Proposed Enterprise Architecture solutions for Industry 4.0 Manufacturing simulation information assets based on TOGAF

for

ICT-4010-02 Enterprise Architecture course, Summer 2016

Cole Rogers

University of Denver University College

07 August 2016

Instructor: Dr. Steven Else

1 Executive Summary

'The vision of Industry 4.0 is significantly higher productivity, efficiency, and self-managing production processes where people, machines, equipment, logistics systems, and work-in-process components communicate and cooperate with each other directly' (Lydon 2016). Succinctly, Industry 4.0 is a vision of future manufacturing environments with a wide-spread adoption and extreme integration of modern Information Technology systems. It is a strategic vision of future manufacturing organizations based on advanced Information Technology. It is also a vision that can strongly benefit from the principles of Enterprise Architecture that enable organizations to *'achieve the right balance between IT efficiency and business innovation'* (The Open Group 2011).

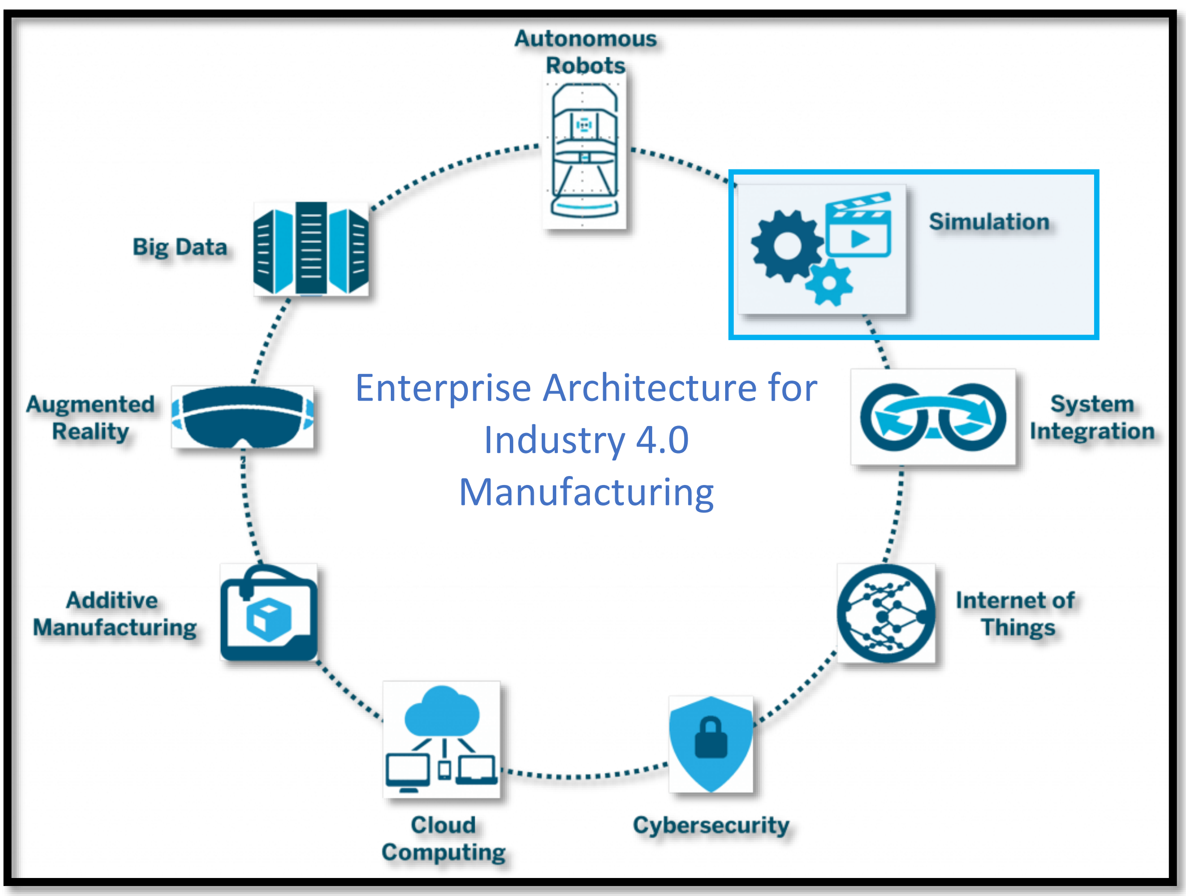
This paper was written to inform Business and IT Executives of the potential enterprise-wide value of Industry 4.0 simulation-based information assets. Combined together, Industry 4.0 and Enterprise Architecture concepts can provide a basis for manufacturing organizations to realize high returns on simulation based knowledge and information. Industry 4.0 provides the strategic technological vision. While Enterprise Architecture, and its associated systems of governance, provide a proven, disciplined, organizing logic for achieving this vision. This paper describes the combination of these concepts and presents a draft proposal to maximize the enterprise-wide value of Industry 4.0 simulation-based information assets. The proposal is based on formal Enterprise Architecture principles strongly influenced by TOGAF, The Open Group Architectural Framework (The Open Group 2011).

Table of Contents

2 Introduction to Industry 4.0 simulation based information assets

The concept of *Industry 4.0 Manufacturing* (I4M) can be described as a convergence of multiple technologies that have the potential to revolutionize the manufacturing industry. These technologies will enable machine-to-machine communication, mass customization, cost effective single batch processing, and both self-assembling & self-aware production systems. Perhaps the most direct definition of Industry 4.0 is offered by the German Federal Ministry for Economic Affairs and Energy (BMWi): *'Industrie 4.0 combines production methods with state-of-the-art information and communication technology'* (BMWi 2016).

Figure 1 – The Facets of Industry 4.0 Manufacturing and its Enterprise Architecture Core



The underlying high level information system technologies that are leading to I4M possibilities include: reliable industrial wireless networks, Internet of Things protocols, additive manufacturing, advanced robotics, big data analytics, and increasingly accurate computational simulations of manufacturing processes using high performance computing clusters. These technologies, and several others, are shown as the facets of I4M in Figure 1. It is important to note that the concept of I4M will enable these various facets to strongly interact with each other through advanced IT. The resulting I4M system can be thought of as a cyber-physical system (Schmidt, et al. June 24 - 26, 2015) (Mosterman and Zander February 2016) (Lasi, et al. August 2014).

As indicated in Figure 1, one primary aspect of the I4M vision is the emergence, and increased importance, of simulation technologies. The core idea of I4M simulation based information assets is that computational simulations of manufacturing processes may provide potential benefits to a diverse group of internal and external business customers. In traditional practice, manufacturing simulations are exclusively used, within siloed information flows, by isolated product development & manufacturing process engineering departments. Though there is an unavoidable reality that high-quality simulations can only be developed by qualified subject matter experts, there is no business justification for restricting enterprise-wide business customers from accessing the information contained in verified simulation results. This is particularly true for organizations striving to achieve the I4M vision through adoption of formal Enterprise Architecture. Figure 5 and Figure 6 of the Appendix provide depictions of the changing roles for simulation based information assets in traditional Industry 3.0, and future Industry 4.0 manufacturing, respectively.

Also emphasized in Figure 1 is the potential central supportive role that Enterprise Architecture (EA) can provide for Industry 4.0 organizations. Because I4M offers the promise of a technological revolution based on advanced modern IT systems, there is a valuable opportunity to intimately connect the facets of I4M with established practices from Enterprise Architecture. The architecture can be thought of as a *'tool that links the business mission and strategy of an organization to its IT strategy'* (Godinez, et al. 2010).

