Towards an Integrated Model of Smart Manufacturing Enterprises

Master Thesis

Abstract

This research aims to provide enterprise architecture modeling support for smart manufacturers (industry 4.0 companies) by introducing several architectural patterns based on ArchiMate. A comparison is made between the ArchiMate 3.0 meta-model and the ISA-95 standard for enterprise systems and control systems integration. Several new constructs are introduced to ArchiMate to compensate for deficiencies found. The results are validated as part of a case study at a large steel manufacturer.

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1 Introduction

Manufacturing companies worldwide are facing the need to improve productivity, quality and implement products with shortening innovation cycles. Further, in the context of Internet of Things (IoT), more and more devices are connected and collect data. The manufacturing industry is currently in the process of adopting this development as part of the new Smart Manufacturing paradigm. In Europe, this trend is more widely known as Industry 4.0.

Part of the introduction of Smart Manufacturing is the integration of the Internet of Things with the production process. Said integration is causing machines on the shop floor to evolve into cyber-physical systems (CPS). For the benefits of Smart Manufacturing to materialize, manufacturers will need some way to maintain alignment between their business needs and the information systems that permeate increasingly through all levels of their operations. A lack of so-called business & IT alignment could result in *a poor fit between functionality provided by CPSes and business needs*, implementation *projects that exceed their estimated costs* or otherwise fail and a general *lack of responsiveness to change* throughout the organization (Henderson & Venkatraman, 1993; Wagner & Weitzel, 2006). Maintaining alignment between a company's strategy and its supporting IT is one of the benefits of enterprise architecture. As the scope of IT within Smart Manufacturing firms expands, so too must the enterprise architect's field of view.

Enterprise architects usually concern themselves with the business processes and the IT systems that support them (i.e. the enterprise domain)(EABOK, 2016). At an insurance company, these processes might include claims handling and reimbursement. For manufacturing, examples include production scheduling, logistics and production workflows. Examples of supporting IT are the Enterprise Resource Planning (ERP) systems and Manufacturing Operations Management Systems (MOMS).

However, as smart manufacturing processes start generating more information at the shop floor, the need for the rest of the business to access and analyze this information emerges. For example, an oven may report its temperature curve in real time. If the temperature curve is sub-optimal, the oven wastes energy. Such an insight could be used as part of operational excellence programs or preventive maintenance.

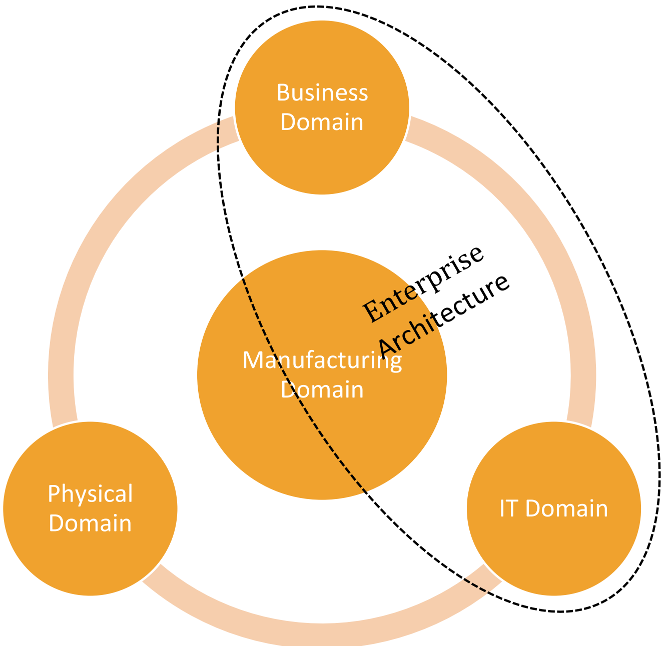


Figure 1: Smart Manufacturing involves the business, IT and physical domains

The management of the physical production process and its supporting systems (i.e. the physical domain) has traditionally fallen under the Operations Technology (OT) domain that is under the control of process engineers. As OT increasingly starts to overlap with IT, it makes sense to consider the physical domain from an IT perspective. Enterprise architects and process engineers will have to work closely together to integrate the information from both domains. As a result of this integration, the dichotomy between the IT and OT domains fades, establishing a single enterprise architecture for the manufacturing domain.

2 Problem Statement

If this integration between business, IT and OT is to be a success, enterprise architects and process engineers will need a shared vocabulary; a modeling language that can express all concepts required for modeling the manufacturing domain. One of the major requirements introduced by Smart Manufacturing is the capacity to model cyber-physical systems as part of the IT landscape. As the name implies, the modeling of such systems will involve not just viewpopints and concepts related to applications and infrastructure, but also to the physical environment (i.e. conditions on the shop floor) (Sacala & Moisescu, 2014).

This research aims to provide enterprise architecture modeling support for smart manufacturers. Such a model should function as a common language for process engineers and enterprise architects, integrating the enterprise and physical domains. This will contribute to the implementation of smart manufacturing principles at manufacturers such that business & IT alignment is maintained, effectively increasing visibility and traceability across the enterprise.

For this research, ArchiMate is the enterprise architecture language of choice. The most recent publication of the standard, ArchiMate 3.0, includes concepts for several physical elements. Being a new release, however, it has never been applied to the manufacturing domain. To ensure that ArchiMate enables the modeling of a smart manufacturer's enterprise architecture, the standard needs to be validated. Representing the manufacturing domain will be a set of standards under ANSI/ISA-95 (alternatively, ISO/IEC 62264), or ISA-95 for short. ISA-95 is a widely accepted standard in the manufacturing industry. Part of ISA-95 is a framework of concepts that describe entities at the shop floor level, where IT and OT interact. To be fully capable of modeling the enterprise architecture of a (smart) manufacturer, ArchiMate 3.0's meta-model needs to be able to express all architectural concepts from ISA-95.

Summarizing the above are the following main research questions:

RQ1. To what extent can ArchiMate 3.0 express the enterprise architecture of any smart manufacturer per ISA-95?

RQ2. If ArchiMate 3.0 cannot fully express the enterprise architecture of any smart manufacturer per ISA-95, how can the meta-model of ArchiMate 3.0 be adapted such that the enterprise architecture of any smart manufacturer *can* be modeled?

3 Approach

This section describes how the main research questions will be answered. To this end, the problem is divided into several sub-questions. Each sub-question is explained below.

Firstly, a subset of *architectural* concepts needs to be derived from the set of general manufacturing concepts defined by ISA-95. ISA-95 was written with IT/OT integration in mind. To apply its concepts to architecture modeling, an assessment needs to be made of which concepts identify as architectural. For this assessment, the same criteria used to define the current set of concepts in ArchiMate will be applied to each concept in ISA-95.

SQ1. Which architecture viewpoints and constructs are needed to model any (smart) manufacturing enterprise up to the process management level per ISA-95?

Secondly, to determine to what extent ArchiMate 3.0 is capable of expressing the architecture of a smart manufacturer, a mapping of the architectural ISA-95 concepts needs to be made onto ArchiMate 3.0. Criteria used for the mapping are whether the meaning of the definitions of concepts overlap, as well as whether the meaning of direct relations to other concepts (depth = 1) overlap. This means a distinction can be made between concepts that do not map at all, concepts that map based on definition, but not surrounding relations, and concepts that map completely.

SQ2. How do the architectural concepts of ISA-95 map onto ArchiMate 3.0?

Thirdly, based on the mapping of ISA-95 concepts onto ArchiMate 3.0, deficiencies in the expressiveness of ArchiMate can be identified based on the deficiency types by Wand & Weber (2002). It is assumed that ISA-95 represents an ontology of the manufacturing domain, which ArchiMate 3.0 must be able to express. Furthermore, whether ISA-95 can fully express ArchiMate is not of interest. Thus, the types of deficiencies identified will be limited to *construct overload*, where several ISA-95 constructs map to one ArchiMate construct, and *construct deficit*, where an ISA-95 construct does not map to any ArchiMate construct.

SQ3. What are the deficiencies in the expressiveness of ArchiMate 3.0 with regards to the manufacturing domain per ISA-95?

Finally, the deficiencies identified need to be analyzed and, if necessary, addressed. In the case of construct overload, an assessment must be made of whether any critical expressiveness is lost as a result of the higher level of abstraction. In the case of construct deficit, it must be determined whether the intended meaning of the ISA-95 concept can be expressed using a combination, or 'pattern', of constructs currently present in ArchiMate 3.0's meta-model. If the current meta-model is found insufficiently expressive, modeling patterns will be suggested that includes new constructs, be they new relations or new concepts.

SQ4. How should the meta-model of ArchiMate 3.0 be adapted such that the deficiencies identified are resolved?

Finally, the proposed meta-model will be validated as part of a case study at a large steel manufacturer, which for anonymity purposes will be named SteelCorp. The intent of the case study is to model a part of the organization, demonstrating the effectiveness of the new meta-model. Furthermore, the case study shall include the following analyses to demonstrate the added value of enterprise architecture for smart manufacturers:

Impact analysis: SteelCorp is currently in the process of restructuring its application landscape as part of the construction of a new production facility. However, it has poor visibility of the dependencies between its current production systems and the machines running on the shop floor. This lack of visibility is causing uncertainty as to the effect that replacing, for example, the Manufacturing Execution System (MES) that is managing the temperature curves of the ovens will have on systems managing other parts of the production process. By improving this visibility through an impact analysis, organizational agility at the plant should increase.

Operational excellence analysis: As part of its continuous improvement program, SteelCorp is constantly learning to increase productivity, product quality and organizational agility. The company has hired data specialists to perform analyses, but such an analysis can take months to complete due to poor traceability of data gathered from the shop floor. By improving traceability, the company should be able to analyze the incoming data more easily. A candidate for the validation of this research is a comparison between two (seemingly) identical plants to determine the causes of performance discrepancies between them.

3.1 Document Structure

Chapter 4 will discuss the research background based on the current state of scientific literature as well as the latest versions of popular industry standards that are in any way related to the research questions. Next, chapter 5 discusses the current suitability of ArchiMate for modeling smart manufacturing enterprises based on a mapping analysis in conjuncture with ISA-95. Based on the results of this analysis, a proposed solution will be discussed in chapter 7. Chapter 8 discusses the results of the validation step (a case study). Finally, chapter 8.5 will summarize the results and provide a conclusion. Each chapter will start with a discussion of the methods used.

4 Background & Related Work

Before proceeding with an analysis of ArchiMate, it makes sense to take a step back and define the relations between the enterprise domain and the physical domain based on previous work related to smart manufacturing, cyber-physical systems and enterprise architecture.

This literature search was conducted using the University of Twente's university library search engine, which aggregates sources like Scopus and Web of Science and allows for filtering of the results. The format of the search query was as such:

"Smart Manufacturing" OR "Industry 4.0" OR "Industrie 4.0" OR "Digital Enterprise" OR "Sensing Enterprise"

A filter was applied to limit the search results to peer reviewed journals and conference proceedings in the English language only. The following keywords were included:

"Article", "Industry 4.0", "Industrie 4.0", "Smart Manufacturing", "Computer Control (Ea)", "Manufacturing", "Cyber-Pyhisical Systems", "Nonlinear Systems", "Logistics", "Optimization", "Productivity", "Communication"

Separate queries were made to gather papers on the following subjects:

Cyber-Physical Systems: Given the increasing overlap between IT and OT, some knowledge of the theory behind cyber-physical systems may prove of use when modeling such an environment.

Traceability: Traceability of data is one of the core values of smart manufacturing. Since an enterprise architecture provides the relationships that make traceability possible, it was deemed useful to explore this subject more in depth.

Process Mining: Since smart manufacturing relates to creating models of the plant, rather than having to model every aspect of the plant by hand, it would be useful to be able to generate certain parts of the model automatically. Since process mining is becoming increasingly commonplace, it was deemed useful to explore this subject givnen the expected modeling effort.

The relevance of each resulting publication was estimated based on title and abstract. The complete set of papers taken into consideration amounts to 243. The sections below discuss the literature in relation to the topics of this research. Topics that proved ultimately not relevant to this research are not discussed here.

4.1 Smart Manufacturing

In 2015, Hermann, Pentek & Otto performed a literature review covering the subject Industry 4.0 to arrive at a definition of the term. They covered the publications on Industry 4.0 in relation to the following subjects: *Cyber-physical systems, Internet of Things, Internet of Services, Smart Factory, Smart Product, Big Data, Cloud, Machine-to-machine.* Based on their findings, they arrive at the following design principles (Hermann, Pentek, & Otto, 2015):

Interoperability: the ability of cyber-physical systems, humans and Smart Factories to connect and communicate with each other via the Internet of Things and the Internet of Services

Virtualization: a virtual copy of the Smart Factory, created by linking sensor data (from monitoring physical processes) with virtual plant models and simulation models

Decentralization: the ability of cyber-physical systems within Smart Factories to make decisions on their own

Real-time Capability: the capacity to collect and analyze data and provide the derived insights immediately

Modularity: flexible adaptation of Smart Factories to changing requirements by replacing or expanding individual modules

Smart machine line operations	Integrated process device and product management
	Benchmarking machine-product interactions
	Machine-power management
	Adaptable machine configurations
In-production high-fidelity modeling	Enhanced control of complex behaviors
	Rapid qualification of components, products and materials
	Integrated computational materials engineering
Dynamic decisions	Performance management based on globally integrated decisions
	Untapped enterprise degrees of freedom in efficiency, performance and time
	Enterprise analytics and business operational tradeoff decisions
	Configurable data and analyses for rapid analytics and model development
Enterprise and supply chain decisions	Smart grid interoperability
	In situ measurement and integrated value chains
	Tracking, traceability and genealogy
	External partner integration and interoperability
Design, planning and model development	Design models in production
	Product/material in production quality
	New product, material or technology insertion

Figure 2: Smart Manufacturing operational benefits (Davis et al., 2015)

For the purpose of this research, these design principles sufficiently define Smart Manufacturing from an engineering point of view. However, since the scope of this research also includes the business domain, it makes sense to define the term from the viewpoint of the business too. The literature does not seem to agree on a single definition, if publications mention business value at all. The choice of definition is therefore based on an endorsement from a major American consortium of manufacturers, the Smart Manufacturing Leadership Coalition (SMLC) as well as the United States Department of Energy. They define the Smart Manufacturing firm as '*data-driven, knowledge enabled and model rich with visibility across the enterprise (internal within a manufacturer and external across manufacturers)*' (Caminiti, 2011; Chand & Davis, 2010a, 2010b; Davis, Edgar, Porter, Bernaden, & Sarli, 2012; Smart Manufacturing Leadership Coalition & United States Department of Energy, 2011). Companies adopting Smart Manufacturing aim to realize the operational benefits listed in Figure 2 (Davis et al., 2015).

4.2 Cyber-Physical Systems

For the sake of consistency, Cyber-physical systems (CPS) will be defined per the same definition Hermann, Pentek & Otto used to conduct their literature review. CPS are *"integrations of computation and physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa."* (Lee, 2008). CPS play a major role in smart manufacturing. Examples of CPS include devices that communicate with the rest of the plant, as well as their intelligent cooperation to achieve increased efficiencies. Due to the introduction of embedded computers to operations technology, the shop floor increasingly starts to generate data. This causes the OT domain to overlap with the domain of enterprise IT.

4.3 Enterprise Architecture

The discipline that *analyzes areas of common activity within or between enterprises or organizations, where information and other resources are exchanged to guide future states from an integrated viewpoint of strategy, business and technology* is called enterprise architecture (EA) (EABOK, 2016). The enterprise architecture discipline acts as a bridge between the business domain, which is comprised of concepts like strategy, mission, people and processes, and the IT domain, which comprises applications and their supporting infrastructure.

The advantages of EA include (Boucharas, van Steenbergen, Jansen, & Brinkkemper, 2010):

Increased business & IT alignment: An increased fit between the strategy of the company and the way the (IT) organization supports this strategy.

Visibility of dependencies: This includes dependencies between information systems (both enterprise-wide and on the shop floor), infrastructure (IT as well as production) and business processes, corresponding to the modularity value of Smart Manufacturing.

A basis for analysis, design and development: By modeling the dependencies between the infrastructure, systems and processes, they become visible to the entire organization. These dependencies can be analyzed and, if they are causing issues, management can decide to design and implement a structure that suits the organization better, leading to an increase in efficiency, reduced IT costs, better regulatory compliance or improved information security. Common analysis types include: impact analysis and total cost of ownership calculation, as well as regulatory compliance and risk assessments. This benefit overlaps with the virtualization and real-time capability values of Smart Manufacturing

Portfolio management: When the organization has identified improvements, EA helps manage the projects that implement these improvements by showing how these projects relate to the strategy of the company. When the strategy changes, EA identifies the projects that contribute to this new direction, in which way they do so, and which projects do not. By enabling better-informed go/no-go decisions, this visibility helps managers make their organization more responsive to change.

There are several standardized frameworks for Enterprise Architecture (EAF) (Urbaczewski & Mrdalj, 2006). These frameworks differ by the stakeholders they address and the methods, common vocabulary, standards and tools that concern the domains for which they are intended. Table 1 shows an overview of some of the most common standardized EAF and provides a short description for each.

Table 1: Overview of some of the most common standardized EAF

Framework Name	**Description**
Zachman Framework	Establishes a common vocabulary and a set of perspectives for describing complex enterprise systems. The framework deals with six questions (what, how, where, who, when and why,) from the perspectives of a planner, owner, designer, builder, subcontractor and user. This is a general purpose framework that covers every imaginable viewpoint, not meant for any specific type of organization. The Zachman Framework does not provide a process for establishing an Architecture.
DoDAF	The Department of Defense Architecture Framework (Department of Defense, 2010) was developed by the US Department of Defense as a standard specific to its domain. The meta-model for DoDAF is shown in Figure 3: DoDAF meta-modelFigure 3. It addresses the physical domain (e.g. materiel), but does not relate physical elements to information in any way.
FEAF	The Federal Enterprise Architecture Framework (Federal government of the United States, 2013) was developed by the U.S. Office of Management and Budget as a domain-specific architecture framework for the US federal government. The framework concerns the following architecture domains: strategy, business, data, applications, infrastructure and security. Notably, the physical domain is missing.
TEAF	The Treasury Enterprise Architecture Framework was developed by the U.S. Department of the Treasury. This framework is derived from FEAF and supports the treasury's processes in terms of products. TEAF is currently deprecated.
TOGAF	The Open Group Architecture Framework, published by The Open Group, is a general purpose architecture framework focused on critical business applications. Rather than providing a set of architecture principles, the framework defines rules for developing such principles.

