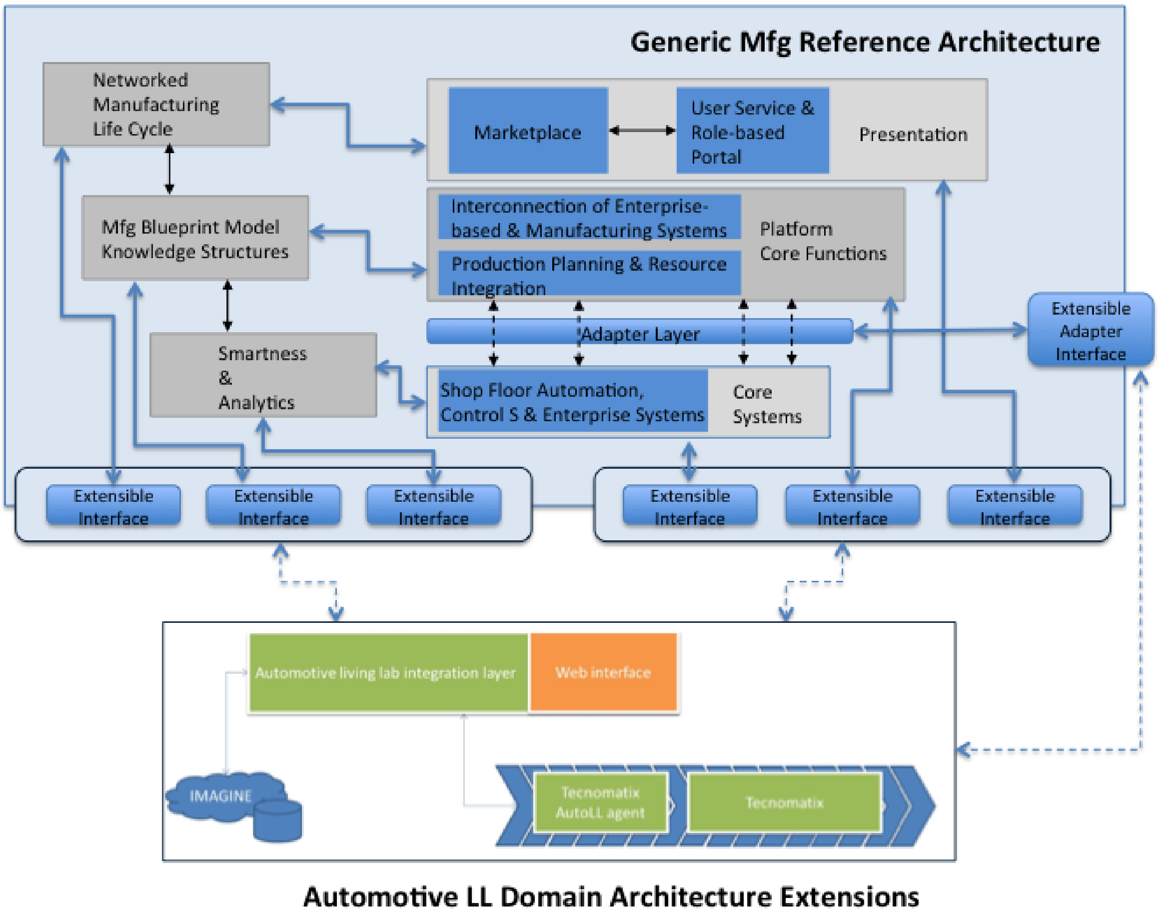

Figure 5-2 High-level of automotive customisation points.

During the implementation of the i_platform for the Automotive LL, most of partners and product data have been found in legacy system such as ERP and MRP. Those data derive from the real situation that almost all suppliers require a pre-certification phase from FIAT in order to be inserted in the suppliers' list. This phase includes the registration of each potential partner, his product range and the associated quality levels, and his capabilities to provide quantities and respect timings to satisfy the just-in-time production process in FIAT.

Most of those data are relevant for the creation and re-configuration of the DMN: having those data inserted manually into the i_platform would be a less-realistic scenario as duplication issues arise.

Therefore, for each system involved as external data source, an external application stub has been designed, with a web service-based interface toward the i_platform and able to stimulate it. Those application stubs allow showing the interactions among i_platform and legacy systems without impacting on running production IT systems.

5.1.2 Simulation & Forecasting Methods & Tools

The smart manufacturing vision incorporates modelling and simulation into the actual operation of the manufacturing process. Here, key elements in smart manufacturing are model-based techniques, simulation, and smart tools to manage information [7].

In the automotive LL, the DMN (supply chain and production lines) is simulated using a supply chain/ plant simulator. The tool selected for the Automotive LL is Siemens Tecnomatix Plant Simulation, a standard in the FIAT Group. For the IMAGINE Living Lab this simulation tool is used to perform live simulations of the production site and its main interactions with inbound and outbound warehouses and will be used to provide and showcase the data flow between production sites and the IMAGINE platform. Finally, it will help validate the rationale and functioning of the IMAGINE platform itself.

The Tecnomatix Plant Simulation software tool enables the simulation and optimisation of automotive production chains and processes. It can optimise material flow, resource utilization and logistics for all levels of plant planning from global production facilities, through local plants, to specific lines. Plant Simulation enables manufacturing network developers and mangers to create well-structured, hierarchical models of production facilities, lines and processes. Plant Simulation models are used to optimize throughput, relieve bottlenecks and minimize work-in-process. The simulation models take into consideration internal and external supply chains, production resources and business processes, allowing manufacturing network developers and managers to analyse the impact of different production variations.