This paper examines the specific supportive, and amplifying, role that EA can provide for the Simulation facet of I4M. Section 3 describes visionary architectural features that organizations can employ to earn a high return on their I4M simulation investments. Section 4 then describes some of the challenges posed by these visionary architectural features. The identified challenges are followed by Section 5 which discusses the challenge in depth and then proposes both target architectural features and associated architectural components to meet the challenges. The paper concludes with brief business case justifications in Section 7, a high-level road map in Section 8, and a Summary of Conclusions in Section 9.

3 Architectural visions for I4M simulation based information assets

The vision for an Enterprise Architecture supporting I4M simulations can be described in terms of three high level strategic information system goals. First the visionary architecture should free simulation data, information, and knowledge from the traditional siloes that it has been confined to. Second the visionary architecture should enable efficient distribution of simulation results throughout the enterprise via published services that can be consumed by a wide variety of both internal and external customers. Third, because simulation results will be only one of many different types of information assets in I4M organizations, the visionary architecture should provide seamless compatibility with standard Enterprise Architecture frameworks, such as TOGAF (The Open Group 2011), and existing I4M reference models, such as RAMI 4.0 (Adolphs 2015), (ZVEI 2016).

This section describes architectural visions for achieving the three goals of (1) removing the traditional confining siloes for I4M simulation based information assets, (2) efficiently distributing I4M simulation results throughout the enterprise, and (3) providing compatibility with accepted EA frameworks. The visionary architectural features are summarized in Section 3.4. Prior to that, Sections 3.1 through 3.3 discuss the basis for these visionary architectural features in terms of a visionary operating model, data domain, and functional & technical capabilities.

3.1 The Visionary Operating Model

The visionary Operating Model for I4M organizations with advanced simulation data flows involves widespread enterprise access to un-structured simulation results. In order to increase the usability of these results, highly standardized Information Systems are needed to provide loose coupling between the simulation system layers and the greater IT architecture. This will require Enterprise Architecture that enables standardized Information Systems to interface with and transport variable un-structured results from disparate simulation systems. This standardization operating requirement of the architectural vision is in many ways similar to that encountered in conventional Service Oriented Architecture (SOA).

The visionary level of integration for I4M simulation based information assets is enterprise-wide availability to on-demand simulation services. Ideally, these results will be pulled by various enterprise-wide simulation service consumers. This is directly in contrast to the traditional manufacturing approach of pushed forward simulation results delivered through static specification documents. Traditionally, specifications are based on prepared simulation results and other up-front product development analyses. However, I4M technology offers the opportunity to completely redefine the concept of a static manufacturing specification in order to support business goals of mass customization and single batch processing.

Because of the need for both high levels of IT infrastructure standardization, and the movement away from forced simulation data integration, it is likely that with respect to simulation data flows I4M organizations will have a quasi-Replication Operating Model. Where this operating model characterization is per the classification system from *Enterprise Architecture As Strategy* (Ross, Weill and Robertson 2006). The expected levels of simulation service standardization will be high, but the levels of simulation service integration could be low, or fluctuating with demand.

3.2 The Visionary Data Domain

In terms of data characterization simulation based information assets will likely exist as a mixture of unstructured content and analytical data. This characterization is per the data domain classifications from *The Art of Enterprise Information Architecture* (Godinez, et al. 2010). The unstructured characteristics of simulation based data arise from both the variety of simulation software packages, and the heterogeneous nature of simulation theory. That is, each manufacturing process can be modeled according to a variety of theories, and each of these models can be simulated, and subsequently analyzed, with a wide variety of software approaches. The analytical characteristics of simulation based data arise directly from its inherently predictive nature. Simulations are analytical predictions, and typically these predictions are based on input from available Operational or Master data sources.

3.3 The Visionary Architectural Functional and Technical Capabilities

From a business executive point of view '*an effective foundation for execution depends on tight alignment between business objectives and IT capabilities'* (Ross, Weill and Robertson 2006). With this in mind, it is highly desirable to ground the visionary architectural capabilities with clearly defined business objectives. *The Art of Enterprise Information Architecture* (Godinez, et al. 2010) provides four primary categories of IT capabilities that are helpful for organizing related capabilities and subsequently matching these to business objectives. For the visionary architecture to support I4M simulation based information assets there are four primary groups of desired IT capabilities.

- Mashup capabilities
- Enterprise Information Integration capabilities
- Predictive and Real Time Analytics capabilities
- Cloud computing and Internet of Things capabilities.

The I4M business objective aligned with Mashup and Enterprise Information Integration capabilities is on-demand mass customization. The I4M organization will leverage simulation based information assets to enable customers to virtually prototype their own designs. IT support for customer driven simulations will require both the harmonizing features of Enterprise Information Integration (EII), and the highly responsive and flexible features of Mashup capabilities. Per the visionary guidance of *Leading Change* (Kotter 2012), the IT capabilities of EII and Mashups will help I4M organizations eliminate *'Unnecessary Interdependencies'*.

The I4M business objective aligned with Predictive and Real Time Analytics capabilities is self-aware and self-assembling production systems. The vision is that of an almost infinitely customizable production line that optimizes its configuration based on the requested features of the product. Instead of the static 20th century production line, which was typically optimized for a single group of closely related products, the I4M production line will be dynamic and capable of supporting a highly *'adaptive corporate culture'* (Kotter 2012).

The I4M business objective aligned with Cloud Computing and Internet of Things capabilities is machine-to-machine communications. The vision is that I4M organizations will employ extensive investments in both autonomous robotics and artificial intelligence (AI). These machines will be capable of communicating through Internet Protocols on robust industrial internet networks. Both robotics and AI entities will be capable of consuming simulation based information assets similar to human users. The machine-to-machine communications will further help eliminate *'Unnecessary Interdependence'* and also increase the level of organizational risk tolerance by reducing human factor considerations.

3.4 Summary of the Architectural Vision

Sections 3.1 through 3.3 have described the operating model, data domain, and capability requirements for an Architectural Vision that will achieve the three high level strategic goals enumerated at the beginning of Section 3. First, the visionary architecture will free unstructured, analytical, simulation data, information, and knowledge from traditional siloes by supporting EII and Mashup capabilities to standardize interface and transport Information System layers. Second, the visionary architecture will provide efficient distribution for, and access to, simulation based information assets through the development of pull-based integration services that enable Predictive & Real-Time Analytic capabilities, Mashup capabilities and Cloud Computing & Internet of Things capabilities. Last, the visionary architecture will view the sub-set of simulation based information assets within the greater context of the full scope of an I4M organization. With respect to this goal the visionary capabilities are not original, but have strong connections to architecture solutions from other domains. This is desirable as it should help provide full compatibility with the greater Enterprise Architecture of the entire I4M organization.

4 Major Enterprise Architecture challenges for I4M simulation assets

Because I4M is still an emerging field experiencing rapid evolution there are few published Enterprise Architectural reference models, standards, or case studies specific for this field. The reality of limited published results is even more severe for EA solutions specific to the Simulation aspects of I4M, as the vast majority of published I4M literature focuses on topics of networking & control systems (Vogel-Heuser, et al. January 2016) (Hankel and Rexroth April

2015) (Marcy April 2016). Consequently, the in-practice architectural issues for I4M simulation data flows are largely unknown. In the author's opinion at this stage of the I4M growth phase it is more appropriate to discuss expected challenges, rather than observed issues.

The author's interpretation of the major challenges for enterprise integration of I4M simulation data are listed in the sub-sections below. These are based on limited published literature for the topics and draw heavily on the author's past experiences developing product simulations and virtual prototypes. Where appropriate, challenges have also been identified based on analogies with similar Information System data flows. The challenges have been categorized into five challenge areas. In depth analysis and proposed solutions for these five architectural challenge areas are discussed in Section 5.

4.1 Reference Model and Standardization challenges

- There is a scarcity of proven EA reference models tailored for I4M, and specifically a lack of consideration for Simulation data aspects within existing models. There is also a wide variety of competing I4M information system standards and best practices.