DoDAF is currently the only standardized EAF that includes the physical domain in some way. However, with the increasing relevance of CPS, more enterprise architecture frameworks that include physical aspects are beginning to surface (Sacala & Moisescu, 2014). They argue that modeling a CPS as part of the enterprise systems requires a physical entity, an association with a business entity and an application that discloses information to that business entity and an interface layer to convey the data from the physical entity to the application.

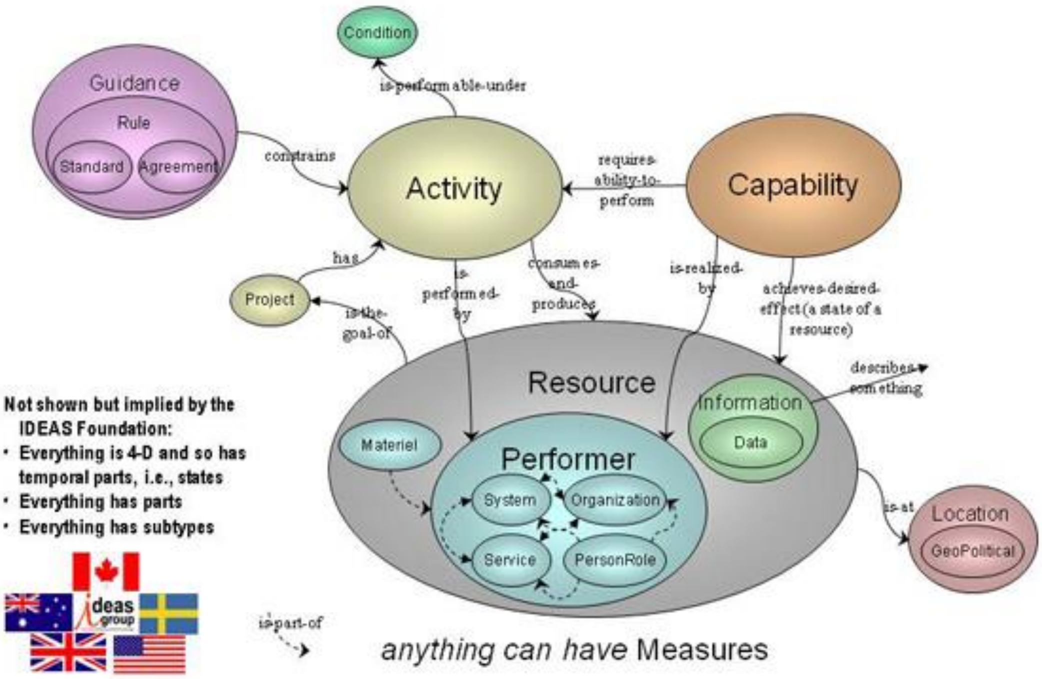


Figure 3: DoDAF meta-model (U.S. Department of Defense, 2016)

The physical domain is also making its way into standardized enterprise architecture modeling languages. ArchiMate 3.0 (The Open Group, 2016) is set to be released shortly. ArchiMate's EAF is based on TOGAF and defines a structured set of views that describe the business, application and IT infrastructure domains and the concepts that describe these domains. What makes ArchiMate a language rather than an EAF per se is that it also defines a common syntax, semantics, graphical notations and viewpoints (Lankhorst et al., n.d.). The latest version of ArchiMate, ArchiMate 3.0, expands the EAF with a physical layer that has relations to both the IT infrastructure and business domains (as shown in Figure 4). Figure 5 and Table 2 show the meta-model and concept definitions of the physical layer respectively.

Table 2: ArchiMate Physical Layer concept definitions (The Open Group, 2016)

Concept Name	**Definition**
Equipment	Equipment represents one or more physical machines, tools or instruments that can create, use, store, move or transform materials
Facility	A facility represents a physical installation, such as a factory, laboratory or warehouse, in or on which equipment can be installed and used
Distribution Network	A distribution network represents a physical network used to transport materials or energy
Material	Material represents a passive structure element that represents tangible physical matter or physical elements

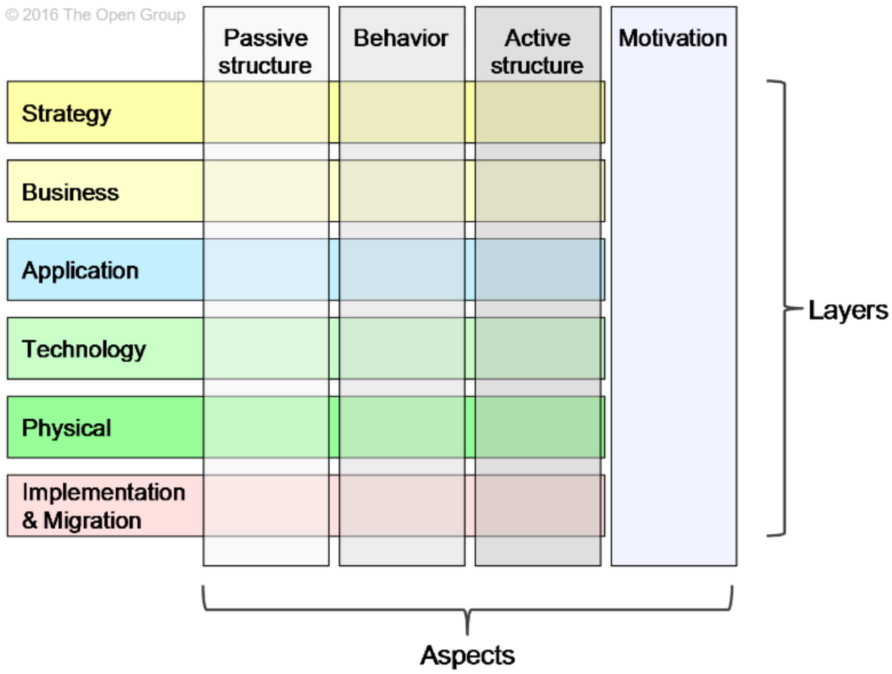


Figure 4: The complete ArchiMate 3.0 EAF (The Open Group, 2016)

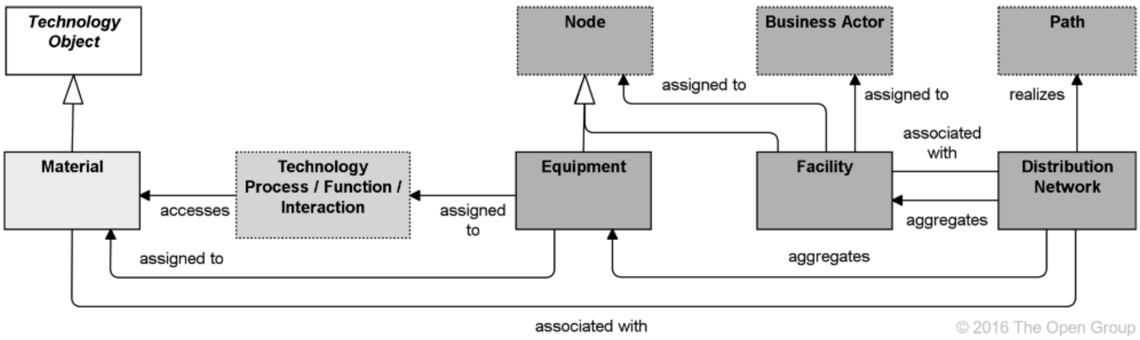


Figure 5: ArchiMate Physical Layer metamodel (The Open Group, 2016)

4.4 ISA-95

Given that the manufacturing domain, per the definition chosen for this research, consists of the business, IT and physical domains, it should be possible to fully model a manufacturer based on the concepts included in ArchiMate 3.0. Manufacturing firms come in many shapes and sizes and to verify whether ArchiMate is suited to model them all, a comparison needs to be made to a formal definition that applies to any manufacturer.

In an effort to define a standards framework for value net modeling in the context of Industry 4.0, (Mazak & Huemer, 2015) suggest a standard published by The International Society of Automation (ISA) that defines enterprise/control systems integration mechanisms for manufacturers, called ANSI/ISA-95 (International Society of Automation, 2010) or ISA-95 for short. ISA-95 is also accepted as an international standard under ISO/IEC 62264. Table 3 briefly lists each part of the standard.

Table 3: ISA-95 Standard Issues

ISA-95 Standard Issue	**Description**
ANSI/ISA-95.00.01-2000	Models and Terminology
ANSI/ISA-95.00.02-2001	Object Model Attributes
ANSI/ISA-95.00.03-2005	Models of Manufacturing Operations Management
ISA-95.04 (in development)	Object models and attributes for Manufacturing Operations Management
ISA-95.05 (in development)	Business to manufacturing transactions

The most important parts or the standard, for the purposes of this research, are the hierarchical process model (part 1) and the common object model (part 2). The following sections discuss each separately.

4.4.1 The Process Model

ISA-95 defines five business process levels. Each level (labeled 4 to 0) distinguishes processes that act on increasingly granular time frames (International Society of Automation, 2010):

Level 4: Strategic control, or Business Planning & Logistics, establishes the basic plant schedule including the products produced, materials used, delivery and shipping. Processes at this level typically act on months, weeks or days.

Level 3: Tactical control (also called *Manufacturing Operations Management*). Responsibilities include workflow/recipe control, producing the desired products, maintaining records and optimizing the production process (continuous improvement). The time frame at this level ranges from days to shifts, hours minutes and seconds.

Level 2: Part of *Process Management*. Level 2 concerns the monitoring, supervisory control and automated control of the production process. Production control classes range from continuous to batch to discrete controls. The time frame for process management ranges from hours to sub-seconds.

Level 1: The second part of Process Management is associated with sensing and manipulating the production process.

Level 0: The actual *production process*. This layer includes physical processes that transform raw materials to the desired product. Examples are the annealing of metal coils or the extraction of minerals from the soil.

The ISA-95 process hierarchy model is also illustrated in

Figure 6.

4.4.2 The Common Object Model

ISA-95 defines several information models that define the core concepts of the standard, as well as the properties associated with them, as part of the Common Object Model (COM). Concepts included are related to the following subjects: personnel, equipment, physical assets and materials. Additionally, ISA-95 defines models for production-specific information, including production scheduling, production performance, product definition and production capability.

4.4.2.1 Relation to Architecture

A mapping of the ISA-95 COM onto the Zachman Framework has already successfully been made (Panetto, Baïna, & Morel, 2007). Their goal was to use ISA-95 to provide traceability of data for key enterprise users. Their mapping describes which parts of the COM provide the information necessary to model each of the viewpoints in the framework (see Figure 7). While the Zachman Framework cannot directly be used to model an enterprise architecture (it is not a language), this mapping does help in abstracting the implementation-level models to the architectural level. For the purposes of this research, however, it will be necessary to make a mapping on the concept level, rather than the model level. Analyzing the information models and compiling a list of definitions of each concept will provide complete set of concepts that describe a manufacturing firm. This set will serve as the basis for the mapping of ISA-95 onto ArchiMate. ISA-95 identifies 105 concepts in total. For the complete list of concepts associated with the COM, please refer to Appendix A.

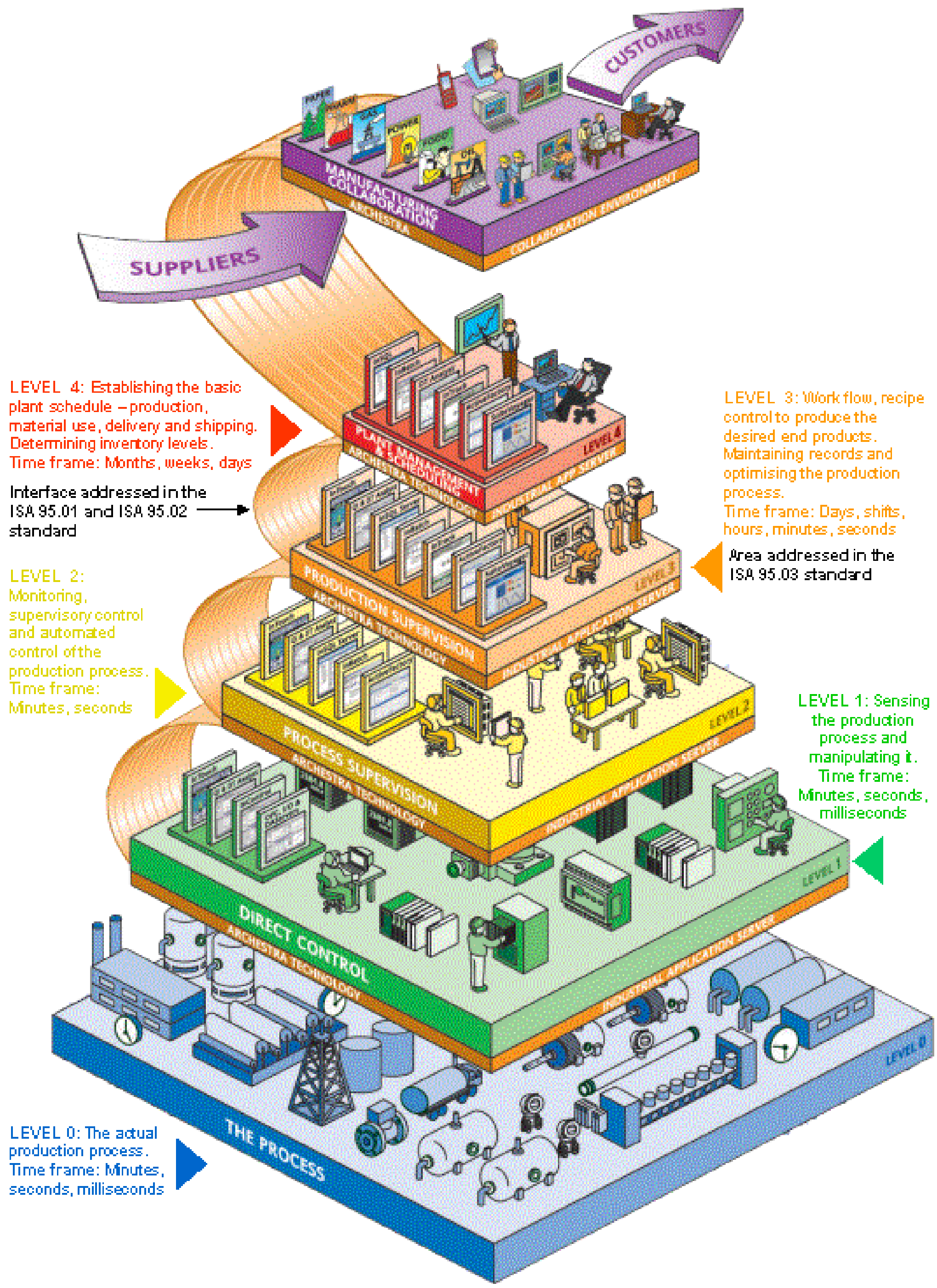


Figure 6: The ISA-95 process hierarchy model (WonderWare, n.d.)

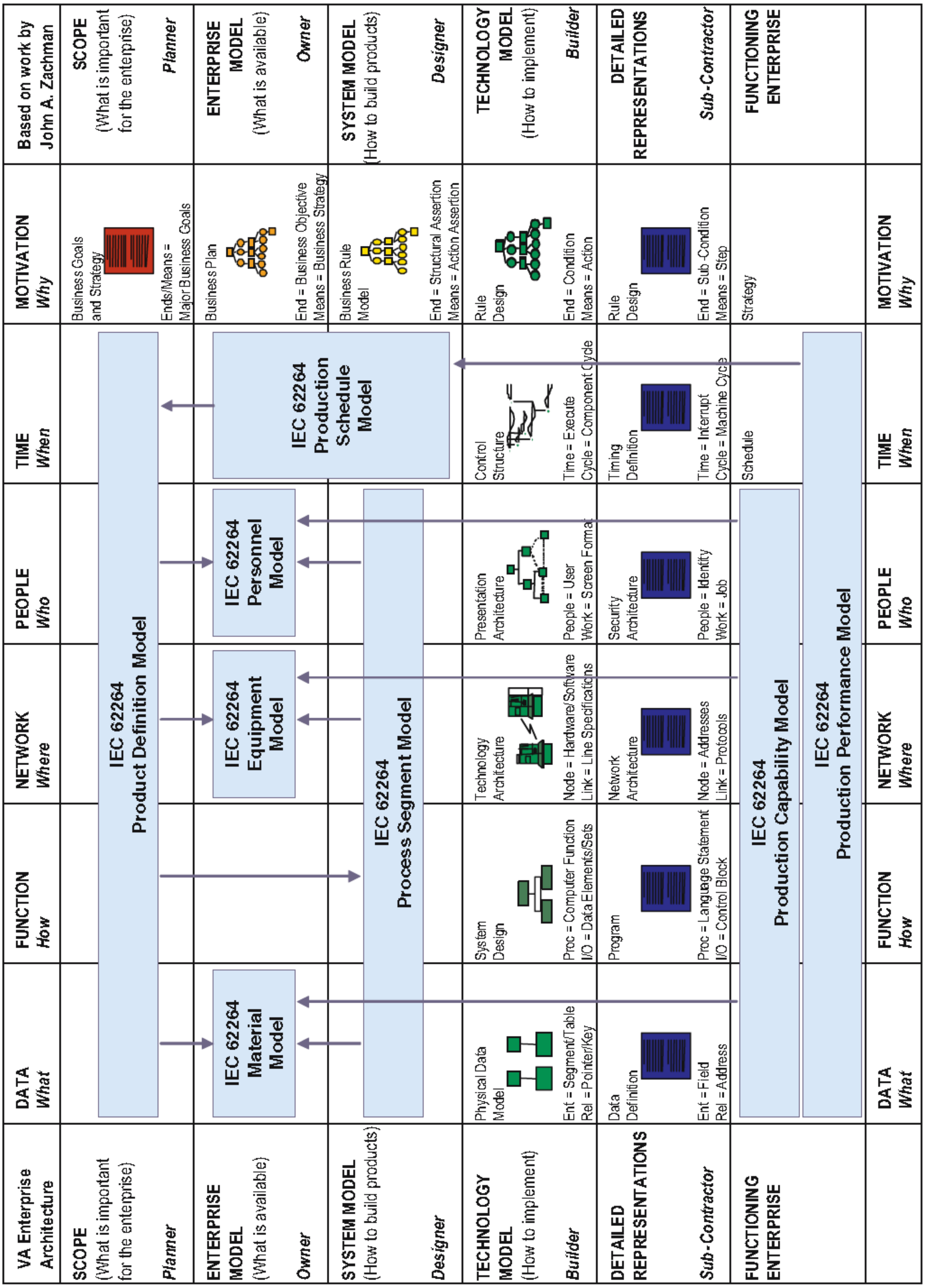


Figure 7: Mapping of ISA-95 (IEC 62264) to the Zachman Framework (Panetto et al., 2007)

5 Mapping of ISA-95 Concepts onto ArchiMate

This chapter describes which concepts from ISA-95 fit with which ArchiMate concepts, as well as which do not, and explains why this is the case. At the end of this chapter, the first two sub-research questions are answered.