Statistical analysis, graphs and charts display the utilization of buffers, machines and personnel and support dynamic analysis of performance parameters including line workload, breakdowns, idle and repair time and proprietary key performance factors. The Tecnomatix Plant Simulation software tool provides decision criteria to help manufacturing network managers evaluate and compare alternative approaches regarding new, sustainable production facilities, and global production networks.

The Tecnomatix-side AutoLL software agent in Figure 5.2 is responsible for interfacing Tecnomatix, responsible of replicating the real-life of a DMN, with the IMAGINE platform through the Automotive Living Lab integration layer. This manages the communication between these two sub-systems and the lifecycle (start/restart/stop) of the Tecnomatix system.

In the simulation models, the occurrence of disruptive events is modelled as a probability inside each element of the model, based on the historical data on failures. It enables to generate events related to a single object, such as supplier interruptions, transportation issues or to a group of objects (e.g. earthquake).

5.1.3 Monitoring Tools for the Automotive Domain Manufacturing Network

The Monitoring module in the i_platform is based on NAGIOS open source network monitoring tool. The approach underlining the i_platform is that the manufacturing network is nothing different from a network itself, so a standard, star-shaped monitoring system architecture as those implemented in closed manufacturing systems would be less than adequate to support.

The monitoring tool applies to a network topology where each node has to be monitored independently against a set of performance metrics and their thresholds. The tools must also provide a way to "navigate" into nodes as drilling down from high-level to down-level topologies, and reveal the metrics associated to the underlying parameters.

NAGIOS and its implementation in i_platform allow using both synchronous and asynchronous (event triggered) data sources, which are particularly effective in dealing with messages from the simulated shopfloor.

The distributed monitoring has been implemented by using software probes running on the simulators' hardware which have been customized to control the output of the Technomatix simulator, generally a text file. The probes have been also hosted on an Intel Next Unit of Computing (NUC) hardware platform to evaluate the speed of deployment by a third party partner.

The monitoring has been realized over the internet to simulate a loosely coupled "as a service" deployment methodology, where the i_platform is hosted and managed on a cloud-based computing infrastructure by a service provider, while the monitoring messages flow back and forth from the production plants and third-party suppliers.

The deployment has posed a few challenges in dealing with the CRF production and administrative networks, which are sitting below a set of firewalls protecting the external access. The challenges have been overcome thanks to a tunnelling software applied on the hosting the system which probes and restricts the network ports to the minimum in order to decrease the risk of breakages.

5.1.4 Interoperability Concerns in the Automotive Domain Manufacturing Network

This layer is responsible for handling the communication between IMAGINE and Tecnomatix, the errors occurred during the supply chain, the DMN reconfiguration and the communications to the DMN manager. The integration module manages the communication between IMAGINE and the supply chain. It interprets the output files of the supply chain, manages the production errors, updates the manufacturing network state in IMAGINE and alerts the manufacturing network manager in case of problems.

Since the IMAGINE platform and portal is based on web services, the Automotive LL has continued in this direction by developing new interfaces and functionalities with an SOA-oriented philosophy and with open source technologies (Java, Spring framework). The integration layer exposes the REST services needed by the Tecnomatix-side AutoLL for the communication tasks.

6 Summary and Conclusions

In manufacturing networks, manufacturing parties, operating globally, expect to be able to source their products and manufacturing systems whenever the need arises irrespectively of where these may be. In order to ensure this global usability and cross-system consistency, new technologies and new requirements, such as, increased connectivity, automated lifecycle management, and supporting knowledge-enabled analytics functions, are regarded as especially important and pursued as a matter of priority.

In response to the above requirements, IMAGINE has developed the concept of dynamic manufacturing networks which places focus on increasing efficiency in all aspects of manufacturing from the use of assets and resources to building agility and robustness into production systems, including supply networks, at global levels.

In this deliverable we focused our attention on aspects of complex event processing and analytics functionality which we introduced in the in the extended version of the i_platform. These serve as the foundations for the IMAGINE architecture v4. We observed that complex event processing and analytics provides the means for achieving synergy between execution and analytics applying core data analytics, modelling and simulation activities to manufacturing operations. It also leads to the ability to improve decisions and adapt to changes enabling flexible manufacturing, optimal production rates, and faster product customisation. This advanced functionality leads to the transformation of dynamic manufacturing systems to smart manufacturing systems.

Smart manufacturing combines technology, knowledge, information, and human ingenuity to develop and apply manufacturing intelligence to every aspect of business [8]. It has the potential to fundamentally change how products are invented, manufactured, delivered and sold.

In this deliverable we critically assessed the functionality of the first three versions of the IMAGINE architecture on the basis of implementations, lessons learned made evident from its trials and experimentation in the context of Living Labs and smart functionality obtained on the basis of event management and analytics processing. We then stipulated seven pillars of the IMAGINE architecture v4 that have the potential to serve as foundations for introducing smart functionality in the IMAGINE architecture and as the basis for developing a multitude of novel manufacturing applications.

Relying on the use of manufacturing knowledge and an advanced linguistic framework (viz. the manufacturing blueprints) coupled with tool support IMAGINE has the ability to exhibit manufacturing smartness manifested in the ability to connect factory-specific processes and information to data and KPIs throughout the supply chain — from raw material availability and customer demand through the delivery of finished goods. This enables greater product customisation, new product simulations and new, more efficient processes and supports the production of precisely defined products, and faster product tracking.

IMAGINE architecture v4 provides concrete architectural guidelines to help developers have a fuller understanding of distributed manufacturing best practices, deploy the best manufacturing solutions and, as a result, realize the best value from their product development initiatives and technology investments.

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