4.2 Knowledge, Information, and Data (KID stuff) challenges

- Traditionally simulation based information assets have been confined within siloed product development and process engineering departments. This has resulted in an enterprise-wide lack of knowledge on how to exploit simulation results.

4.3 Information Technology challenges

- There is a gross lack of simulation data standardization, and an ever increasing proliferation of simulation software packages and applications.

4.4 Business Processes, Policy and Procedure challenges

- The I4M revolution has created a need for a re-defined concept of manufacturing specifications. In turn, this new definition will create the need for new business processes to provide customers with options for mass customization.

4.5 People and Cultural challenges

- The heritage of manufacturing has included a predominant bias for manufacturing based on human interactions, not machine to machine interactions. I4M organizations face the challenge of removing this bias and increasing organizational reliance on artificial labor and automation.

5 Analysis and proposed solutions to the EA challenges for I4M simulation based information assets

This section describes proposed solutions for the major EA challenges for I4M simulation based information assets described in Section 4. First the challenges are reviewed for each of the five categorized challenge groups presented in Section 4. Next proposed target information system architectural features are discussed that are capable of meeting these challenges. Finally, the discussion leads to proposed target architectural components that could satisfy the requirements of the target architectural features. These component proposals are intended to closely align with the Component Model concepts from *The Art of Enterprise Information Architecture* (Godinez, et al. 2010), as such they draw heavily from the ideas of that book.

Although this section does not closely follow the the procedures of the TOGAF Architectural Development Method (ADM) it is intended to be consistent with it. In this sense, the target information systems architectural features and proposed architectural components were developed consistent with the main objectives in Phase C of the TOGAF ADM. Phase C states '*Develop the Target Information Systems (Data and Application) Architecture, describing how the enterprise's Information Systems Architecture will enable the Business Architecture and the Architecture Vision'* (The Open Group 2011). Baseline Architectures have not been identified because of the emerging *"bleeding edge"* status of the I4M industry. However, Target Information Systems Architectural features, and associated architectural components, are proposed to meet the challenges identified in Section 4.

5.1 Proposals to meet the Reference Model and Standardization challenges

5.1.1 Review of the challenges

The challenges identified in Section 4.1 are largely a consequence of the immaturity of the I4M industry. As of this writing the leading I4M specific reference model is RAMI 4.0 created by the German Electrical and Electronic Manufacturer's Association (ZVEI 2016). While RAMI 4.0 is an excellent resource for I4M use cases, in it's current form, it does not consider the full spectrum of challenges associated with simulation based information assets. A related challenge is the multiple existing international information systems standards applicable for

I4M such as IEC 61512, IEC 62264, IEC 62890, ISA-88, and ISA-95. However, these standards largely pre-date the major developments of the I4M movement and do not explicitly address the specific challenges of I4M simulation based information assets.

Further, many of the existing reference models and information system standards have been developed largely due to investment and leadership from the German Federal Ministry for Economic Affairs and Energy (BMWi). Publications sponsored by BMWi, and its Platform Industrie 4.0 initiative (Platform Industrie 4.0 March 2016) (Platform Industrie 4.0 April 2016), have positively contributed to useful standardization. However, global growth of I4M would significantly benefit from an increased harmonization of existing standards in order to support the goal of international standardization.

5.1.2 Target Information System Architectural Features

The immaturity of I4M reference models and lack of globalized I4M standards can be addressed with Enterprise Architecture features that will accommodate the future growth and coalescing standardization of the industry. The architecture needs to be capable of adapting to the emergence of new reference models and standards. Also, the architecture should avoid over-committing to any one specific reference model or group of information system standards.

5.1.3 Proposed Architectural Component

One component well suited for providing architectural adaptability and flexibility is the Enterprise Service Bus (ESB). While in *The Art of Enterprise Information Architecture* (Godinez, et al. 2010) the ESB is primarily cast as the Connectivity and Interoperability layer of the Component Relationship Diagram, in this paper it will be described as a proposed architectural component. The purpose of the ESB is to both flexibly support the I4M internet protocol communication layer while also providing mediation services between various I4M applications, and other components. The ESB is well suited for addressing the challenge of immature I4M reference models and standards because of its layered design as a communication component. The ESB provides strong capabilities to accommodate changes to data exchange standards. This will provide significant business value as the data exchange standard for I4M simulation based information based assets evolves. For example, the evolution away from XML based communication to JSON or some other future globalized data exchange standard.

5.2 Proposals to meet the KID stuff challenges

5.2.1 Review of the challenges

For many manufacturing organizations there is an enterprise-wide lack of knowledge regarding simulation capabilities. The capabilities of computational simulations of manufacturing processes have traditionally been confined within SME groups of product development and engineering departments. Increased business value for simulation data can be realized by disseminating this knowledge throughout the enterprise.

However, dissemination of these data will present I4M organizations with the knowledge based challenge of knowing how to use simulation results in innovative ways to develop new business opportunities. This is not simply a training challenge, but will require organizational commitment and investment to develop enterprise-wide awareness of the value offered by I4M simulation based information assets.

5.2.2 Target Information System Architectural Features

The enterprise-wide awareness of I4M simulation based information asset capabilities and usefulness can be improved through architectural features that streamline the search for, and application of, registered simulation services. The target features would enable consumers (both human and machine) to identify and try-out simulation results that match specified desired search criteria. For example, a consumer would access a simulation results search portal and request simulations that can model a specific manufacturing process. Matching search results would be provided, and the consumer could then try-out selected simulations on a specified product. The target information system architecture will support both finding simulation services and consuming them.

5.2.3 Proposed Architectural Components

'Search and Query Presentation Services …. focus on the intranet search limited to the information resources within the enterprise' (Godinez, et al. 2010). A Component for these services could be adapted to provide I4M simulation based information assets. A key benefit of this approach is that Search & Query Presentation Service (S&QPS) components have been shown to work for unstructured information and analytical data (Godinez, et al. 2010).

As discussed in Section 5.2.2, in addition to identifying I4M simulation based information services there is the need for an architectural component that can enable their consumption. This can be achieved through mashed-up web applications delivered through a Mashup Hub (MUH) component (Godinez, et al. 2010). The service consumer will specify both the product they want to simulate and the simulations they want to execute. The component will then assemble a new web application that executes the product simulation.

Together the Search & Query Presentation Service and Mashup Hub components will help the I4M enterprise share simulation based information assets with a conceptually unlimited variety of consumers. These components will make it easier for consumers to both find and use these services. Ideally, the components should increase the use of simulations throughout the I4M enterprise in order to support the business goals described in Sections **Error! Reference source not found.** and 3.

5.3 Proposals to meet the Information Technology challenges

5.3.1 Review of the challenges

The output of computational simulation results varies widely among different software packages. This lack of standardization presents a challenge for data exchange between the various simulation service consumer nodes which will be distributed across the enterprise. A similar challenge, but on a different of layer of the Information System stack, is presented by the wide variety of simulation software package types and applications. The enterprise must plan potential support for both widely varying simulation data formats, and a wide variety of different simulation software systems.

5.3.2 Target Information System Architectural Features

Both of these challenges have a close analogy with the group of challenges found with legacy information systems. Similar to simulation data and applications, legacy information systems have an abundance of disparate, proprietary, data formats and application programming interfaces (APIs). Architectural features for solving legacy information system challenges include layers to wrap the proprietary APIs with standardized APIs. Similarly, architectural layers are needed to harmonize the disparate data using standardized transport carriers with supporting data translation services.