5.1 Analysis Structure

The first part of the analysis will be dedicated to defining which concepts from ISA-95 should be considered architectural concepts. Appendix A provides a reference for each concept. ISA-95 standardizes the information exchange between levels 3 and 2 of the manufacturing enterprise on an abstraction level that is well suited for systems implementation, which is why it defines a large amount of concepts that are quite narrowly defined. Conversely, ArchiMate is meant as a general purpose architecture language and defines concepts at a highly abstract level. Much like for the mapping of ISA-95 onto the Zachman framework (Panetto et al., 2007), it is necessary to first perform a normalization to a level of abstraction that is the same as that of the concepts to which the mapping will be made. Since ArchiMate is a language rather than an EAF, it will be necessary to normalize each concept of ISA-95 (rather than the models to which they belong).

The next step of the analysis will be to map each ISA-95 architecture concept to a concept in ArchiMate. Using the list of concepts resulting from the normalization step, each ISA-95 definition is compared to each ArchiMate definition. A mapping will be made between concepts which definitions have the same meaning. Once there is a mapping of concept definitions, an analysis can be made of whether the direct relations of each concept are also shared between ISA-95 and ArchiMate.

Finally, based the resulting mapping, a classification can be made of any mapping deficiencies. A deficiency (Wand & Weber, 2002) in the mapping is a possible risk to the expressiveness of models based on it. Classifying each deficiency will help find a suitable solution to it in a further stage.

5.2 NB: The Excel Spreadsheet

The following sections will on multiple occasions refer to an Excel spreadsheet. This spreadsheet contains the results of both the normalization step as well as the mapping of ISA-95 concepts to ArchiMate. It also contains the argumentation for each normalization and mapping. The spreadsheet provides a visual impression of a large amount of information, which in the opinion of the author is preferable over adding another 20 pages to this document. The Excel spreadsheet can be downloaded here[1].

5.3 Concept Normalization

Before mapping ISA-95 to ArchiMate, a subset of *architectural* concepts needs to be derived from the set of general manufacturing concepts defined by ISA-95. ISA-95 was written with IT/OT integration in mind. To apply its concepts to architecture modeling, an assessment needs to be made of which concepts identify as architectural. For this purpose, it is necessary to perform a normalization of ISA-95 concepts to a level of abstraction that is the same as that of ArchiMate's concepts.

5.3.1 Method

The method for the normalization of ISA-95 will be the same that was used to define the current set of concepts for ArchiMate, based on a layered structure of specialization levels (Lankhorst et al., n.d.). Figure 8 illustrates this layered strucutre. Starting at the top, concepts are defined in a highly abstract manner as simply entities and relationships between them. At the next level,

[1] http://bit.ly/2amGJqi

concepts are specialized as either passive structure concepts, behavior concepts or active structure concepts, corresponding to the basic structure of the ArchiMate language. Concepts are then further specialized as enterprise architecture concepts. Finally, concepts are specialized to a finely grained level of abstraction at the project level. At each specialization step, the utility of the specialization must be argued based on the modeling goals that the designer has in mind.

Since the ISA-95 concepts need to be normalized to the same level as the concepts in ArchiMate to which they will be compared, each architectural concept will need a specialization relation to one of the concept types defined as part of the *dynamic system* level (see Figure 5). If a specialization relation cannot be defined, the ISA-95 concept is not architectural. Any specialization relation will be agued based on the definition of the ISA-95 concept in question.

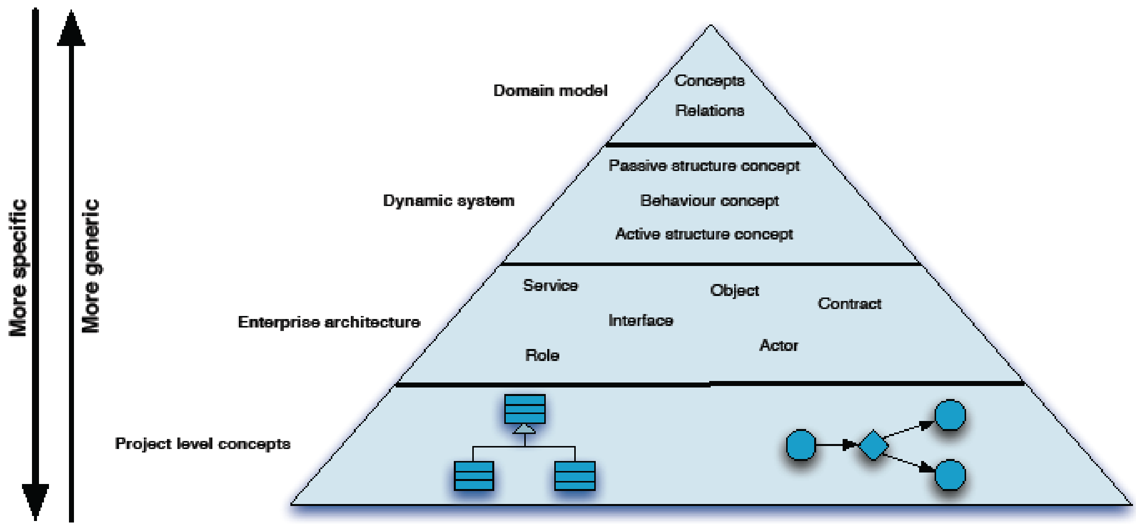


Figure 8: ArchiMate Specialization Layers (Lankhorst et al., n.d.)

5.3.2 Results

The results of the normalization analysis are included schematically as part of the Excel spreadsheet, specifically on the *'Dynamic System Specializations'* tab. Concepts with black names have a specialization relation of some kind. Cells marked blue indicate the relation specifics. Non-architectural concepts are marked as underlined and with red text. Each colored cell contains a comment explaining the reasoning behind the specialization relation.

5.4 Concept Definition Mapping

To determine to what extent ArchiMate 3.0 is capable of expressing the architecture of a smart manufacturer, a mapping of the architectural ISA-95 concepts needs to be made onto ArchiMate 3.0. First, concepts will be mapped based on definition. Using this mapping of definitions, it will be possible to also map the relationships between concepts.

5.4.1 Method

Based on the list of architectural concepts resulting from the previous step, as well as the definitions provided in the specifications of ArchiMate (The Open Group, 2016) and ISA-95 (International Society of Automation, 2010) (see Appendix A for a summary of the meta-model), a mapping can been made of concepts that share definitions to such a degree that they can be considered to have the same meaning.

The definition of each architectural ISA-95 concept is compared to the definition of every ArchiMate concept. The specialization relation defined during the normalization analysis limits the concepts to which an ISA-95 concept can map. For example, an ISA-95 concept that specializes a passive structure concept, can only map to an ArchiMate concept that also specializes a passive structure concept.

5.4.2 Results

The result of the concept definition mapping analysis has been included as part of the Excel spreadsheet, specifically the *'Enterprise Architecture Layer'* tab. When two concept definitions match, the corresponding cell is marked blue and contains a comment explaining the reasoning behind the mapping. If, as determined by the next part of this analysis, the direct relationships of a concept also overlap, the cell will be marked green instead.

5.4.2.1 n-to-m mappings

In some cases, it turns out that that several concepts from ISA-95 match several other concepts from ArchiMate. This results in an ambiguous mapping scenario, making it impossible to classify any mapping deficiencies before the ambiguity is resolved. This section discusses each case where an n-to-m mapping occurs and disambiguates each occurrence.

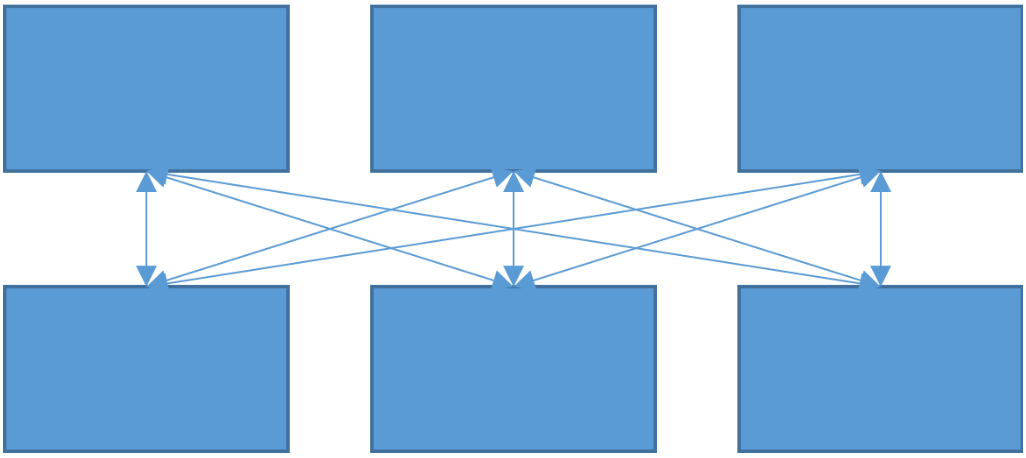


Figure 9: n-to-m mapping illustration

N-to-M mapping case 1

Process Segment, Process Segment Dependency, Operations Segment, Operations Segment Dependency

Map to

Business Process, Business Function, Business Interaction, Business Event

There appears to be an n-to-m mapping in this scenario. However, strictly comparing the definitions of the ISA-95 concepts, as well as the relations they share to surrounding concepts (depth = 1), these concepts turn out to be synonymous. This eliminates the issue. This case shall be further referred to as *Process Segment*.

N-to-M mapping case 2

Equipment Class, Equipment

Map to

Business Role, Location, Equipment, Facility

In this scenario, Equipment and Equipment Class are not synonymous per the ISA-95 meta-model. However, given that ArchiMate does not distinguish between classes and instances, Equipment Class and Equipment can safely be abstracted to mean the same thing. This eliminates the issue. This case shall be further referred to as *Equipment*.

5.5 Concept Relations Mapping

The final step in the mapping process is to compare the relations of the mapped concepts for each meta-model. Using the concept definition mapping discussed in the previous section, it becomes possible to compare the direct relations of the mapped concepts. Once the relationships have been mapped, further analysis may uncover any deficiencies in the ArchiMate meta-model's expressiveness with regards to modeling the enterprise architecture of a smart manufacturer.

5.5.1 Method

A concept can only be mapped if the other meta-model also mirrors its direct relations. Given the mapping of concepts based on their definitions, the relations comparison involves matching the relations between the concepts from ISA-95 and their mapped concepts in ArchiMate, both at a depth of 1. Both the strength and direction of each relation need to be taken into account. In ArchiMate, there is a strict hierarchy of relationship strengths. A strong relationship can be expressed as a weaker type, not vice versa (Lankhorst et al., n.d.). Table 4 lists all relationship types from strongest to weakest.

Table 4: ArchiMate relationship types (Lankhorst et al., n.d.)

Relation	**Description**
Composition	Indicates that a concept consists of a number of other concepts
Aggregation	Indicates that a concept groups a number of other concepts
Assignment	Links behaviour concepts with active structure concepts (e.g. roles, components) that perform them, or roles with actors that fulfil them
Realisation	Links a logical entity with a more concrete entity that realizes it
Specialisation	Indicates that an object is a specialization of another object
Used by	Models the use of services by behaviour concepts and the access to interfaces by structure concepts
Access	Models the access of behaviour concepts to business or data objects
Association	Models a relation between concepts that is not covered by another, more specific relationship.

For each ISA-95 concept that has a definition mapping, a list was made of its relations to other ISA-95 concepts. If the related ISA-95 concept also maps to an ArchiMate concept, an inquiry was made on whether a relation exists between the two ArchiMate concepts. If a relation indeed exists, its meaning was compared to the meaning of the relation in ISA-95. If these relations are similar, a mapping can be made. If the relations are not similar, or if there exists no relation at all, no mapping is possible.

5.5.2 Result

The result of the relationships mapping was also included in the concepts matrix in the Excel spreadsheet. The cells marked green represent a concept with both a definition fit and relationships fit. If a concept that maps based on its definition does not have a relations fit, a comment was added explaining why.

5.6 Conclusion

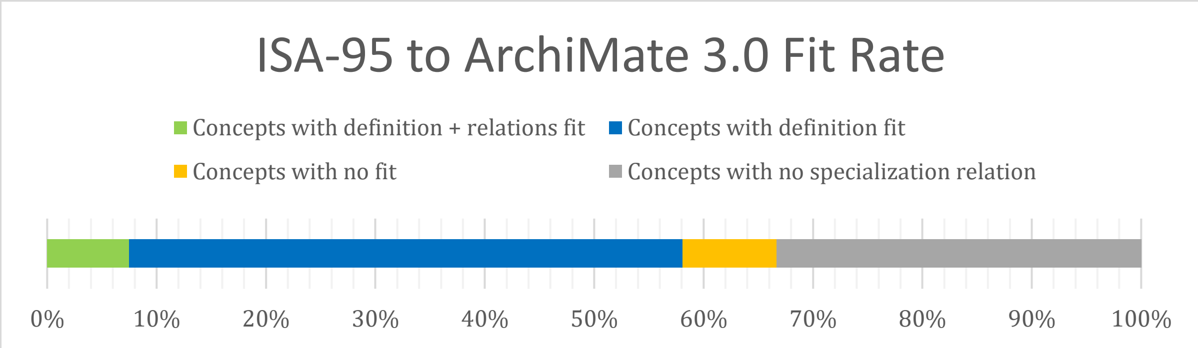


Figure 10: Fit-rate of ISA-95 concepts with ArchiMate, illustrated schematically

Based on the analysis results provided in this chapter, the first couple of sub-questions can be answered. The actual analysis results have, for the sake of readability, been left out of this report and are instead made available as an Excel spreadsheet, which can be downloaded here[2].

SQ1. Which architecture viewpoints and constructs are needed to model any (smart) manufacturing enterprise up to the process management level per ISA-95?

Each concept from ISA-95 has been classified as either architectural or non-architectural. Of all ISA-95 concepts, 66% are architectural. The remaining 33% are non-architectural concepts.

For a reference on which concepts specifically are considered architectural, please refer to the Excel spreadsheet.

SQ2. How do the architectural concepts of ISA-95 map onto ArchiMate 3.0?

The set of architectural ISA-95 concepts has consequently been mapped to ArchiMate 3.0, first by definition and then by relationships to other architectural concepts at a depth of 1.

As it stands, 8% of ISA-95 concepts can be mapped to ArchiMate immediately. 50% has one or more relationships that cannot be mapped one-to-one. 9% of concepts has no matching definition in ArchiMate. Architectural concepts that do not have a definition *and* relations fit pose issues that need to be resolved before ArchiMate can be used to model a smart manufacturing enterprise. The next chapter discusses these issues and proposes solutions.

The mapping of ISA-95 concepts onto ArchiMate can be found as part of the Excel spreadsheet.

[2] http://bit.ly/2amGJqi

6 Deficiencies

Chapter 5 has concluded that not all of ISA-95's concepts map to ArchiMate 3.0 one-to-one. Based on the completed mapping, any potential gaps in ArchiMate's meta-model can be classified. Classifying each potential gap will help find a suitable solution to it in a further stage. At the end of this chapter, the third sub-research question is answered.

6.1 Method

Based on the completed mapping, several deficiencies may be uncovered. The complete set of mappings will be analyzed for deficiencies. Table 5 describes each type of deficiency as defined by Wand & Weber (2002).

Table 5: Types of deficiencies (Wand & Weber, 2002)

Type	**Description**
Construct overload	Several ontological constructs map to one grammatical construct
Construct redundancy	Several grammatical constructs map to one ontological construct
Construct excess	A grammatical construct might not map to any ontological construct
Construct deficit	An ontological construct might not map to any grammatical construct

Since this research assumes that ISA-95 describes the manufacturing domain perfectly, it shall be referred to as an ontology of the domain. ArchiMate must, as a language, be able to describe the manufacturing domain. It shall be referred to as the grammar in this case.

Despite normalizing ISA-95 to architectural concepts only, its architectural concepts may still be defined at a lower abstraction level from ArchiMate. As such, there are several occurrences where several ISA-95 concepts map to one ArchiMate concept. Here, construct overload occurs. Such a case must be judged on whether any critical expressiveness is lost.

Likewise, when ArchiMate does not define a concept that is defined in ISA-95, a construct deficit occurs. Deficits (gaps) are of particular interest, since they limit the expressiveness of ArchiMate in terms of the manufacturing domain.

For this research, it is irrelevant whether or not ISA-95 can express the ArchiMate meta-model. Thus, construct redundancy and construct excess are excluded from the analysis.

Finally, when a mapping cannot be classified as one of the deficiencies mentioned, it should be considered sound (i.e. the concepts from ISA-95 and ArchiMate map one-to-one). Sound mappings are not discussed as part of this chapter.

As part of this analysis, each mapping between ArchiMate will be classified as either one of the above deficiencies, or as sound.

6.2 Results

This section discusses the results of the deficiencies analysis per deficiency type.

6.2.1 Construct Overload

Construct overload, where one ontological concept maps to several grammatical constructs, occurs in the following cases:

Business Object

Business Object is used to represent information objects that are used on the shop floor and may serve as a placeholder for more complex entities like a schedule or a bill of materials. Specifically, the following concepts map to Business Object:

- Qualification Test Specification
- Equipment Capability Test Specification
- Physical Asset Capability Test Specification
- Material Test Specification
- Material Assembly
- Material Definition Assembly
- Material Class Assembly
- Personnel Segment Specification
- Equipment Segment Specification
- Material Segment Specification
- Material Segment Specification Assembly
- Physical Asset Specification
- Operations Material Bill
- Personnel Specification
- Equipment Specification
- Physical Asset Specification
- Material Specification
- Material Specification Assembly
- Operations Schedule
- Segment Requirement
- Personnel Requirement
- Equipment Requirement
- Physical Asset Requirement
- Material Requirement

Where a business object is used as a placeholder, the model will depend on relationships to other entities to provide the expressiveness needed to express the intended meaning of the concept. If this level of expressiveness cannot be achieved, this causes a construct deficit. Construct deficits are discussed in the section 6.2.2.

Business Role
Personnel Class and Equipment map to Business Role. This happens specifically in the case where Equipment refers to an automated production unit. This abstraction loses the direct distinction between a manual and an automated role. However, depending on whether a given role depends on an actor or not, this distinction can still be derived.