5.3.3 Proposed Architectural Components

A proven technique for successfully meeting the challenges of legacy information systems is Service Oriented Architecture (SOA). An architectural component well suited for supporting SOA is the Enterprise Information Integration (EII) component. This component provides EII services which '*are delivered through a set of tools and products that help enterprises derive more value from the complex, heterogeneous information spread across their systems'* (Godinez, et al. 2010). In the context of I4M simulation based information assets, the EII component will be responsible for integrating both the wide variety of simulation data formats and the wide variety of simulation application APIs.

Because simulation data and applications have a track record of continuously changing, it is desirable for the EII component to provide application and data wrapping, as is done for many SOAs. The EII component will also need to closely interface with the Search & Query Presentation Services and Mashup Hub components described in Section 5.2.3. It is important to note that these other components will likely have a strong dependency on the EII component because of its integrator role.

5.4 Proposals to meet the Business Process, Policy, and Procedure challenges

5.4.1 Review of the challenges

I4M technology will require a business process evolution away from static manufacturing specifications. For over a century traditional manufacturing businesses have relied on the concept of static specification documents to communicate product information and manufacturing procedures. The I4M revolution offers innovative manufacturer companies to re-develop the concept of a specification to better satisfy the demands of potential single-batch processes and mass customization.

A direct downstream affect of re-defining specifications will be the need for new business models to support customer options for mass customization. In addition to the need for re-developed business process specifications, the potential of mass product customization based on customer inputs demands new business processes and policies to effectively accommodate order of magnitude increases in customer choices. Pricing models, purchase contracts, certifications, and warranties could all be drastically changed by I4M technology.

5.4.2 Target Information System Architectural Features

The target architectural features to support the challenge of a re-defined dynamic specification will need to balance the I4M organization's need for business control and its opportunity for providing customer driven manufacturing services. The target information system should enable customers to simulate their own customized product ideas, but within the constraints of well defined business rules. These rules could be based on a mixture of strategic business financial and ethical considerations. For example, some I4M organizations may have a financial strategy to only enable customer-driven simulations for certain restricted groups of products. Also, some I4M organizations may want to restrict customers from simulating certain types of ethically questionable products such as drugs, firearms, explosives, or chemicals.

5.4.3 Proposed Architectural Components

The balancing and regulatory roles of the target information systems architecture described in Section 5.4.2 can be provided through the use of Enterprise Content Management (ECM) components. As their name implies these components manage enterprise content through the enforcement of business rules. For I4M simulation based information assets the content being managed could be either types of simulations, or the types of allowed for a specific product group. The business objective is to enable customer driven product specification, but within the constraints of established business rules. The ECM component will provide enforcement of the business rules, perhaps based on user authorization levels.

5.5 Proposals to meet the People and Cultural challenges

5.5.1 Review of the challenges

Manufacturing processes have long been operated, controlled, and managed by humans. The future of I4M includes the possibility that human interactions with the manufacturing process will be significantly different than in traditional roles. This role change will present a challenge to I4M organizations, who will need to balance technological gains with considerations for human factors. The potential of I4M processes with little or no human interaction is a concern to many organizations. The challenge is to fully enable the power of technologies, like artificial intelligence and industrial automation, without eliminating human well-being safe-guards and human based chains of command.

Additionally, many I4M organizations will face the challenges associated with replacing human employees with machines. New technologies have tended to reduce the human workforce size for many types of manufacturing business processes. It is expected that these trends could be exacerbated by I4M technologies like advanced simulation capabilities. For example, many product development engineering and sales-person jobs could be threatened by the combined affects of enabling universal access to I4M simulation based information assets. The need for these human roles will be reduced by enabling customers to simulate their own product ideas, and also enabling machines to first simulate their own behaviour and then self-assemble into machine optimized production configurations.

5.5.2 Target Information System Architectural Features

In terms of safety, the science fiction writer Isaac Asimov clearly expressed much of the concern regarding artificial intelligence and robotics with his proposed three laws of robotics:

1. *'A robot may not injure a human being or, through inaction, allow a human being to come to harm'* (Asimov 1950).
2. *'A robot must obey the orders given it by human beings except where such orders would conflict with the First Law'* (Asimov 1950).
3. *'A robot must protect its own existence as long as such protection does not conflict with the First or Second Laws'* (Asimov 1950).

For I4M manufacturing operations that involve hazardous materials or hazardous processes the concerns identified by Asimov will be a cold hard reality. These organizations are likely best served by a proactive approach that includes target information systems architectural features designed to ensure human safety and well being. These features should provide safety systems input to I4M simulation services through direct interfaces to I4M plant safety and control systems. Additionally, the safety and control systems must have authority to override I4M simulations of machine self-assembly processes.

In terms of the concerns regarding human role changes posed by I4M simulation based information assets organizations may benefit by enabling employees to adapt to new roles through embracement of simulation technology. This can be accomplished, as discussed in Section 5.2, through information systems architecture that increases the awareness of simulation asset capabilities and usefulness. It also can be stimulated by architectural features that provide self-directed training, such as Knowledge Management Systems.

5.5.3 Proposed Architectural Components

A Health Safety & Environment (HSE) component is proposed to address the safety concerns for I4M simulation services that do not consider human safety and well being factors, such as machine self simulation. The HSE component is proposed to provide a connecting interface between the ESB component and the I4M plant control and safety systems layer. The HSE component will have the responsibility for ensuring that I4M simulation services are continuously listening for control and safety system alerts and alarms. To satisfy this responsibility, the HSE component will need to act as a trusted repository of up to date safety policies.

A Knowledge Management System (KMS) component is proposed to meet the human role change concerns described in 5.5.2. The functionality of this component will provide users will self guided learning resources to promote an enterprise culture that embraces I4M simulation technology. Additionally, the Knowledge Management System component can interface with the Search & Query Presentation Services and Mashup Hub components described in Section 5.2.3 to provide on-demand learning examples demonstrating the benefits of I4M simulation services for specific use cases.