Material
Material Class, Material Definition, Material Lot and Material Sublot map to Material in ArchiMate. Because of this abstraction, Material loses the distinction between a class of material and a specific type of material used as part of a process. Furthermore, the difference between a class of material and an identifiable (group of) its instances is lost. In the case of Material Lots, this causes issues discussed in section 0.

6.2.2 Construct Deficit
Several deficits (or gaps) have been identified as part of the mapping analysis. When a gap occurs, the ISA-95 concept cannot be expressed in ArchiMate. Each gap is explained in the sections below.

Test Specifications
Various concepts in ISA-95 are related to a test specification, that is used to test certain properties of said concepts. A Test Specification maps to a Business Object. The ArchiMate meta-model only allows for an association relationship between Active Structure concepts and a Business Object. The dependency in ISA-95 is, however, stronger (<is tested by>).

Assemblies
An assembly is a collection or set of related elements. In ISA-95, they are represented as classes related to aggregation relationships between elements. In ArchiMate, every element can also have an aggregation relation with an element of the same type. There is, however, no class that represents information about this relation.

Process Segment Parameters
A process segment (maps to business process) in ISA-95 is a collection of several concepts, including specific parameters that do not fall into the category of personnel, equipment, physical

asset or material. The 'other' parameters are known as process segment parameters. ArchiMate allows only well-defined concepts to be related to a business process.

Material Lots

While an ISA-95 Material can be directly mapped to an ArchiMate material, a problem occurs when attempting to map a Material Lot. A requirement for a Material Lot is that, based on the ID of a lot, it should be possible to determine its current state. This requires traceability to an information object, i.e. a Business Object. While it is possible to relate a Material Lot to a Business Object by means of an association, the relationship between a physical object and information object is deemed more meaningful.

Operations Definitions

The operations definition describes the relation between a production, maintenance, inventory or quality operation, the way in which it is implemented and the resources that are needed to carry out the process. A framework for these kinds of *manufacturing operations* is defined by the first part of ISA-95. ArchiMate only loosely defines business processes, independent of their context.

Operations Schedule

ISA-95 defines a schedule concept. It is implemented as a set of operations requests, which directly relate to an operations definition. There is no similar concept in ArchiMate.

Operations Performance

ISA-95 makes a distinction between the definition of a process, the planned process and the actual process. Once executed, Operations Responses are returned for every Operations Request (which make up the schedule). In ArchiMate, an Operations Response can be represented as either a Business Object or Data Object, depending on whether this information is collected digitally or not. The actual production information is, however, much too volatile to model as part of the architecture.

6.3 Non-architectural concepts

There are several ISA-95 concepts that have been deemed non-architectural per the normalization analysis. While these concepts do not need to be mapped to ArchiMate, they do describe a part of the manufacturing domain. Thus, ArchiMate should at least be able to express the meaning of these concepts.

One large group of non-architectural concepts concerns the properties of objects (or resources) in the manufacturing domain. Specifically, properties can be associated with people, equipment, physical assets and materials. A resource can have zero or more properties, each describing some relevant information about said resource. For example, properties associated with a person can include their personal set of skills, while properties associated with a material might include its grade, length or weight.

Another non-architectural concept is the Equipment Asset Mapping, which describes an assignment relation between a piece of equipment and physical asset. Information is also stored about this relation, such as the time duration in which the equipment is assigned to the physical asset.

6.4 Conclusion

Based on the analysis provided in this chapter, the following question can now be answered:

SQ3. What are the deficiencies in the expressiveness of ArchiMate 3.0 with regards to the manufacturing domain per ISA-95?

To determine which deficiencies in the expressiveness of ArchiMate 3.0 exist, when attempting to express ISA-95, the result of the mapping analysis described in chapter 5 was classified using the criteria set forth by Wand & Weber (2002). They argue that several types of deficiencies exist, chief among which for the purposes of this research are:

- Construct overload, where several ISA-95 concepts map onto a single ArchiMate concept, as well as;
- Construct deficit, where an ISA-95 concept does not map to any ArchiMate concept

Multiple instances of construct overload were identified, as described in section 6.2.1. Several ISA-95 concepts map to Business Object, Business Role and Material. For Business Object and Material, some cases of construct overload lost critical expressiveness. This means that Business Object and Material are not currently sufficiently expressive to express their ISA-95 counterparts. Patterns that improve the expressiveness of these concepts will be discussed as part of the next chapter.

Furthermore, instances of construct deficit were also identified. Specifically, the following concepts cannot be mapped to ArchiMate:

- Test Specifications
- Assemblies
- Process Segment Parameters
- Material Lots
- Operations Definitions
- Operations Performance

The next chapter will discuss ways to express these concepts either through patterns of existing ArchiMate concepts, or through patterns that make use new constructs.

7 Solution Design

Now that the mapping analysis of ArchiMate with relation to the manufacturing domain is complete, the identified gaps can be used to define solutions that allow ArchiMate 3.0 to express all the necessary concepts in ISA-95. This chapter discusses At the end of this chapter, the fourth sub-research question is answered.

7.1 Method

Using the mapping of ISA-95 concepts onto ArchiMate, several gaps have been identified. A gap is a situation where a 1:1 mapping cannot be achieved, either because a relationship between ISA-95 concepts cannot be mirrored in ArchiMate, or because an ISA-95 concept does not exist in ArchiMate at all. To read about the gaps found, please refer to section 0.

To achieve full coverage of the manufacturing domain in ArchiMate, solutions need to be found that fill these gaps, allowing the concepts from ISA-95 to be meaningfully expressed. The goal of the solution design will thus be to find modeling patterns based on the meta-model of ArchiMate, preferably using existing constructs only. If it is not possible to use existing constructs, a pattern will be proposed based on either constructs from another language (e.g. BPMN), or based on new constructs that need to be introduced to ArchiMate. A pattern will always be motivated based on a comparison between the ISA-95 and ArchiMate meta-models, arguing why the pattern solves a particular mapping problem.

7.2 Requirements

Criteria used to evaluate the design choices for each pattern will be the *intended scope* of Archimate, the *degree of similarity* of concept definitions between languages (i.e. only map concepts that match both in terms of definition and relations to other concepts) and the *level of model complexity* introduced as the result of a potential change. Another concern is that, ideally, models that a manufacturer is likely to have already defined should remain relevant. This means that definitions of existing concepts can only be broadened, rather than narrowed down.

In the case where a new construct must be introduced to ArchiMate, the following requirements apply:

Table 6: ArchiMate Modeling Concept Requirements (Lankhorst et al., n.d.)

Requirement	**Description**
Concept Coverage	ArchiMate identifies the following groups of concepts that must be covered by the language: product, process, organisation, information, application and technology.
Enterprise Level Concepts	ArchiMate prioritizes overview and coherence over specificity and detail.
Concept Mapping	Concepts in ArchiMate must be able to map to more fine-grained, project specific concepts.
Unambiguous definitions of concepts	There can be no ambiguity as to the meaning an definition of modeling concepts. The following properties of a concept definition must be specified: informal description, specialisation, notation, properties, structuring, rules and restrictions and guidelines for use.
Conformance to international standards	The architecture description language must follow and, whenever possible, influence international standards.
Structuring mechanisms	The following mechanisms must be supported: compisition, decomposition, generalisation, specialisation and aggregation.

Abstraction	Relations between concepts may correspond to different levels of abstraction.
Consistency	It must be possible to perform consistency checking of architectures.
Tracing of design decisions	It must be possible to register, trace and visualise the requirements, constraints, design decisions and architectural principles that are used in the construction of the architecture.
Extensibility	The language should be easy to maintain and extend, should the need for new concepts arise.

Additionally, the following requirements correspond to analysis capability:

Table 7: ArchiMate Analysis Capability Requirements (Lankhorst et al., n.d.)

Requirement	**Description**
Analysis of architectural properties	It must be possible to perform qualitative and quantitative analyses of properties of architectures.
Impact of change analysis	Impact of change analysis must be supported. This includes the impact of a change on other architectural elements, on the architecture itself and on the characteristics of the architecture.

Finally, ArchiMate lists several requirements on the visualisation of the language:

Table 8: ArchiMate Visualisation Requirements (Lankhorst et al., n.d.)

Requirement	**Description**
Representation of concepts	The visual representation of ArchiMate concepts must be easily adaptible
Consistency of presentation	The visual representation of ArchiMate concepts needs to be consistent and unambiguous
Visualisation independence	Visualisation techniques should be independent of the actual concepts used in a model
Visualisation generation	Automatic generation of vvisualisations from architecture models must be supported
Viewpoint definition	A viewpoint definition must state the stakeholder for which it is intended, the concerns covered by the viewpoint and the concepts and format that should be used
Adaptability of viewpoints	Viewpoints must be adaptable and extensible independent of visualisation techniques
Viewpoint coverage	ArchiMate has to support often used 'general' viewpoints for frequently occurring stakeholders

Aside from these specific requirements, ArchiMate requires the following genereal quality criteria:

Table 9: ArchiMate General Quality Requirements (Lankhorst et al., n.d.)

Requirement	**Description**
Conceptual Integrity	The degree to which a design can be understood by a single humand mind, despite its complexity. A good design exhibits a coherent vision, which is easy to understand by others.
Orthogonality	Do not link what is independent

Generality	Do not introduce multiple functions that are slightly divergent
Economy	Do not introduce what is irrelevant
Propriety	Do not restrict what is inherent

7.3 Solutions per problem

7.3.1 Test Specifications

Figure 11: Test Specification Pattern for ArchiMate 3.0

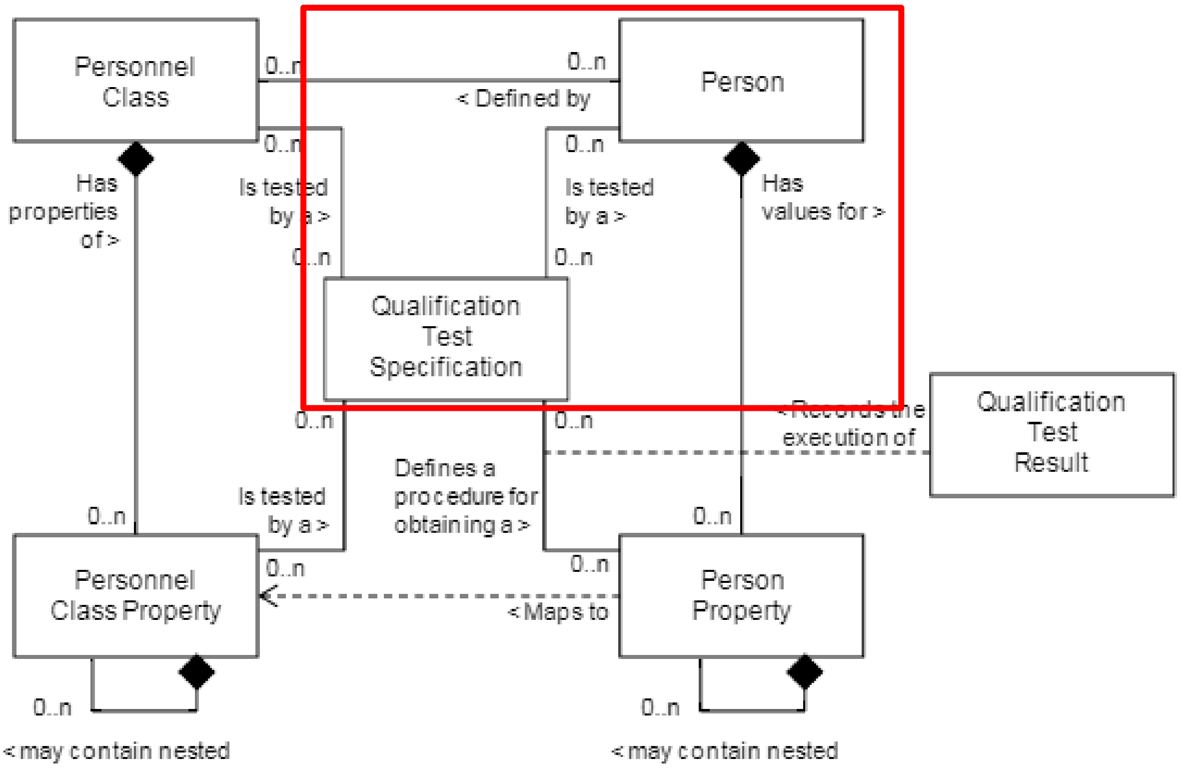


Figure 12: Example of a Test Specification in ISA-95, outlined in red. In this case, it applies to a Person.

Various concepts in ISA-95 are related to a test specification, that is used to test certain properties of said concepts. Often, these concepts are mapped to active structure concepts in ArchiMate. For example, a Person (maps to Actor) relates to a Qualification Test Specification (maps to Business Object). Figure 12 illustrates this relation. A Business Object is, however, a passive structure concept. The ArchiMate meta-model only allows for an association relationship between Active Structure concepts and a Business Object. The dependency in ISA-95 is stronger (<is tested by>). This causes problems for the mappings listed in Table 10. Please read the table as follows, from left to right: An ISA-95 concept has a relation to another ISA-95 concept. The first concept maps to an ArchiMate concept, the second concept maps to another ArchiMate concept.

Table 10: Unmappable Relations between Concepts and Test Specifications

Concept	Is Related To…	Concept Maps To…	Relation Maps To…
Person	Qualification Test Specification	Business Actor	Business Object
Personnel Class	Qualification Test Specification	Business Role	Business Object
Equipment	Equipment Test Specification	Business Role, Equipment, Facility	Business Object
Equipment Class	Equipment Test Specification	Business Role, Equipment, Facility	Business Object
Physical Asset	Physical Asset Test Specification	Equipment, Facility	Business Object
Physical Asset Class	Physical Asset Test Specification	Equipment, Facility	Business Object
Material Class	Material Test Specification	Material	Business Object
Material Definition	Material Test Specification	Material	Business Object
Material Lot	Material Test Specification	Material	Business Object
Material Sublot	Material Test Specification	Material	Business Object

A stronger relation between an Active Structure concept and a Business Object can only be established via a Behavior concept, specifically the <assigned to> (for Active Structure concepts) and <accesses> (for Business Objects) relations with Business Service/Business Event/Business Process. Since the physical layer relates to Business Process/Business Function/Business Interaction and not services or events, this leaves Business Process as the common denominator. This results in the pattern proposed in Figure 11, which enables every mapping in Table 10.

The proposed pattern is structured as follows. Firstly, there must exist an active structure element, like a Business Actor or a Business Role. This is the element that needs to be 'tested'. This element needs to be related to a Business Process via an assignment relation. The Business Process denotes that there will be some activity of testing the active structure object. This reflects the activity of 'testing' that is implied by the <is tested by> relation in ISA-95. Finally, the Business Process is related to a Business Object via an accesses relation. The Business Object reflects the test specification, which describes the aspects of the active structure object that need testing.

7.3.2 Assemblies

An assembly is a collection or set of related elements. In ISA-95, they are represented as classes related to aggregation relationships between elements (see Figure 13). In ArchiMate, every element can also have an aggregation relation with an element of the same type. There is no class that represents information about this relation. For example, to express the size of an assembly, it would be necessary to create a model element for each element in the collection. This makes sense in a scenario where each instance of a class is meaningfully different. For example, since every person has different qualifications, it is meaningful to model people separately as part of a team. However, in the case where the elements of a collection are *not* meaningfully different, e.g. a set of materials used for the production of a batch (bill of materials). In this case, it makes more sense to model each material as a class rather than as separate instances. However, the quantity of the material used for the production of said batch is still meaningful information. Both alternatives below present a solution that makes use of a parameter to a relationship to express meaning. Such a pattern can also be used to express the Operations Material Bill Item concept per ISA-95.

The following patterns that make use of parameters to add the required expressiveness to ArchiMate. For a detailed descriptions of the requirements for a parameter, please refer to section 7.5.1.

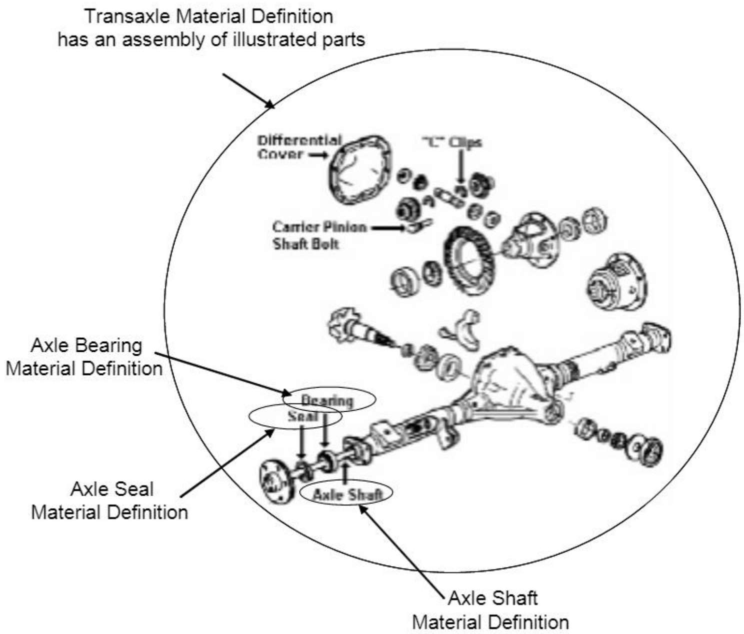


Figure 13: Example of a material assembly (International Society of Automation, 2010)

Alternative 1

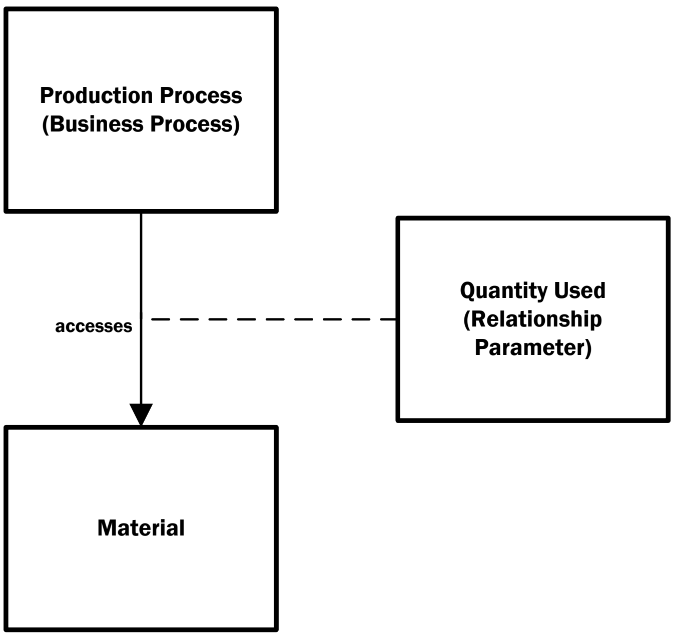


Figure 14: Implicit Bill of Materials pattern for ArchiMate 3.0

To model such information relevant to an assembly, parameters for the relation between the class (e.g. a material) and the assembly (e.g. a bill of materials) is proposed. While ISA-95 defines assemblies broadly, in the specification they only occur in relation to materials. A placeholder mapping for assembly would be a business object. Currently, there exists an indirect relation between Business Object and Material through Business Process. The information relevant to an assembly could be attached to the relation between Material and Business Process as a (set of) parameter(s). This implementation eliminates the need for a separate Business Object by modeling the bill of materials implicitly through the set of relations between said Business Process and the Materials used.

A pattern for the implicit bill of materials is shown in Figure 14. The accesses relation between Business Process and Material currently exists in ArchiMate 3.0. However, the pattern also includes a parameter for the accesses relation, shown at the end of the dotted line. This parameter describes an aspect of the relation, in this case the quantity of the material used as part of the production process.

Alternative 2

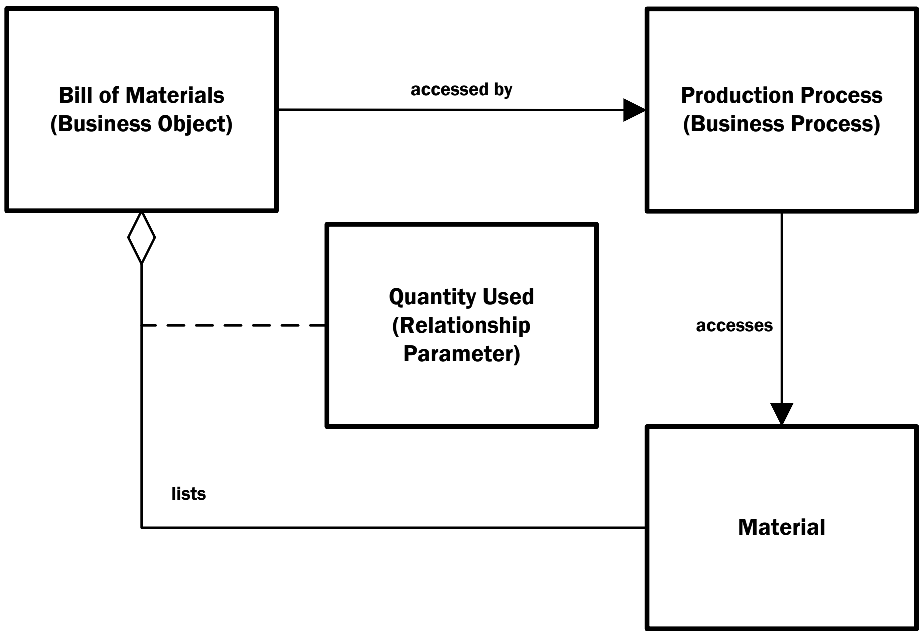


Figure 15: Explicit Bill of Materials pattern for ArchiMate 3.0

However, the solution presented in alternative 1 does not allow for a bill of materials to be modeled explicitly if so desired. For such a scenario, a direct relation between Business Object and Material is necessary. In this case, an aggregation relationship is proposed. An aggregation relationship indicates that a concept (the bill of materials) groups a number of other concepts (materials). While Materials are meaningful independent of one another, the bill of materials groups them for the purposes of use in a production process. The proposed parameters would be attached to this relationship. This solution is, however, not perfect either. The relation between Business Object and Material makes the relation between Business Process and Material redundant, since the Bill of Materials will always be related to a production process (Business Process).

Figure 15 shows a pattern for the modeling of an explicit bill of materials. There are two major differences between this pattern and the pattern for an implicit bill of materials, shown in Figure 14. Firstly, this pattern includes a Business Object that denotes the bill of materials. This Business Object is related to the Business Process via an accesses relation. This relation currently exists in

ArchiMate. The bill of materials lists one or more Materials via an aggregation relation. This aggregation relation is newly introduced for this purpose. Secondly, the information describing the assembly is related to the aggregation relation between Material and Business Object, as denoted by the dotted line.

7.3.3 Process Segment Parameter

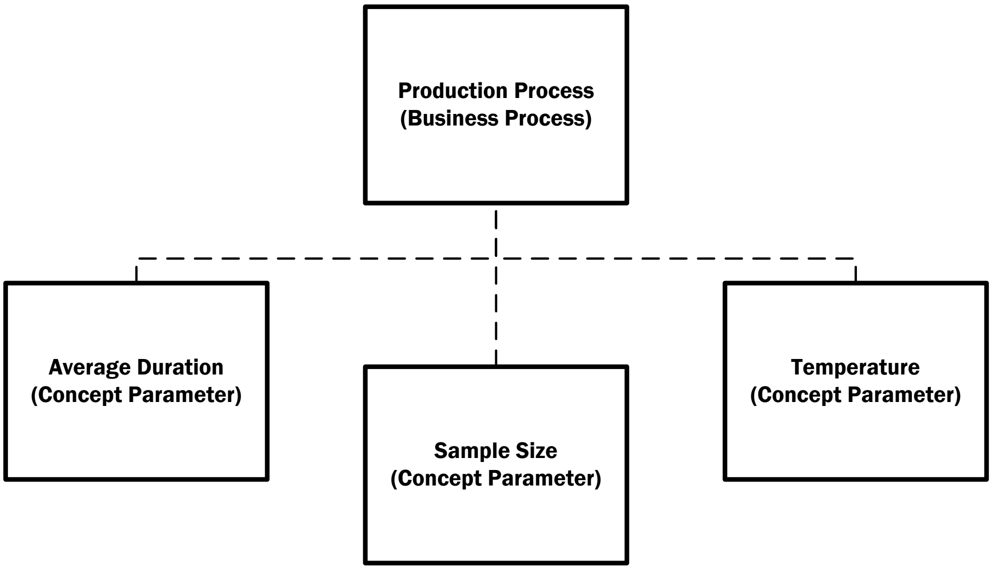


Figure 16: Concept Parameters (example)

A process segment (maps to business process) in ISA-95 is a collection of several concepts, including specific parameters that do not fall into the category of personnel, equipment, physical asset or material. The 'other' parameters are known as process segment parameters. For a production process, an example might include the known lead time of a process step (e.g. the steel coil needs to be in the oven for 10 minutes). For a quality process, a parameter might be the size of the sample to be pulled (e.g. 1 coil per batch).

ArchiMate allows only well-defined concepts to be related to a business process. The only concepts that fit with the description of Process Segment Parameter (i.e. related to business process and not a person, equipment or material) are Business Service and Business Event (behavior), or Business Object (passive structure). A timer like in the oven example would typically be modeled as an event, but a parameter like sample size cannot be expressed formally in ArchiMate. If needed, such information can be included as part of the sub-process name (e.g. take a quality sample, size 1). Modeling this information as such works as a way to capture it informally, e.g. for presentation purposes. However, for analysis purposes, a more formal approach will be required, since information stored in a concept name cannot be queried easily.

The proposed solution is to introduce parameters related to a business process. This is similar to the solution introduced to model assemblies, with the difference being that the parameters are related to a concept rather than a relation. Examples of parameters are average duration, sample size or temperature. This parameter pattern can also be used to model other manufacturing object parameters, per the ISA-95 object properties. The parameter pattern for concepts is illustrated in Figure 16. For a more detailed description of the requirements for a parameter, please refer to section 7.5.1.

7.3.4 Material Lot

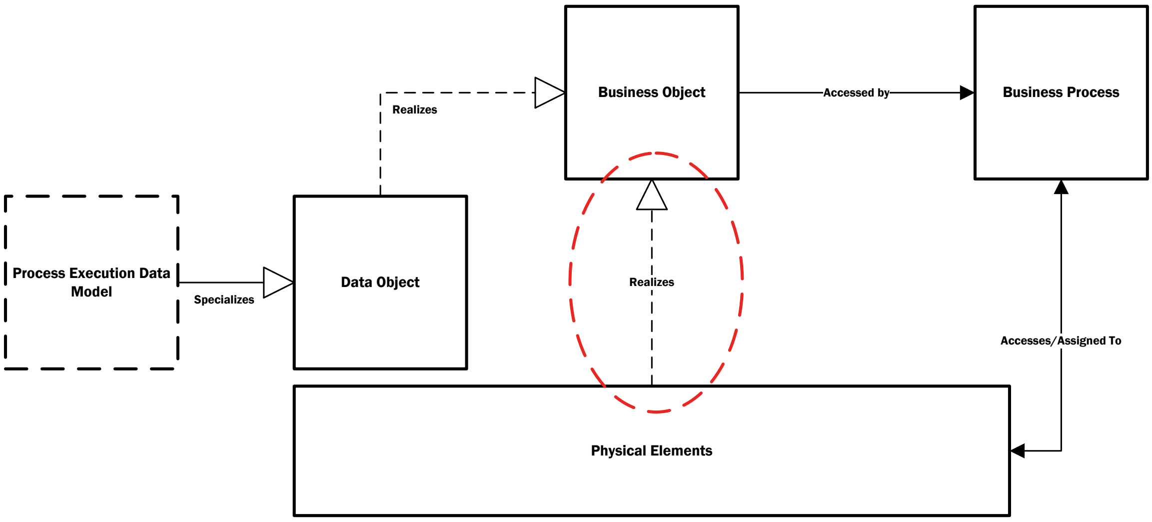


Figure 17: Informational Representation of a Material

While an ISA-95 Material can be directly mapped to an ArchiMate material, a problem occurs when attempting to map a Material Lot. A requirement for a Material Lot is that, based on the ID of a lot, it should be possible to determine its current state. This requires traceability to an information object, i.e. a Business Object. It is possible to associate a Material with a Business Process and a Business Object with a Business Process. It is even possible to draw an association between Material and Business Object. In the case of a Material Lot, however, the relationship between Physical Object and Information Object is more meaningful than an association. The relationship should describe how the informational object reflects the state of the physical object it represents.

To accomplish this expressiveness, a realization relationship is proposed. A realization relationship links a logical entity with a more concrete entity that realizes it. Thus, a realization relation is strong enough to describe how a physical object is represented by an information object. Furthermore, a Data Object may realize a Business Object. This Data Object can, by means of an indirect relation, be considered as the digital representation of said Material stored in some information system. This extrapolation would not be valid if a weaker relation should be used between the physical object and the Business Object. Finally, by linking the data model of said Data Object to the architecture, it becomes possible to perform analyses of a material's production lifecycle.

The same logic also applies to other physical elements. For example, a piece of equipment may be used as part of a business process, causing it to change state (e.g. from 'idle' to 'in use'). Per ISA-95, entities associated with processes include materials, as well as physical assets, equipment and people. Because of this relation in ISA-95, the same realization relation that is proposed for ArchiMate between Material and Business Object is also proposed as a relation between Business Object and Business Role, Business Actor, Equipment and Facility.

Table 11: Proposed relations

Concept	Mapped ISA-95 Concept (e.g.)	Relation	Concept
Material	Material Lot	Realizes	Business Object
Business Role	Personnel Class	Realizes	Business Object
Business Actor	Person	Realizes	Business Object
Equipment	Equipment Class	Realizes	Business Object
Facility	Physical Asset	Realizes	Business Object

Figure 16 illustrates the proposed extension. The newly added realization relation is marked with a red circle. For the sake of legibility, the 'Physical Elements' block serves as a placeholder for the ArchiMate concepts listed in Table 11. The figure also shows how an indirect realization relation between Data Object and a Physical element can be derived using the realization relation between Data Object and Business Object. Finally, the Business Process concept is included to show that the newly added realization relation is only intended for those concepts that have an accesses or assigned to relation with Business Process.

7.3.5 Operations Definition

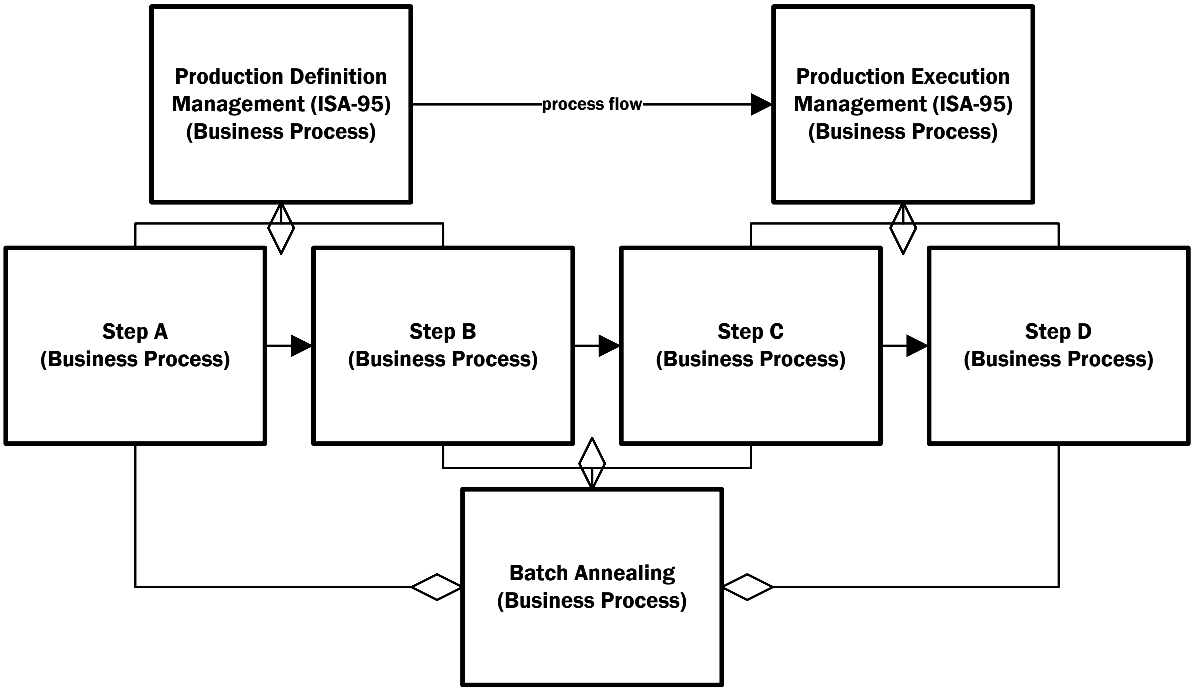


Figure 18: Operations Definition Pattern (example)

The operations definition describes the relation between a production, maintenance, inventory or quality operation, the way in which it is implemented and the resources that are needed to carry out the process. A framework for these kinds of *manufacturing operations* is defined by the first part of ISA-95. ArchiMate only loosely defines business processes, independent of their context. However, the ISA-95 process framework can be implemented in ArchiMate (see Figure 18). It can then provide structure through composition relations from framework processes to processes that are company-specific.

Figure 18 shows a pattern for how to apply the ISA-95 framework to company-specific business processes. Such processes are modeled as sub-processes (hence the composition relation) of ISA-95 processes. Since both ISA-95 processes and their sub-processes have flow relations between them, sub-processes cannot compose more than one ISA-95 process. If a process in a currently existing model cannot fulfil this requirement (e.g. Batch Annealing in Figure 18), that process needs to be decomposed such that each sub-process only has one relation to an ISA-95 process.

ISA-95 also explicitly defines a Bill of Materials in relation to an Operations Definition. A business object best fits the definition, but a business object cannot have a relation to a material (except through a business process). ArchiMate does implicitly define a bill of materials through the accesses relation between business process and material. The pattern introduced for Assemblies solves this issue.

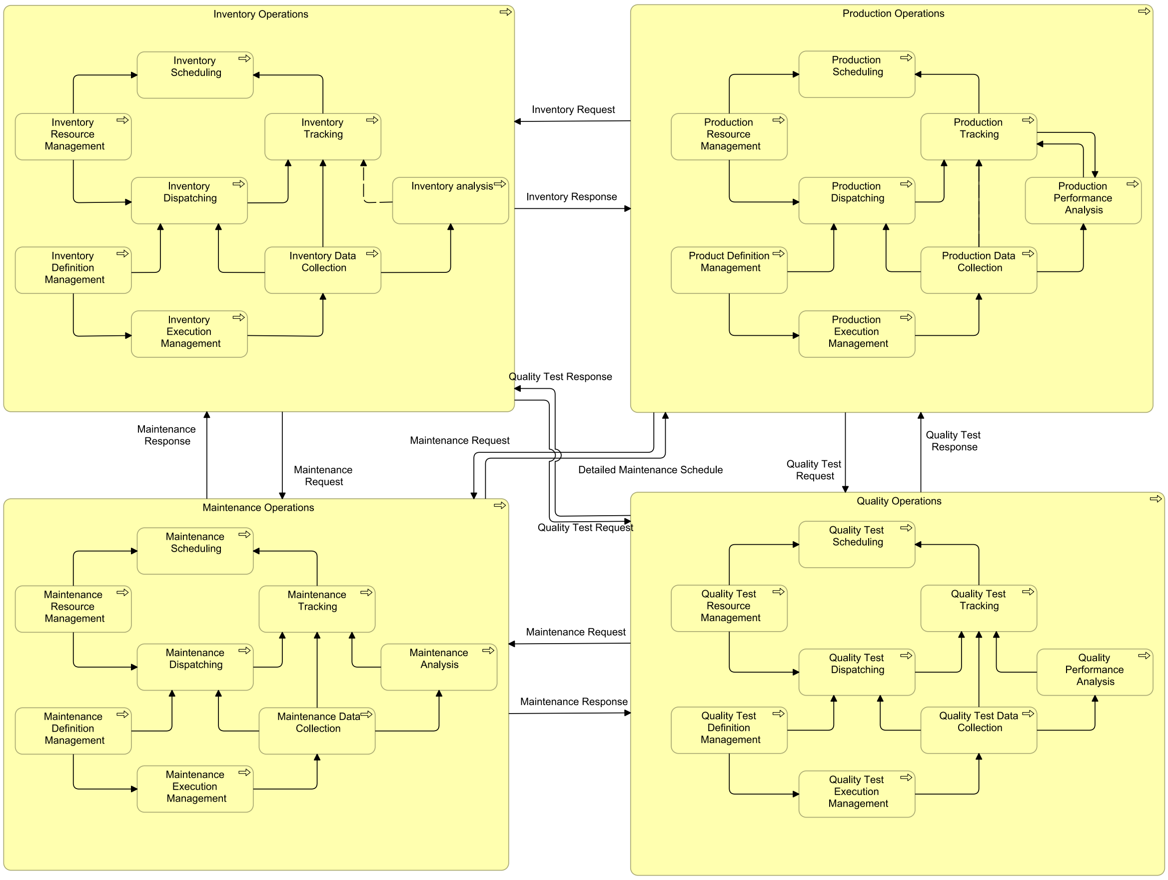


Figure 19: Manufacturing Operations (level 3) Process Framework implemented in ArchiMate