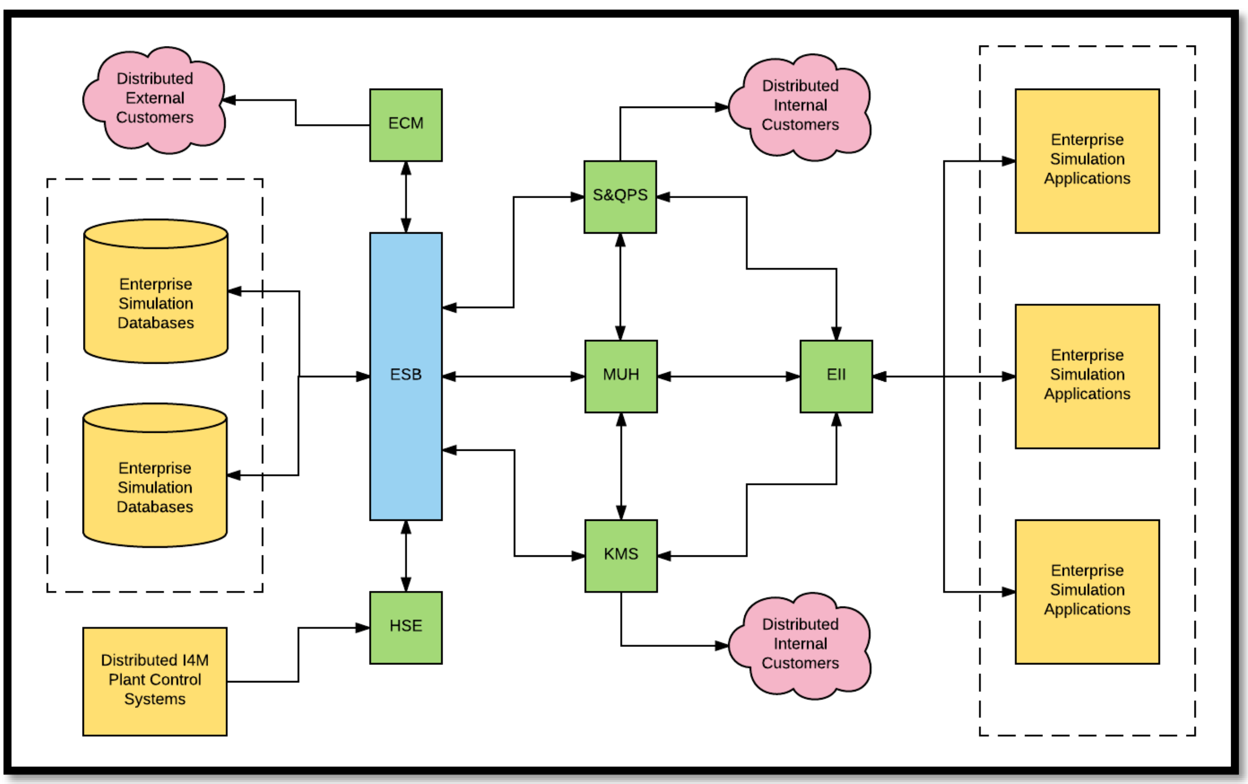
6 Summary of the proposed solutions

Sections 5.1 through 5.5 presented proposed information systems architectural components to address the challenges associated with I4M simulation based information assets. A total of seven architectural components have been proposed:

- Enterprise Service Bus (ESB) component
- Enterprise Information Integration (EII) component
- Enterprise Content Management (ECM) component
- Search & Query Presentation Services (S&QPS) component
- Mashup Hub (MUH) component
- Knowledge Management Systems (KMS) component
- Health Safety & Environment (HSE) component

These components need to be assembled together to provide enterprise-wide value. A convenient way to show this is the Component Relationship Diagram discussed in *The Art of Enterprise Information Architecture* (Godinez, et al. 2010). A proposed high level relationship diagram for the proposed components is shown in Figure 2. The diagram shows the basic relationships between the seven components and the I4M simulation based data & applications. The diagram also shows conceptual relationships between the components and both internal and external customers, who will consume the simulation services.

Figure 2 – A proposed high level component relationship diagram



7 Basic business case justifications for the proposed solutions

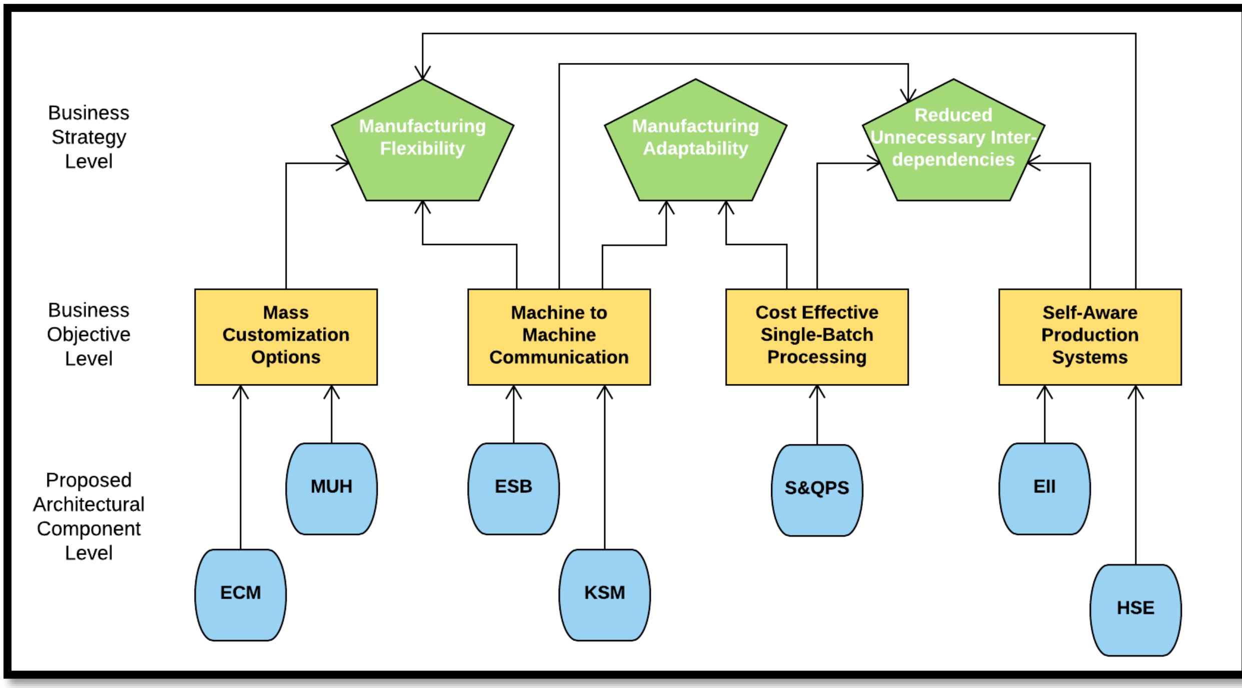
To avoid unnecessary architectural investments, it is important to justify the proposed solutions in the context of a business case. Aspects of the business case have been previously mentioned in sections 3 through 5. These have been re-iterated in this section to the strengthen the associations between business objectives and proposed architectural components.

The high level strategic goals of a I4M organization may assume different forms, but generally the underlying strategic ideas will be based on using I4M technology to increase organizational flexibility & adaptability while also eliminating un-necessary interdependencies. In terms of the simulation facet of I4M, this paper has discussed four main business objectives that support the underlying strategic goals. These are:

- Machine-to-machine communication; including machine requested simulations
- Availabiliity of mass customization options through customer driven virtual prototyping
- Cost effective single batch processing supported by simulation cost functions
- Both self-assembling & self-aware production systems; including self simulation

Figure 3 presents a TOGAF themed goal-objective-service diagram for the seven architectural components proposed in Section 5. Each component has been connected with the primary business objective that it supports in context of I4M simulation based information assets. In turn, each business objective has been connected with the primary high-level I4M strategic goals that it supports. Note that these connections are not exclusive, but are intended to provide a basic business case justification for the proposed components by showing their connection with the simulation asset business objectives and strategic I4M organizational goals.

Figure 3 – TOGAF themed Goal / Objective / Service diagram for the proposed components