7.3.6 Operations Schedule

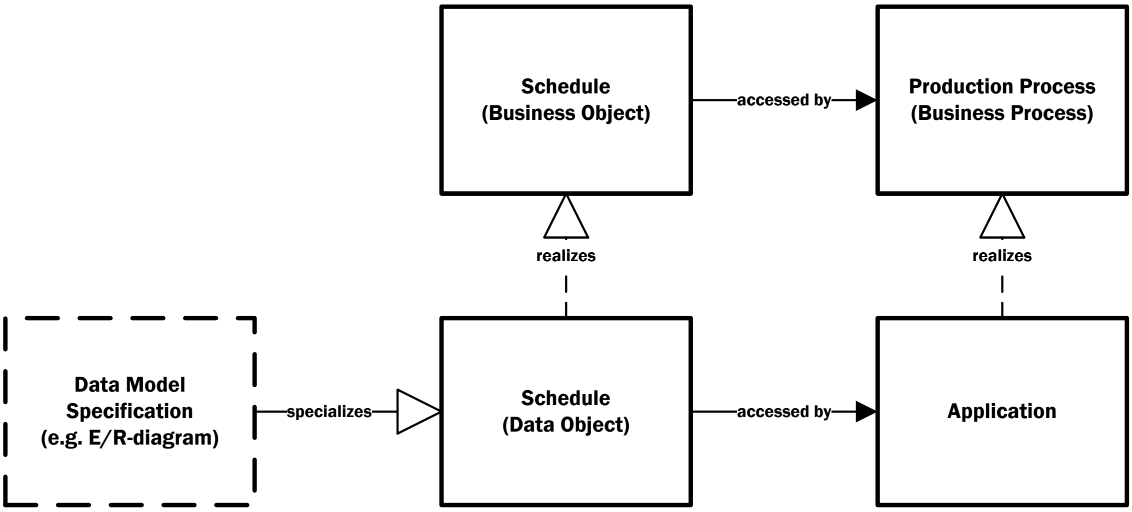


Figure 20: Operations Schedule Pattern

ISA-95 defines a schedule concept. It is implemented as a set of operations requests, which directly relate to an operations definition. There is no particular ordering (time sequence) to the set. There is no similar concept in ArchiMate. In fact, the representation of time is a known issue with the language. While the schedule itself could be modeled as a business object. another issue arises with regards to the relation between a business object and a business process. A business process is typically modeled as a class in ArchiMate, while the schedule must relate to instances to be meaningful. It would either be necessary to model each instance of the process separately, or to model no relations to business processes at all, effectively making the schedule a placeholder object. The first is preferable from an analysis standpoint, while the second is preferable from a complexity standpoint, although having no dependencies means there will be nothing to analyze either. A compromise between these two options is to, rather than model each instance as part of the architecture, include a reference to the data model used to store each instance (see Figure 21). This data model can then serve as the basis for a query. The way in which this query is structured shall depend on the viewpoint for which the information is required. For example, a query based on product ID may reveal which execution path was followed for the production of that unit.

7.3.7 Operations Performance

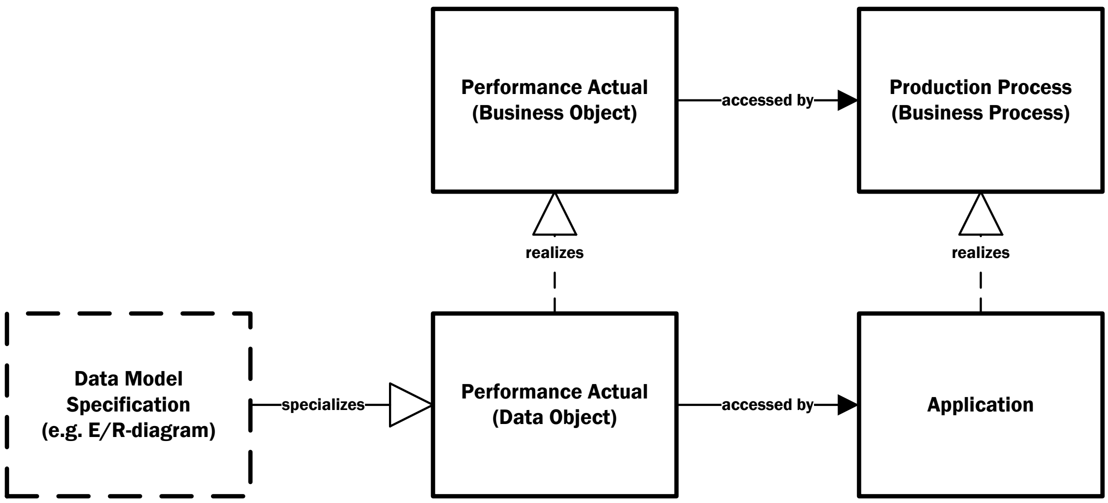


Figure 21: Performance Actual Pattern

ISA-95 makes a distinction between the definition of a process (operations definition), the planned process (operations schedule) and the actual process (operations performance). Once executed, Operations Responses are returned for every Operations Request (which make up the schedule). An Operations Response is made up of 'actuals', which represent the real people, equipment, materials and physical assets used. In ArchiMate, an Operations Responses can be represented as either a Business Object or Data Object, depending on whether this information is collected digitally or not. The actual production information, such as the actual execution of the process, any errors that may have occurred, is however much too volatile to model as part of the architecture. Instead, it is recommended to relate an Operations Response object to a specification of the data model, describing how the data can be obtained externally (e.g. an E/R-diagram). Based on this specification and the relation to a data object accessed by some application, it will be possible to generate a query for analysis purposes.

7.4 Unmappable Concepts

There are some concepts that, in spite of the patterns introduced, cannot be mapped to ArchiMate. This concerns specifically the objects produced by of the execution of Test Specifications, Test Results.

- Qualification Test Result
- Equipment Capability Test Result
- Physical Asset Capability Test Result
- Material Test Result

These Test Results rely on the properties of the objects tested for their meaning. The property concepts in ISA-95 were deemed non-architectural and thus the test results become meaningless. It was decided to leave Test Results out of scope for this reason.

7.5 Adaptations to ArchiMate

The patterns described in section 7.3 have introduced several constructs that are new to ArchiMate 3.0. This section explains the requirements for each of them. The general requirements for adaptations are described in section 7.2.

7.5.1 Parameters

While several tools for ArchiMate have already informally implemented parameters for concepts and relations, this idea has never made it into the standard specification. For the purpose of the patterns introduced for the modeling of the enterprise architecture of a smart manufacturer, it will be necessary to incorporate parameters into the ArchiMate meta-model. Parameters are used as part of the following patterns: *implicit bill of materials*, *explicit bill of materials*, *process segment parameter pattern*.

A parameter shall be defined as an object that describes some property of the construct to which it is related. Parameters fulfil ArchiMate's analysis of *architectural properties* requirement for manufacturing objects like the bill of materials or a process segment. For analysis purposes, it shall be required to declare a type for each parameter introduced. These types should correspond to common types used in DBMS or programming languages. The table below gives in indication of the basic types that should be supported. More diverse types may be implemented based on the language in which a tool or database is implemented.

Table 12: Parameter Data Types

Type	**Example**
Currency	€100, $3.50
Date/Time	20/06/2016, 20 June 2016, 3:00:00 PM, 15:00:20
Number	1234, 3.14159
Reference	E.g. a link to a data model
String	Lorem ipsum dolor sit amet

These basic types can be used to model more complex information, such as a range (e.g. minimum or maximum capacity) or duration (e.g. 30 minutes). Units of measurement can be accounted for as part of processing logic for these parameters. This means 30 minutes would be modeled as a number parameter with the value 30. A parameter should be nameable, just like all other concepts in ArchiMate.

Parameters attached to a concept (e.g. a Material) can be inherited by objects specializing that concept. This way, it should be possible to define standard parameters for object types (e.g. a steel coil always has a diameter, length and grain), When a parameter is attached to a relation between concepts, that parameter applies to that relation only (i.e. not to derived relations following the same path).

The suggested notation for parameters is a regular shape connected with a dotted line to the construct which the parameter describes. Figure 22 illustrates the parameters extension.

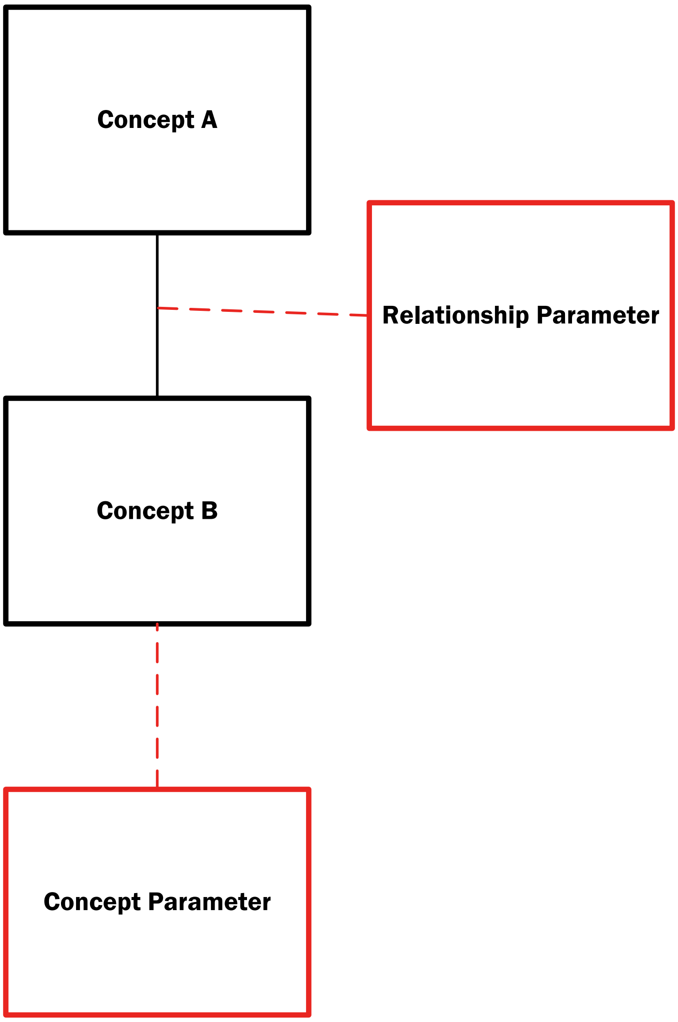


Figure 22: ArchiMate parameters extension

7.5.2 Aggregation relation between Business Object and Material

An aggregation relation between Material and Business Object is introduced to model an explicit bill of materials. ArchiMate 3.0 allows a Business Object and a Material to be related via an association. The relation between a bill of materials (which maps to a Business Object) and a material is, however, more meaningful; a bill of materials *lists* a material. Thus, an aggregation relation was chosen to represent this meaning, since it is the weakest relation that allows the intended meaning to be expressed. An illustration of this extension can be found as part of Figure 23.

7.5.3 Realization relation from Material, Equipment, Facility, Business Role and Business Actor to Business Object

To represent how physical objects are related to (digital) information objects that represent them, a realization relation was added between physical entities that can be involved with a production process (i.e. Material, Equipment, Facility, Business Role and Business Actor) and a Business Object. A realization relation was chosen, since it is strong enough to express that the Business Object should reflect the state of the physical object. Furthermore, since Business Object and Data Object are also related by means of a realization, this allows a Data Object to represent data stored about a physical object in some information system via an indirect relationship. If the relationship between the physical object and the Business Object was weaker, this indirect relationship would not be possible.

It has been argued that a realization relation may be too strong, since it is possible that the information stored about a physical object may not reflect the *true* state of a physical object. Consider the following example:

A bakery makes bread to order for its customers. A customer has placed an order online for a loaf of bread, to be picked up when ready. Early in the morning, the baker starts his work and prepares the bread. When the bread comes out of the oven, it moves to inventory for the customer to come pick it up. However, the baker does not immediately update his information system since that would interrupt his workflow. Rather, he finishes the batch and then sits down in front of his computer. Thus, a finished bread is not registered as such, at least for a while. This has implications for the business; the customer cannot be notified to pick up their order until the information representation of the bread is updated.

While the above is a concern, mainly in terms of data quality, this does not affect the realization relation. Its definition only requires that some logical entity is realized by a more concrete entity. It does not require the quality of data involved to be of a certain quality.

An illustration of this extension can be found as part of Figure 23.

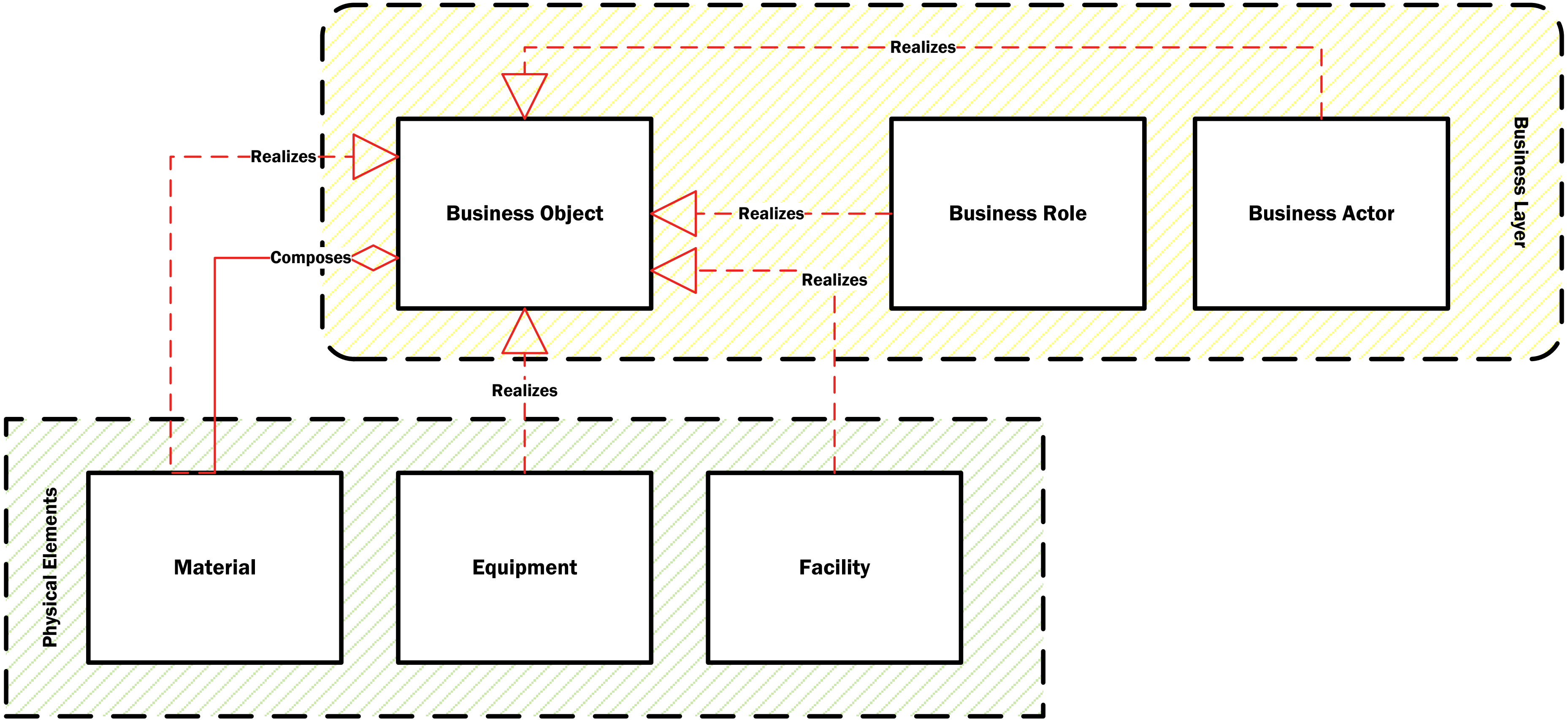
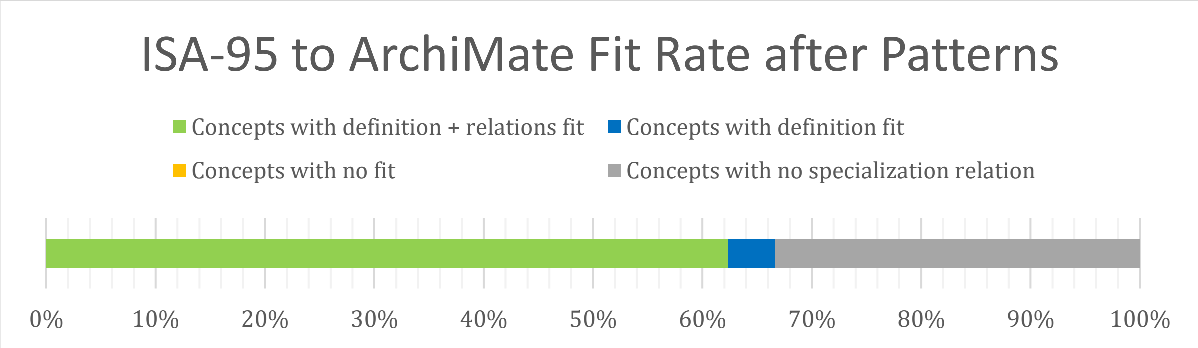


Figure 23: ArchiMate bill of materials extension and digital representation extension

7.6 Conclusion



For each gap identified in ArchiMate with regards to architectural concepts in ISA-95, a pattern has been established to achieve coverage of the concepts and relations involved. These patterns allow the fourth and final sub-research question to be answered:

SQ4. How should the meta-model of ArchiMate 3.0 be adapted such that the deficiencies identified are resolved?

Eight patterns are introduced, mostly composed of existing constructs. Limiting a pattern to existing constructs was, however, not always possible. Hence, three new constructs are introduced:

1. *Concept Parameter* and *Relationship Parameter*. These concepts describe information about a concept or relation respectively. For example, a steel coil (Material) is of a certain length, or a certain quantity steel coils is used in the production process. The requirements for these parameters are described in section 7.5.1. For the purposes of modeling the manufacturing domain, these parameters are used to model parameters for a production process (Process Segment Parameters) and to model a Bill of Materials, both implicitly and explicitly.
2. An *aggregation relation between Material and Business Object* is proposed to enable the modeling of an explicit bill of materials.
3. *A realization relation between Business Object and Business Actor, Business Role, Material, Equipment and Facility* will allow for both the current physical and informational state of a physical object to be modeled.