8 High-level road map for implementing the proposed solutions

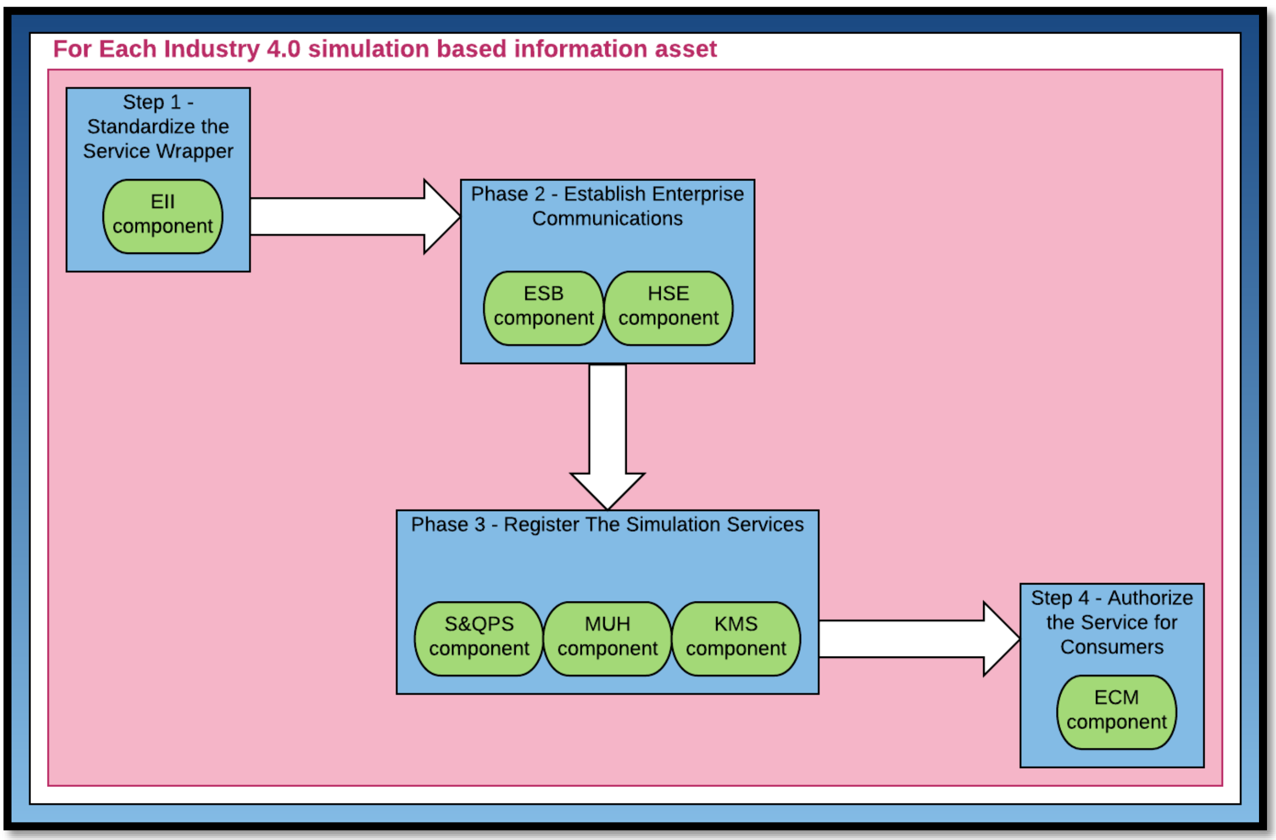
An important point regarding the proposed architectural components is that, with the exception of the KSM and HSE components, these components all have an established basis for mainstream information systems. The ESB, EII, ECM, MUH, S&QPS components are all discussed in detail by *The Art of Enterprise Information Architecture* (Godinez, et al. 2010). The components were intentionally selected with established basis in mind because it avoids the implementation and testing challenges associated with the introduction of new custom components. This is also true for the KSM and HSE components, which have established bases in traditional industrial manufacturing organizations.

A reasonable first step for implementing the proposed solutions would be the construction of a capable EA team. This team should have not only EA experience, but also specific knowledge and understanding of both the I4M industry, and advanced computational simulation technologies. The team will need to develop techniques for implementing the proposed architectural components. Because of the dynamic, emerging technology, nature of the I4M industry "big bang", all at once, type implementations are not advisable. Further, business research has shown that "big bang" implementations are not typically successful for large highly connected information systems like those that will exist in I4M.

'Large systems-based implementations have a lousy track record of success. Many companies have implemented extensive ERP systems, expecting their core business processes to be automated into a foundation. The size, complexity, disruption, cost, and learning required all contributed to the failure of more than 50 percent of these implementations, with millions of dollars and much management goodwill going down the drain.' (Ross, Weill and Robertson 2006)

It could even be argued that there is no value for any type of "big bang" implementation in I4M organizations, which are striving for flexibility and adaptability. With consideration for these arguments against "big bang" approaches, an incremental, and possibly both lean and agile (Bente, Bombosch and Langade 2012), implementation approach is recommended. As a starting point for future I4M simulation based information asset EA projects, a rough cut high level implementation road map has been developed in Figure 4. This map shows the recommended sequence of component implementation for each I4M simulation service. It starts with phase 1 in which standardizes the service wrapper with the EII component in order to eliminate proprietary data format and API concerns. Then it proceeds in phase 2 with establishing enterprise communications first through the ESB backbone component, and then with the HSE safety services component. With communications in place phase 3 then registers the simulation service with the S&QPS, MUH, and KMS components. The results of phase 3 will enable internal customers to find and consume the service. Lastly, in phase 4, the ECM component can be enabled to authorize the service for consumption by external customers.

Figure 4 – High level implementation road map for I4M simulation services



9 Conclusions and recommended next steps

This section summarizes the main thoughts of this paper in terms of how Enterprise Architecture can be used to maximize the value of I4M simulation based information assets. From the perspective of an organization that is already committed to the simulation facet of

I4M there are two main value proposals for supporting simulation based information assets with EA. First, EA can enable these organizations to maximize the value of their existing I4M simulation based information assets. Second, EA can amplify the value of advances in simulation technology. The following three sub-sections discuss these two value proposals, and also provide a brief discussion of recommended next steps for an I4M organization that wants to apply EA for their simulation based information assets.

9.1 The maximizing value of EA for I4M simulation based information assets

There are two primary ways that simulating a manufacturing process or product behaviour can provide value to an organization. The simulation can predict, in a probabilistic sense, how the process or product might behave under varied conditions. This mode of simulation is akin to virtual testing for the product or process. Alternatively, simulations can be used to examine, compare, or contrast the behaviour of different products under controlled conditions. Within product development literature this mode of simulation is often referred to as virtual prototyping. While EA can increase the value of virtual testing simulations, such as through automated testing, this paper has been written with assumption that the strongest argument for supporting I4M simulations with EA is to maximize the value of virtual prototyping.

Section 7 discussed the general strategic I4M business goals of flexibility, adaptability, and reduced inter-dependencies. These can be supported by business objectives of mass customization, machine-to-machine communication, single batch processing, and self aware production systems. By leveraging Enterprise Architecture, it becomes possible to introduce aspects of virtual prototyping simulations within all four of these objectives. The I4M organization with Enterprise Architecture supported I4M simulation based information assets can realize significant strategic advantages.

The proposed architectural components discussed in sections 5 and 6 will enable virtual prototyping simulation services throughout the enterprise. The organization will become more flexible by offering external customers the options of mass customization through customer-driven virtual prototyping and single-batch processing. At the same time, organizational adaptability will be increased, and inter-dependencies will be reduced, by enabling production units to first simulate and then optimize their own configuration through machine-to-machine communications and self-awareness.

9.2 The amplifying value of EA for I4M simulation based information assets

The exciting future of Industry 4.0 Manufacturing is likely to be strongly affected by technological advances in computational simulations of manufacturing processes. These advances could take the form of increased accuracy with which the process is modeled. Advances could also occur with respect to how simulations are used within the manufacturing organization. This paper has discussed possibilities for this second type of advancement in which Enterprise Architecture frees simulation assets from traditional siloes and makes these available throughout the enterprise as published services. The value of this Enterprise Architecture type of advance is that it will amplify the value of domain specific modeling advances by disseminating the results of these advances throughout the enterprise.

Long cycle times can exist between simulation advancements, testing, and eventual incorporation into a manufacturing process or product. Typically, the simulation advancements occur within academia or inside an organizations research & development (R&D) department. Testing then occurs in a (R&D) testbed that employs appropriately modified production line technologies. Once testing is satisfactorily completed new production line capabilities are developed to incorporate the results of the simulation advancement.

I4M simulation based information assets that are supported with EA could potentially reduce the long cycle times associated with technical simulation advancements. This would be achieved through improved means of communication and reduced inter-dependencies. Once the simulation advancement has been made by the R&D team it can quickly become available as a new simulation service through the high-level implementation road map shown in section 8. Testing then occurs through successive controlled batch processing as the production unit machines become aware of, and try-out, the new simulation service. The benefit of this approach to the organization is a reduced R&D cycle time. The approach also enables the R&D team to focus more on small incremental simulation improvements and less on major overhaul improvements. The result could be increased R&D agility through something similar to the continuous integration concepts from lean and agile software development (Bente, Bombosch and Langade 2012).

9.3 Recommended next steps for applying EA to I4M simulation assets

As of the writing of this paper, the summer of 2016, it is fair to say that Industry 4.0 Manufacturing is still in its early infancy. Progress of the industry has mostly been made in

Germany through the Platform Industrie 4.0 (Platform Industrie 4.0 2016) initiative of the German government (BMWi 2016). The early adopters have largely been manufacturing technology companies with substantial means to conduct research & development test demonstrations, such as GE (Annunziata October 2015) and Siemens (Siemens 2013). However, there is a growing awareness of the potential for Industry 4.0 within both general (Brynjolfsson and McAfee 2014), (Schwab 2016) and business literature (Baur and Wee 2015), (Hannah January 2015), (Deloitte 2015).

Mid-sized and small US based organizations who want to develop EA support for their I4M simulation based information assets face significant challenges. However, as discussed in section 8 the architectural components proposed in this paper are well suited for incremental implementation. The recommended first step is building a strong EA team. As discussed in section 8 the team should have both EA and simulation technology expertise. It is also recommended that the team be dedicated for the I4M simulation asset EA project.

Once a good team is in place the first phase of implementation, shown in Figure 4, can be started. It’s recommended to start with a simple well understood process or product simulation. The first phase of implementation can then borrow knowledge, techniques, and practices from conventional SOA to wrap the simulation service with appropriate data normalization and transport layers suitable for machine-to-machine communications. Then in the second phase of implementation enterprise wide communications can be established between the service publisher and various consumers. It’s recommended that a light weight data exchange standard be used for initial phase 2 work, such as JSON. After communications have been established and verified with testing the service can be registered in phase 3 of the implementation plan. For the first implementation iteration it is recommended to limit the service registration to the Search & Query Presentation Services component. This reduces the required iteration work, and it is expected that the other registration components will have a similar API allowing them to be integrated without significantly more effort. Last, it is recommended that phase 4 be omitted for the first implementation iteration. This is because organizations will want to master internal simulation service consumption before making these services available to external customers. With that in mind it is recommended that the ECM component should not be brought online until several implementation iterations have been successfully completed.

10 Appendix

This appendix presents depictions of the changing role simulation services could have in Industry 4.0 Manufacturing. Figure 5 shows a depiction of the tradition role for simulation services in the Industry 3.0 Manufacturing architecture. Figure 6 then depicts the changed role for simulation services with respect to future Industry 4.0 Manufacturing architecture.

Figure 5 – Depiction of the traditional role for simulation services in Industry 3.0 Manufacturing

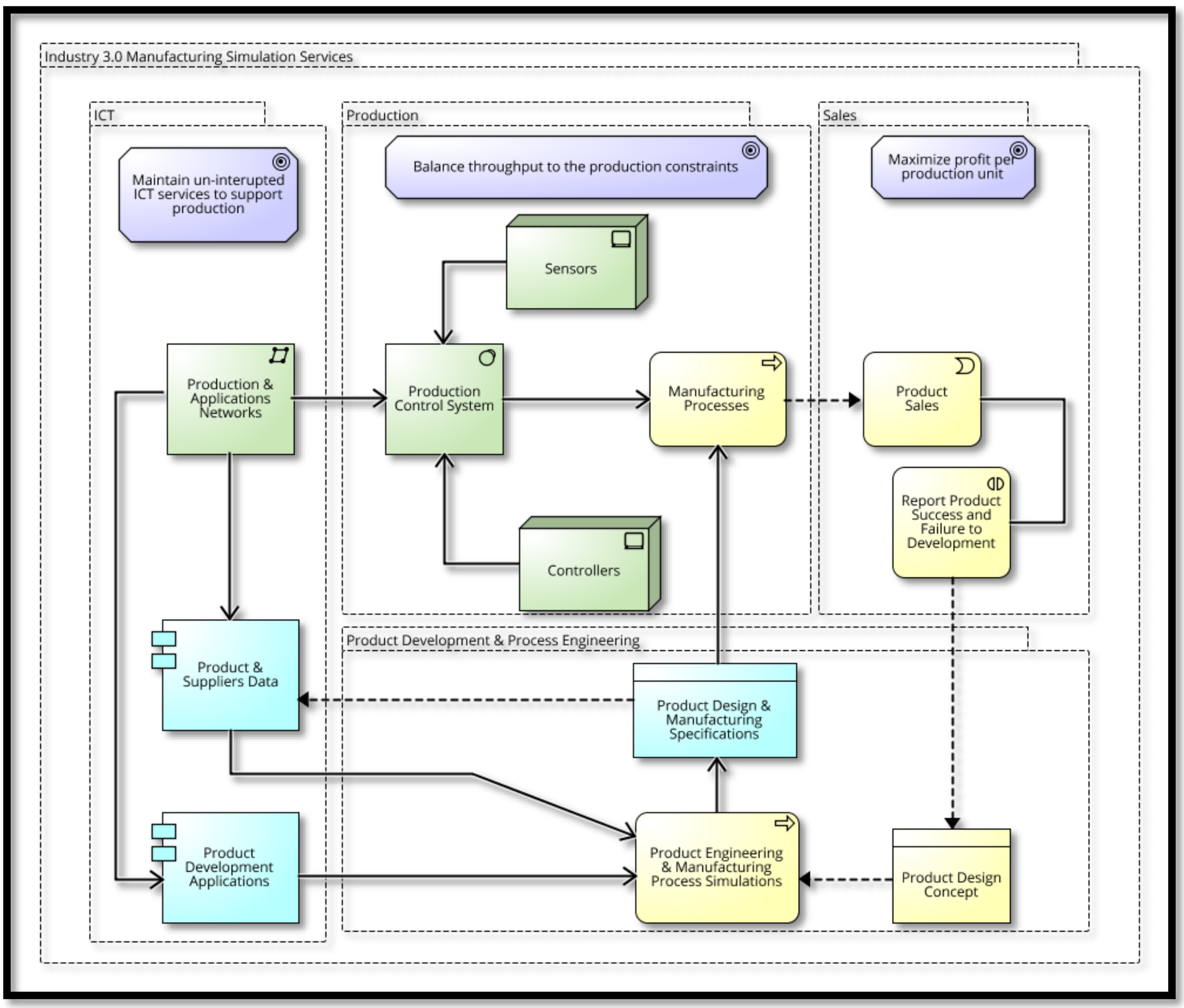
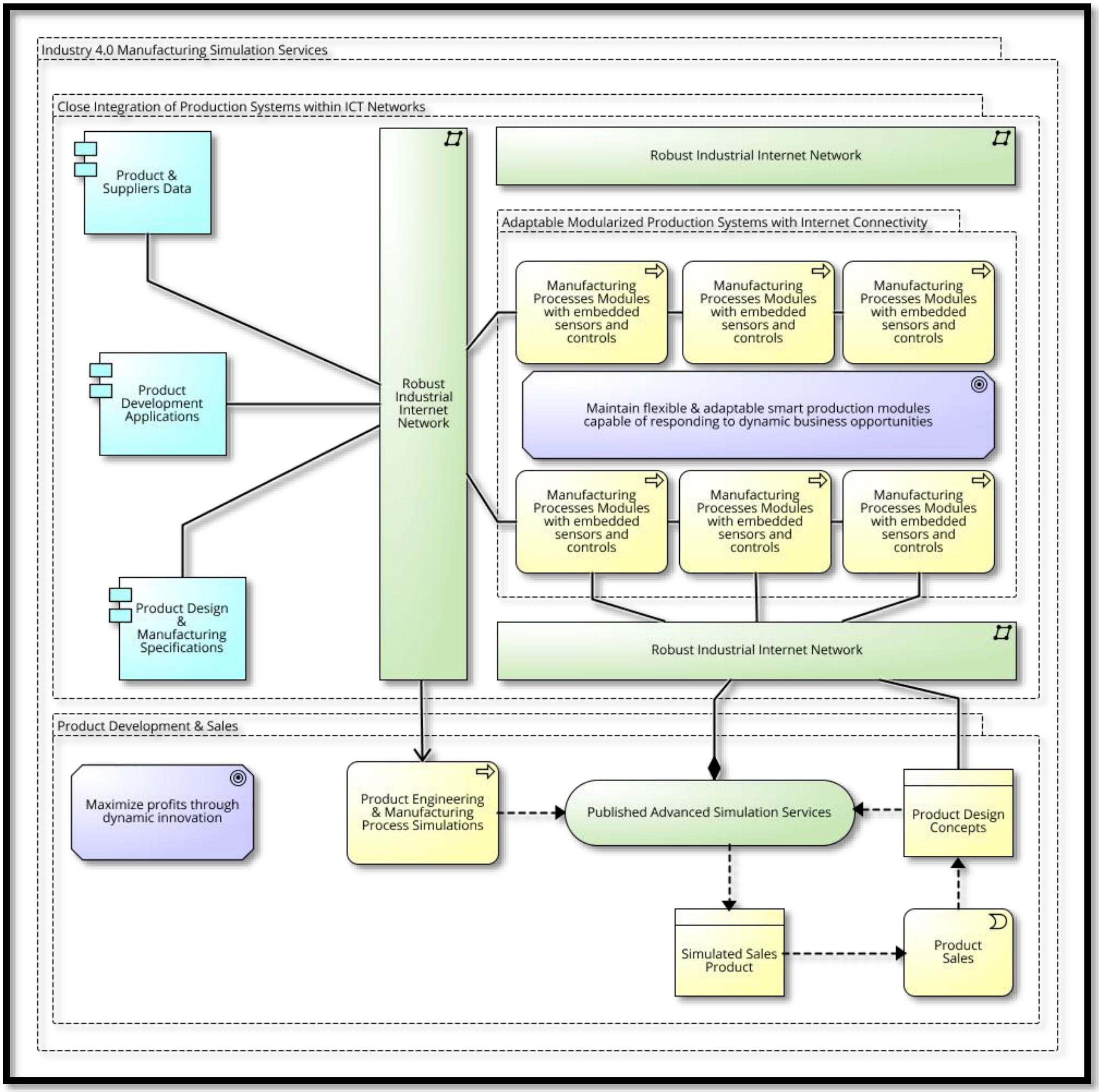