The requirements for the proposed extensions are explained in section 7.5. The implementation extensions as part of ArchiMate 3.0's meta-model is illustrated schematically in Figure 23 and Figure 22. Newly introduced elements are marked red.

Applying the patterns allows 62% of ISA-95 concepts to be mapped onto ArchiMate. This is 92% of all architectural concepts. The remaining 8% cannot be mapped since they rely on non-architectural concepts for their meaning and have thus been left out of scope.

8 Validation

This chapter discusses the validation of ArchiMate 3.0, including the patterns introduced by this research, as part of a case study at a large European steel manufacturer. For purposes of anonymity, the company shall be referred to as SteelCorp.

8.1 Method

Having established several patterns for the modeling of manufacturing enterprises, a case study will validate whether ArchiMate (plus patterns) can be effectively used to model such a manufacturing environment at the shop floor level. The case presented concerns a large steel manufacturer that intends to make a change in one of its production processes. First, the as-is situation is presented using ArchiMate, supported by an informal description of the scenario. Next, the challenges concerning the process are outlined to motivate the proposed changes. Finally, the to-be scenario will be discussed using ArchiMate as well as an informal description. The goal is to have each ArchiMate model tell the same story as the accompanying description, without leaving out any details relevant to the change effort. If this is indeed possible, ArchiMate can be used to model a manufacturing enterprise.

8.2 Case Description

SteelCorp is a multinational steel manufacturer based in Europe. The company produces several steel-based products. One step in the manufacturing of these products is often the annealing process. The annealing process uses heat to change qualities of the steel to suit the needs of a customer. SteelCorp is looking to optimize this process and harmonize the application landscape surrounding the batch annealing process at one of its plants. However, knowledge of the applications supporting the process is fragmented between stakeholders in the organization, leaving decision makers unsure which applications to cut, replace or maintain. To support this decision making, they have asked their consultants at Wipro to establish the enterprise architecture surrounding the process. This will involve establishing the batch annealing process formally as part of the business domain, as well as its relation to the physical and digital domains.

8.3 As Is Situation

This section describes the current process and application landscape informally, as well as formally using architecture diagrams in ArchiMate. Figure 24 shows the physical production process. Figure 25 shows which application services are used at which point in the process. Finally, Figure 24 shows how and which information flows between applications and processes.

8.3.1 Production process

The annealing process starts after a steel coil has been milled from a larger steel piece. The operator brings up a list of the coils that await processing. The annealing oven processes steel coils in batches of three, so the operator needs to decide which coils should enter the oven together. This decision is made based on the temperature curves that are required to produce the desired end product for each coil. When these temperature curves are similar, the coils are suitable to be included in the same batch. Which coils are chosen for the current batch is recorded in the Production Planning System (PPS) as well as an Excel sheet that is used by the operator only.

The selected batch is encased in a socket made up of a hood, an inner hood, an air circulator, a thermoelectric device and a convector plate placed beneath each coil. The coils are stacked in the socket using a crane.

Once the socket is assembled, it is driven into the oven using a forklift truck. Once the coils are in the oven, the operator dials in the desired temperature. Coils typically stay in the oven for up to two days. When this baking time is completed, the socket is removed from the oven, again using a forklift truck.

After the coils leave the oven, they are cooled to around 400 degrees Celsius using nitrogen. At this point, the coils are removed from the socket using a crane. They are then moved to the inventory to cool down further to around 180 degrees. When the temperature of a coil is low enough, the PPS and Excel sheet are updated. This completes the batch annealing process. The product then moves on to cold rolling, after which the steel is cut and the final product shipped to the customer.

8.3.2 Application Landscape

The batch annealing process is supported primarily by the Production Planning System (PPS), that registers the steel coils that move through the oven, as well as the utilization of each oven. On the shop floor, the operator uses an Excel spreadsheet to register which coils make up a batch, as well as the planned temperature curves for each batch. The oven itself contains a thermometer that feeds data into a technical data warehouse. The data warehouse is used to generate reports for operational as well as quality purposes. The quality reports are published through an application called NiCo. Operational reports are published through Prime. Prime also aggregates information from the PPS as part of its reports, such as which coils are currently waiting to enter the oven.

8.3.3 Challenges

One of the major implications of registering the status of each batch once before the batch is driven into the oven, and once again after the coils are cooled down in inventory, is that there is a period of time during which an oven is not actually being utilized, while the records in the PPS show that it is. The operators on the shop floor are aware of this flaw in the system and are able to work around it by driving in the next batch of coils once an oven becomes available. Registration in the PPS is done after the fact. The Excel spreadsheet used by the operators often does contain the right information, but it is not linked to the data warehouse or to the reporting software Prime.

This brings up the second issue; data is being handled and stored redundantly between the PPS and the Excel spreadsheet and, consequently, the two systems often do not reflect the same truth. Since maintaining the Excel sheet is done in an informal way as well as manually, mistakes or ambiguities occur often. Thus, data quality becomes low. However, the information in the Excel spreadsheet is usually more up to date than the information in the PPS. While, eventually, some of the information in the spreadsheet is registered in the PPS, this will not serve once real time process controls are put in place, as is the desire of management.

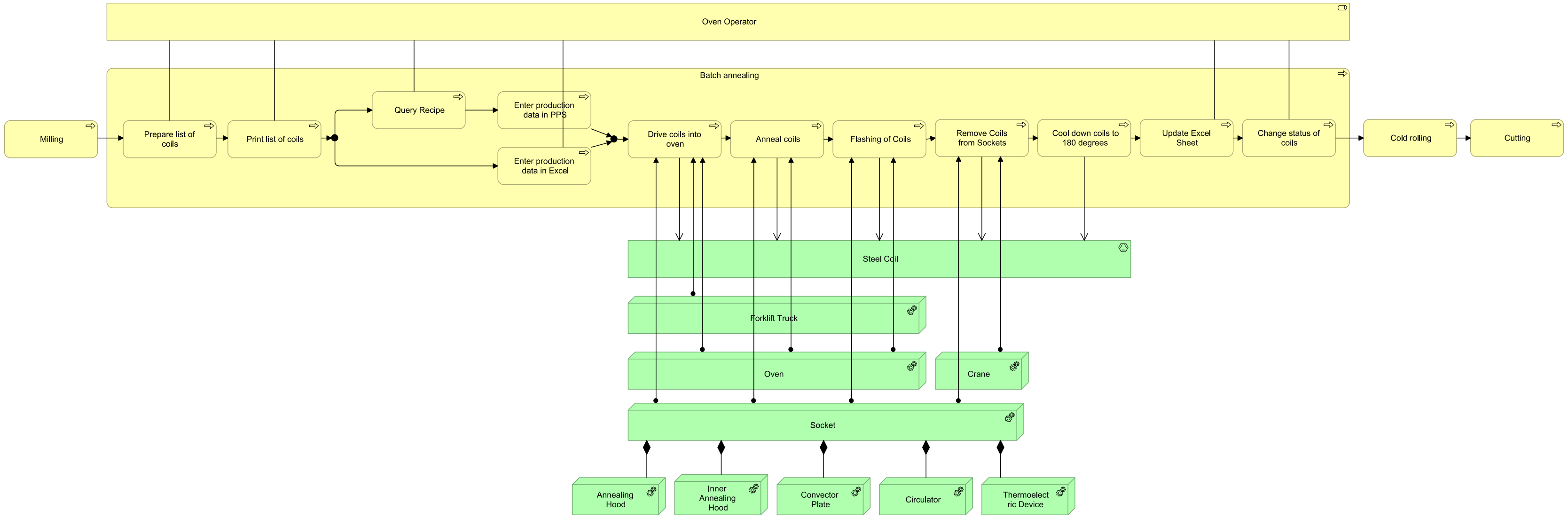


Figure 24: Batch Annealing Physical Process (As Is)

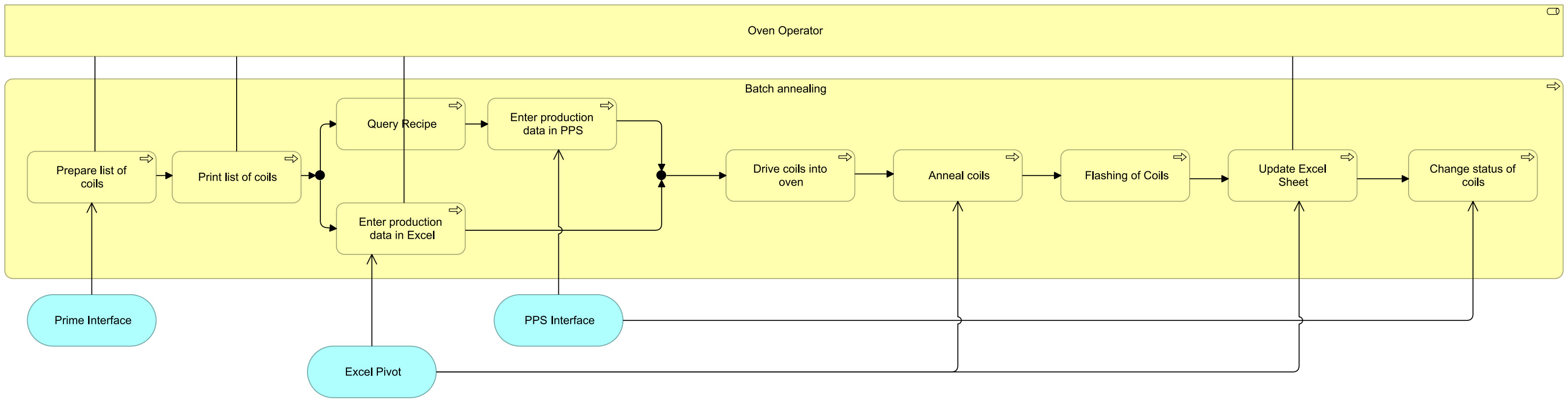


Figure 25: Batch Annealing Supporting Applications (As Is)

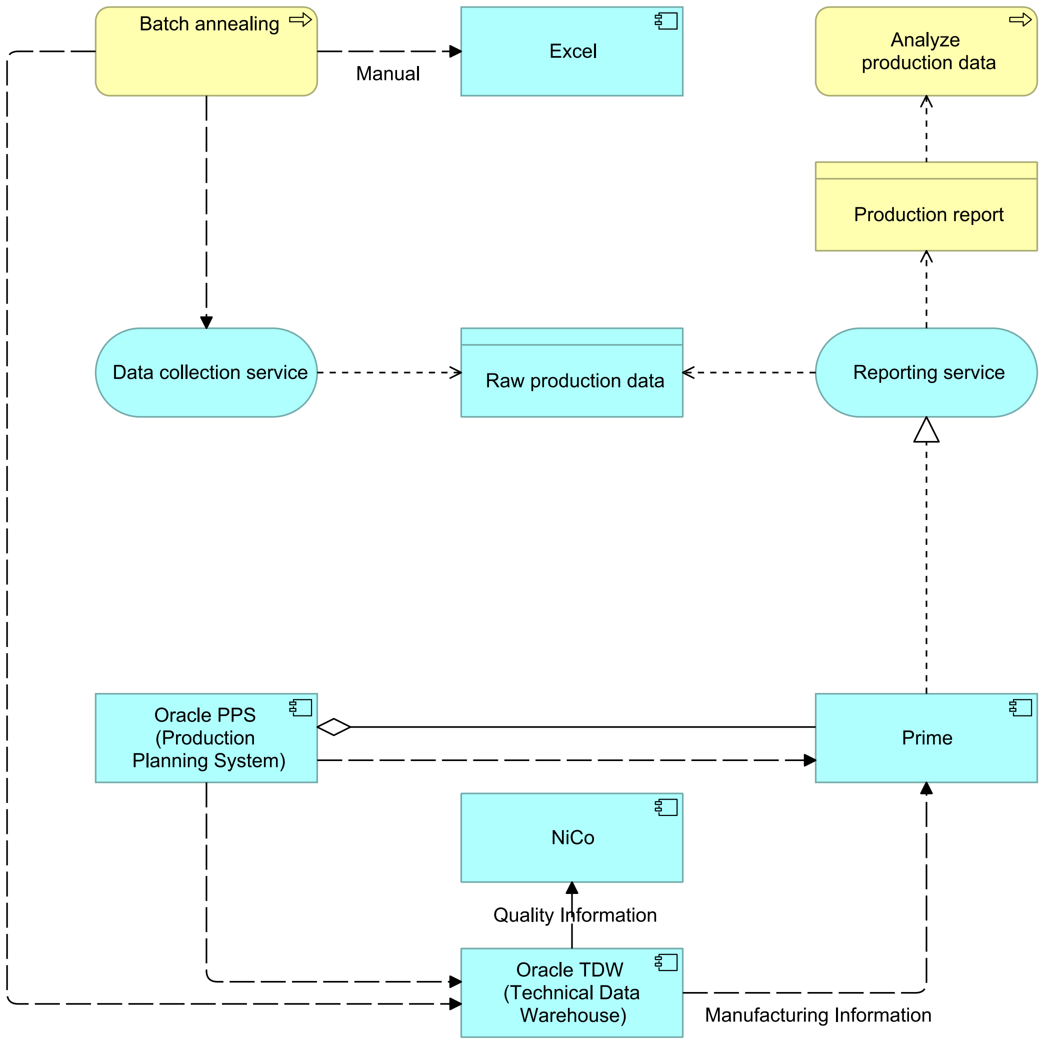


Figure 26: Batch Annealing Information Flow (As Is)

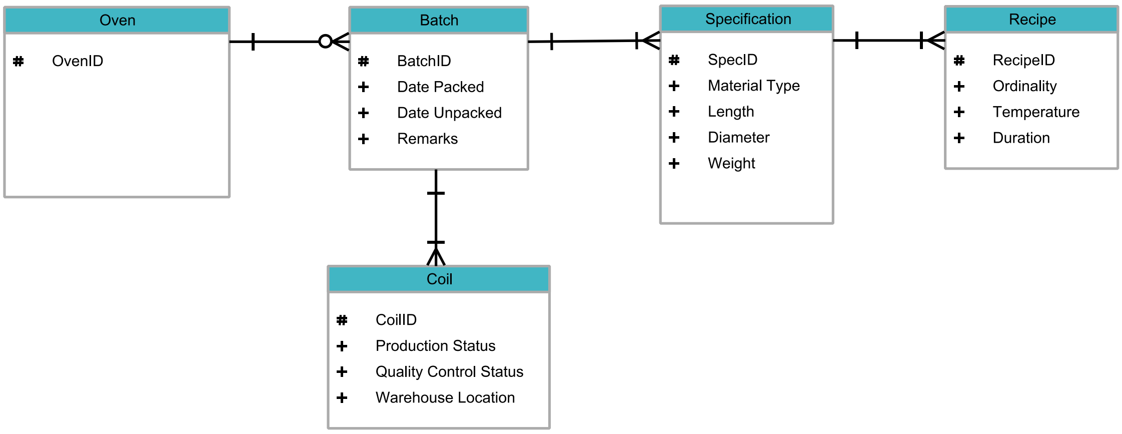


Figure 27: The way in which the Excel spreadsheet is structured

8.4 To Be Situation

Given the challenges described in the previous section, as well as a general need to improve efficiency at the plant, SteelCorp has decided to reform the batch annealing process in a number of ways. Firstly, the Excel spreadsheet will be phased out and its role will be replaced by the PPS. This will involve automating some of the process steps that currently involve data contained in Excel. Since data collection will involve less manual steps, data quality is expected to increase. Secondly, to increase oven utilization, SteelCorp plans to generate optimized batch lists from the PPS, rather than having employees combine each batch manually. Thirdly, to minimize waiting times once a batch leaves the oven, SteelCorp wants to know how long it takes for a coil to cool down in inventory. For this reason, they will install thermometers that monitor each coil periodically. Finally, actual oven temperature curves will be recorded and stored in the data warehouse. Analysis of these temperature curves will allow management and operators to optimize energy efficiency and maintenance downtime.

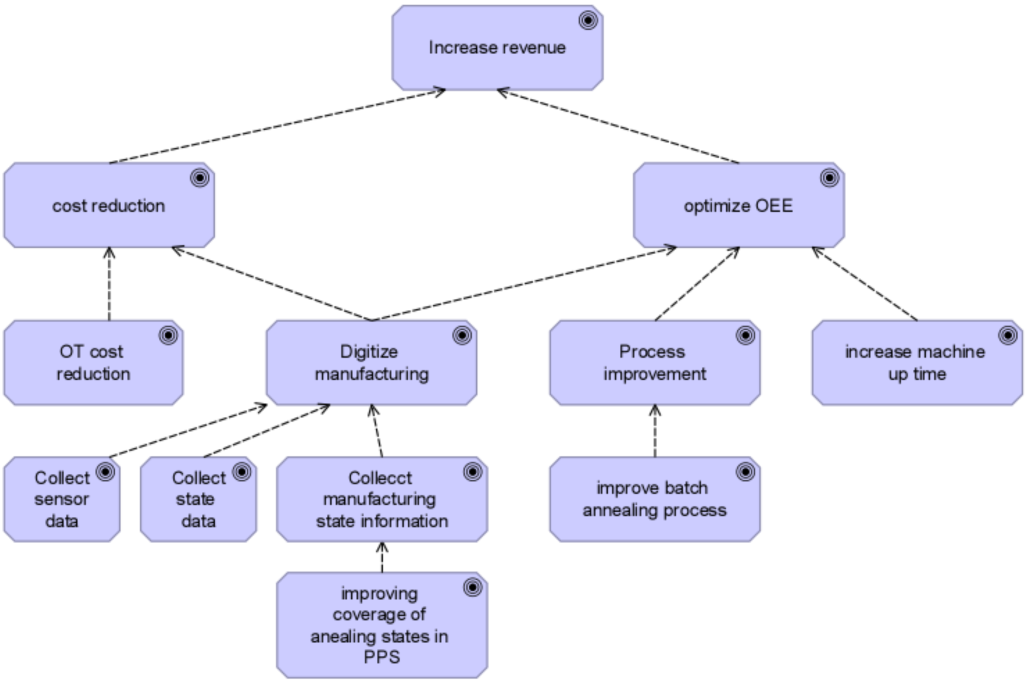


Figure 28: Change goals

8.4.1 Production Process

The improved batch annealing process is characterized by a reduction in activities performed by the oven operator. First, the oven operator will retrieve an optimized batch list from Prime. This batch list tells the operators which coils should enter the oven next. The new batch is confirmed in the PPS and sent to the oven immediately. Note that the manual activities associated with manipulating the Excel spreadsheet that was previously used during this stage of the process is missing completely.