Figure 6 – Depiction of the potential role for simulation services in Industry 4.0 Manufacturing



11 References

Adolphs, Peter. *RAMI 4.0: An Architectural Model for Industrie 4.0.* Presentation, Berlin, Germany: Platform Industrie 4.0, 2015.

Annunziata, Marco. *The Moment for Industry.* White Paper, Schenectady, NY: General Electric, October 2015.

Asimov, Isaac. *I, Robot.* Greenwitch, Conneticut: Fawcett Publications, 1950.

Baur, Cornelius, and Dominik Wee. "Manufacturing's next act." *McKinsey & Company*, June 2015.

Bente, Stefan, Uwe Bombosch, and Shailendra Langade. *Collaborative Enterprise Architecture: enriching EA with lean, agile, and enterprise 2.0 practices.* Waltham, MA: Elsevier, Inc., 2012.

BMWi. "What is Industrie 4.0." *Platform Industrie 4.0.* July 2016. http://www.plattform-i40.de/I40/Navigation/EN/Industrie40/WhatIsIndustrie40/what-is-industrie40.html (accessed July 2016).

Brynjolfsson, Erik, and Andrew McAfee. *The Second Machine Age.* New York, New York: W. W. Norton & Company, 2014.

Deloitte. *Industry 4.0 challenges and solutions for the digital transformation and use of exponential technologies.* White Paper, Zurich, Switzerland: Deloitte AG, 2015.

Godinez, Mario, Eberhard Hechler, Steve Lockwood, Martin Oberhofer, and Michael Schroeck. *The Art of Enterprise Information Architecture.* Boston, Ma: IBM Press, 2010.

Hankel, Martin, and Bosch Rexroth. *Industrie 4.0: The Reference Architectural Model Industrie 4.0 (RAMI 4.0).* Trade Paper, Frankfurt am Main, Germany: ZVEI - The German Electrical and Electronic Manufacturers' Association, April 2015.

Hannah, Mike. "Industry 4.0: Turning the vision into reality." *Manufacturing Business Technology*, January 2015.

Kotter, John P. *Leading Change.* Boston, MA: Harvard Business Review Press, 2012.

Lasi, Heiner, Peter Fettke, Hans-georg Kemper, Thomas Feld, and Michael Hoffman. "Industry 4.0." *Business & Information Systems Engineering*, August 2014: Volume 6 Issue (4), pp. 239-242.

Lydon, Bill. "Industry 4.0: Intelligent and flexible production." *InTech: A publication of the International Society of Automation*, May / June 2016: 12-17.

Marcy, Alex. " Industrial networking technologies add value to existing infrastructure." *Control Engineering*, April 2016.

Mosterman, Pieter J., and Justyna Zander. "Industry 4.0 as a Cyber-Physical System study." *Software & Systems Modeling*, February 2016: Volume 15, Issue 1, pp. 17–29.

Platform Industrie 4.0. *Interaction Model for Industrie 4.0 Components.* Discussion Paper, Berlin, Germany: The German Federal Ministry for Economic Affairs and Energy (BMWi), March 2016.

Platform Industrie 4.0. *Network-based communication for Industrie 4.0.* Discussion Paper, Berlin, Germany: The German Federal Ministry for Economic Affairs and Energy (BMWi), April 2016.

—. *Platform Industrie 4.0.* August 2016. http://www.plattform-i40.de/I40/Navigation/DE/Home/home.html (accessed August 2016).

Ross, Jeanne W, Peter Weill, and David Robertson. *Enterprise Architechture As Strategy: Creating a Foundation for Business Execution.* Boston, MA: Harvard Business Review Press, 2006.

Schmidt, Rainer, Michael Mohring, Ralf-Christian Harting, Christopher Reichstein, Pascal Neumaier, and Philip Jozinovic. "Industry 4.0 - Potentials for Creating Smart Products: Empirical Research Results." *Business information systems : 18th International Conference.* Poznań, Poland: Springer, June 24 - 26, 2015. pp. 16 - 27.

Schwab, Klaus. *The Fourth Industrial Revolution.* Geneva Switzerland: World Economic Forum, 2016.

Siemens. "Industrie 4.0 - The Fourth Industrial Revolution." *YouTube.* December 5, 2013. https://www.youtube.com/watch?v=HPRURtORnis (accessed July 2016).

The Open Group. *TOGAF(R) Version 9.1.* Standard, San Francisco, CA: The Open Group, 2011.

Vogel-Heuser, Birgit, Susanne Rosch, Juliane Fischer, Thomas Simon, Sebastian Ulewicz, and Jens Folmer. "Fault Handling in PLC-Based Industry 4.0 Automated Production Systems as a Basis for Restart and Self-Configuration and Its Evaluation." *Journal of Software Engineering and Applications*, January 2016: Vol.9(1) pp. 1-43.

ZVEI. *Industrie 4.0.* August 2016. http://www.zvei.org/en/subjects/Industry-40/Pages/default.aspx (accessed August 2016).