Next, the coils are driven into the oven. The physical process does not change from the as-is situation, but information generated by thermometers in the ovens is now captured and stored in the data warehouse. Coils stay in the oven for roughly two days, after which they are moved out of the oven to cool down. During the cooling down process, the temperature of each coil is regularly monitored, registered and stored. Temperatures will eventually be measured automatically, although there will be a period during implementation in which temperatures will be collected manually. Once the coils are sufficiently cool, a status update is made in the PPS.

8.4.2 Application Landscape

There are a couple of major changes made to the application landscape. Most notably, the Excel spreadsheet has been cut and replaced entirely by the PPS. The PPS now stores all production planning information and is used as a data source for production reports in Prime, which includes the optimized batch lists. The data warehouse is now also directly linked to the production process, since oven temperature data is now stored for temperature curve analysis. An undetermined database solution will be used to store cooling down temperature data.

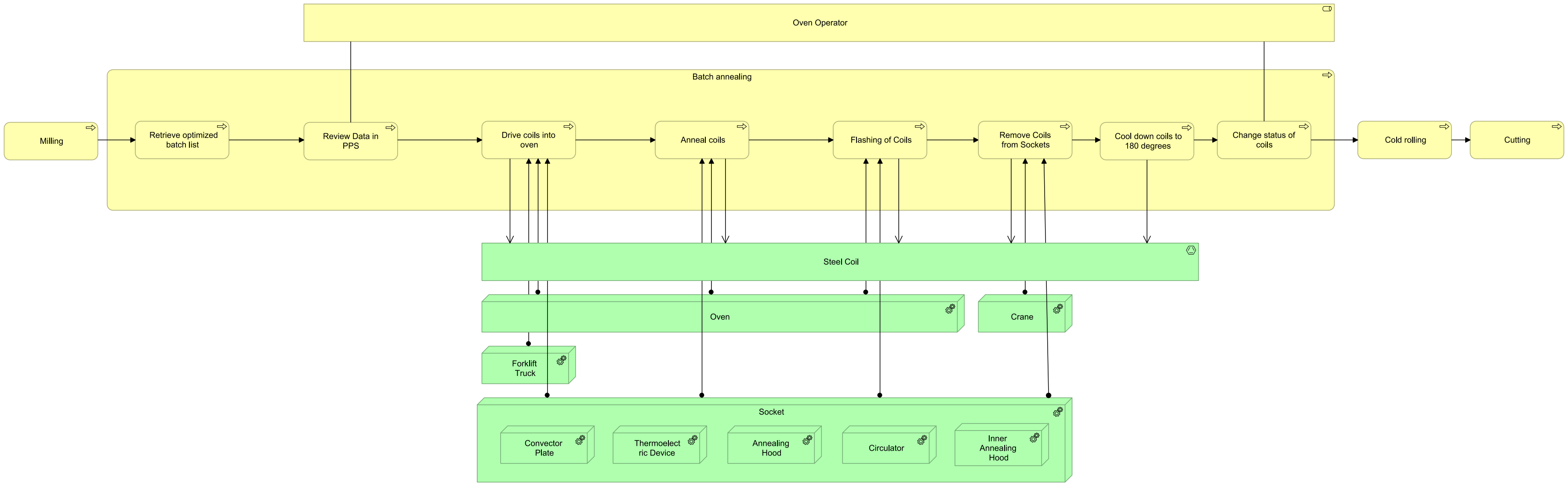


Figure 29: Batch Annealing Physical Process (To Be)

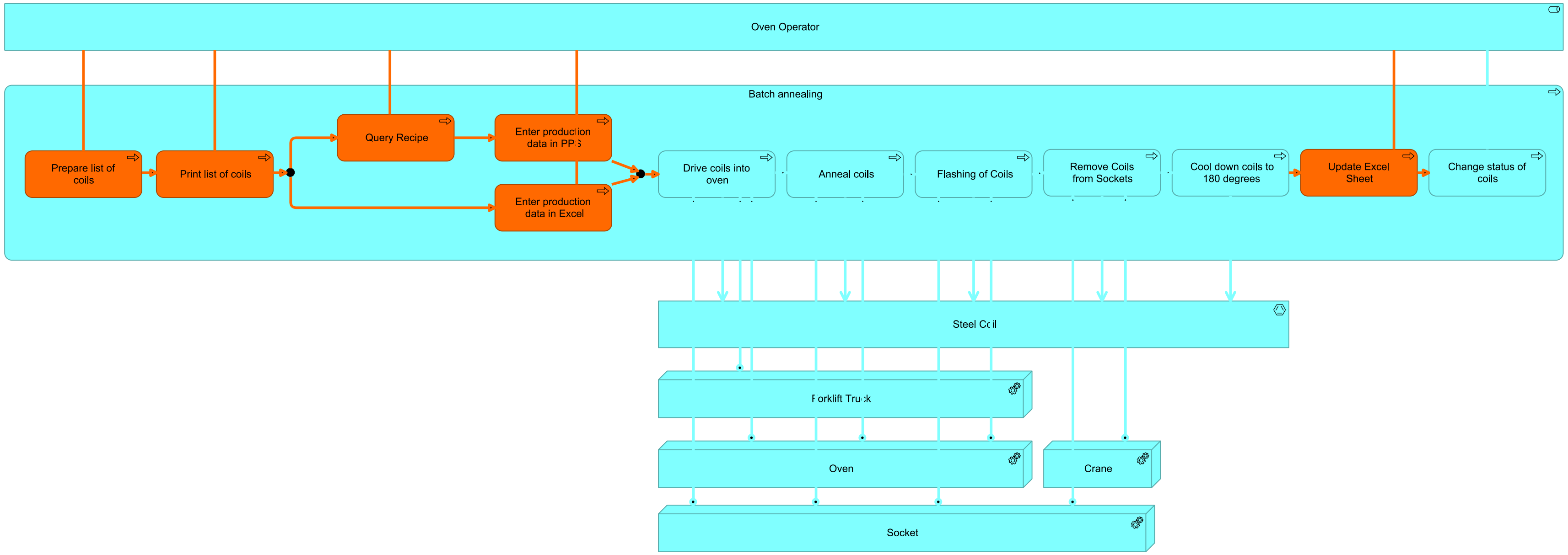


Figure 30: Physical process impact of change analysis

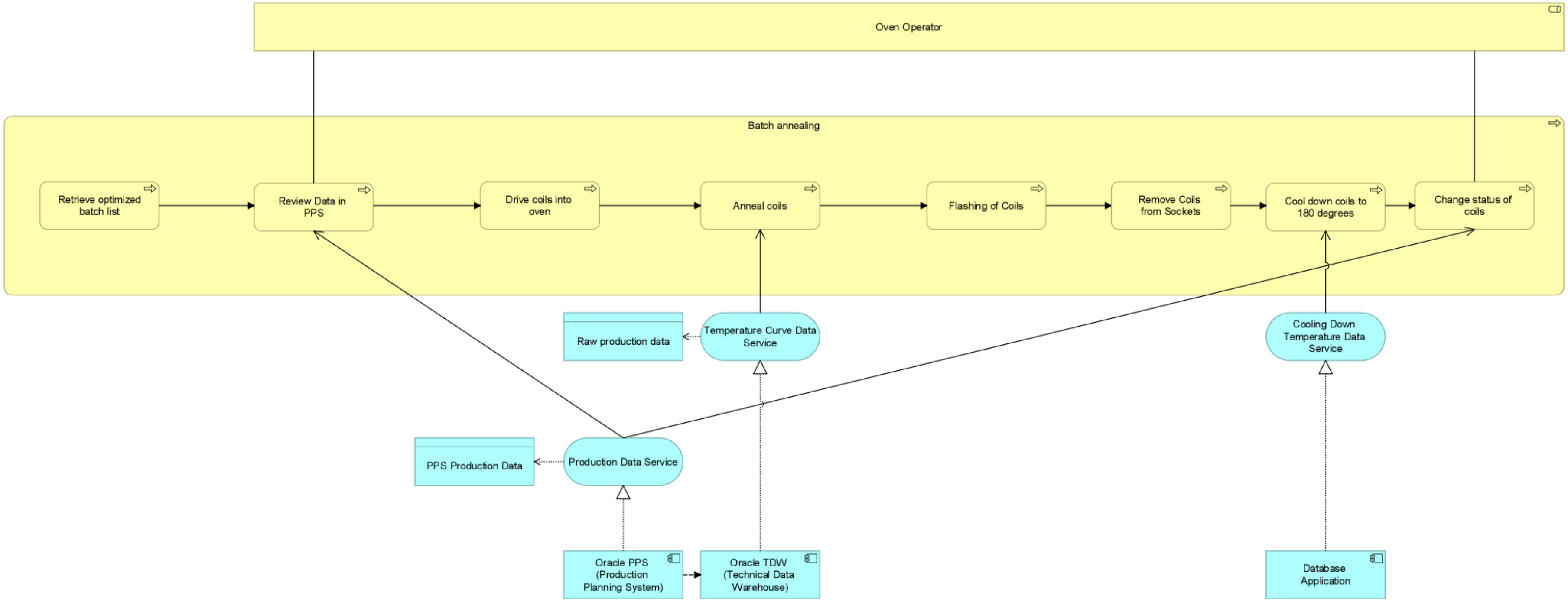


Figure 31: Batch Annealing Supporting Applications (To Be)

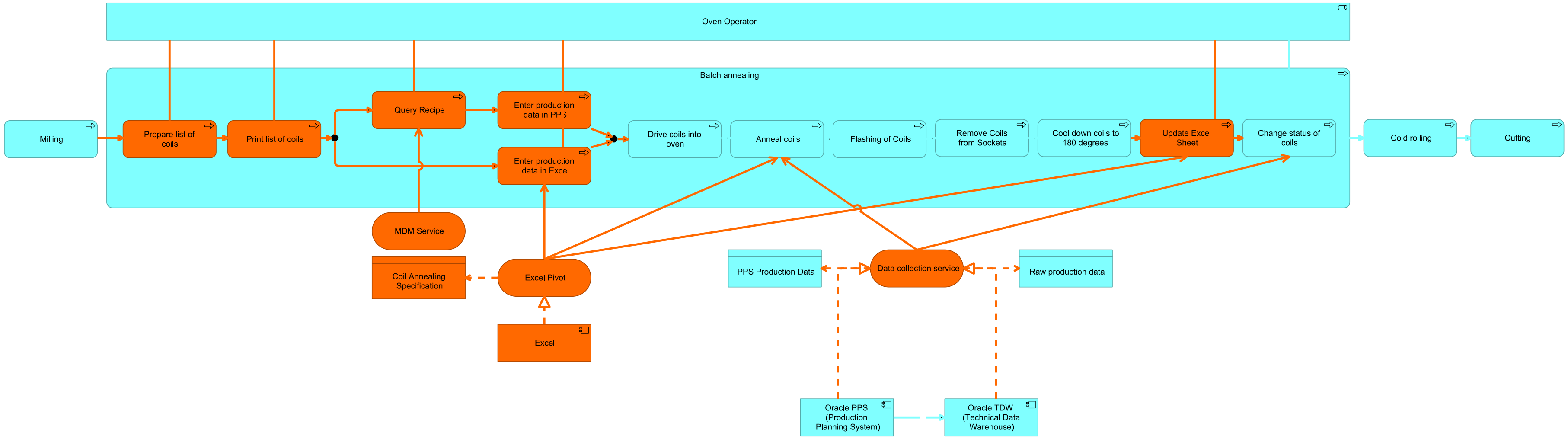


Figure 32: Application landscape impact of change analysis

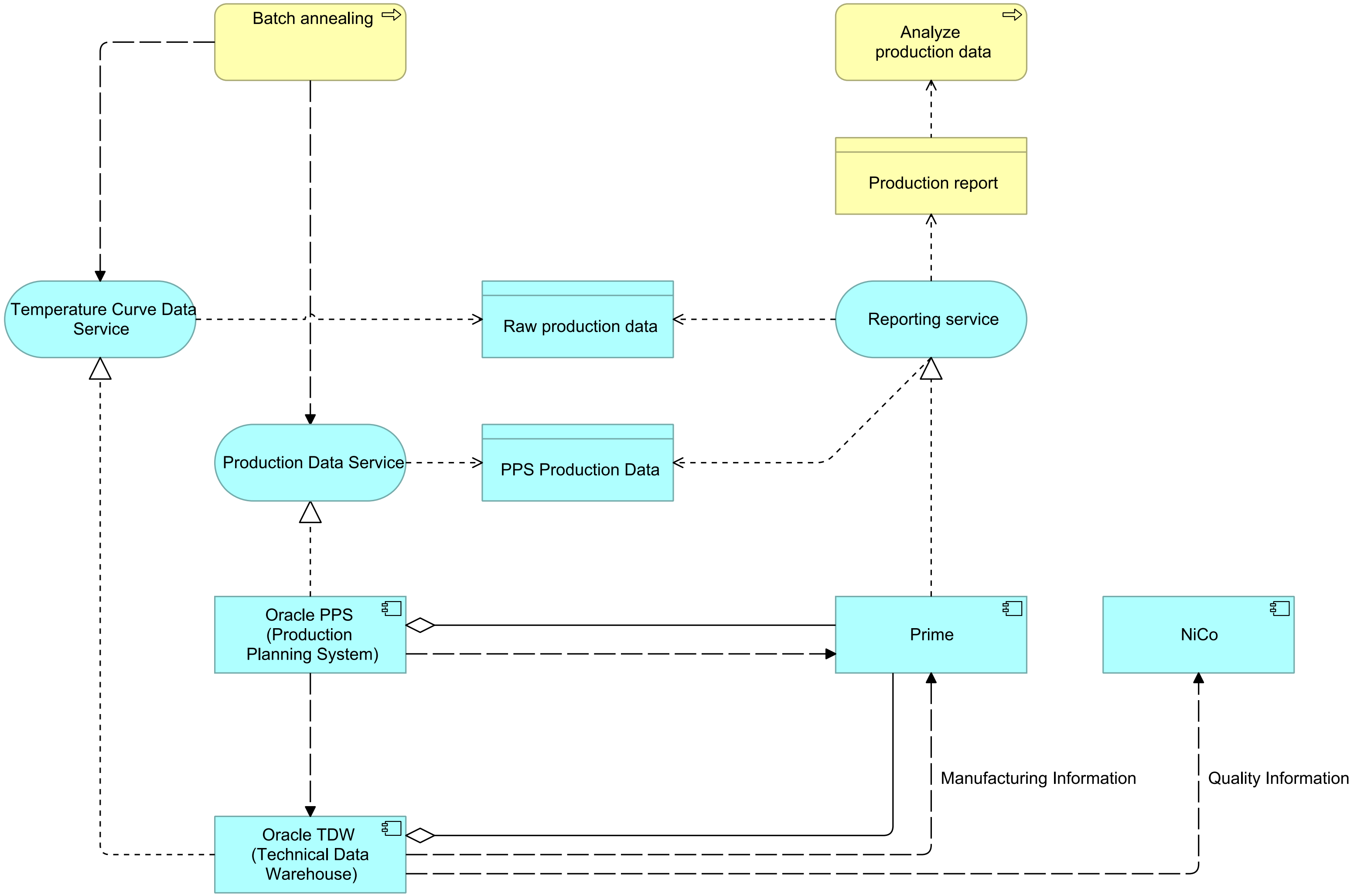


Figure 33: Batch Annealing Information Flow (To Be)

8.5 Operational Excellence Analysis

Another use case of an architecture model is the calculation of an operational excellence score for a part of the plant. This score may be used by decision makers to determine whether a planned change will have the desired effect performance-wise. To illustrate how such an analysis based on the architecture model might work, an operational excellence score will be calculated for the as-is and to-be situation with regards to the cooling down of steel coils at SteelCorp.

The operational excellence score is based on three factors: quality, availability and utilization. Each of these three factors is scored based on their conformance to some norm. For example, may want to achieve 1 defect in 100.000.000 products produced. A quality score of 10 (on a scale of 1-10) would reflect a perfect success. To determine the overall operational excellence score, the average is taken of the three scores.

8.5.1 As-is

Currently, when steel coils come out of the oven, they are placed into inventory to cool down. Operators assume this process takes around a day for every coil. Thus, every coil stays in inventory for a day after it leaves the oven. This day cooling down time will serve as the norm for the availability score of this process step.

8.5.2 To-be

However, SteelCorp expects that the cooling down time of coils is actually variable, depending on the type of steel used, the thickness of the coil and the temperature at which the oven was running. Thus, by determining the cooling down time of a certain type of coil, it may be possible to improve operational excellence by reducing the time a coil spends in inventory. By moving a coil out more quickly, that coil can be delivered to the customer sooner, improving availability. Furthermore, inventory space is freed up for the next coil, improving utilization.

To determine the actual cooling down time of coils, the company wishes to change the current process in several ways. Firstly, an operator will be assigned to manually measure the temperatures of every coil as part of a pilot phase. During this phase, temperature data will be collected to establish a baseline cooling down time for a certain type of coil. At a later stage, this measurement process will also be automated, allowing operators to determine the moment at which each individual coil is cooled down in real time.

8.5.3 Analysis

The factor that determines whether a coil can be moved out of inventory is its current temperature. In the current process, there is no way to tell the temperature of a coil. In the to-be process, however, data will be collected which can be used to tell whether a coil is sufficiently cooled down. The architecture of the to-be situation looks as follows:

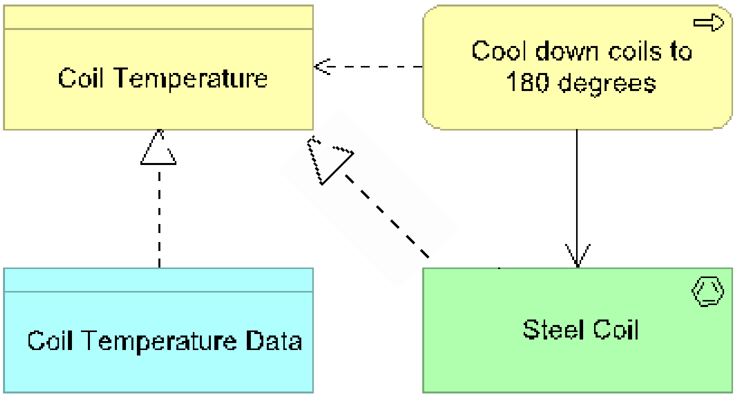


Figure 34: Cooling Down Stage To-Be Architecture

As shown in the diagram above, prominent entities in the cooling down process include the coil and a business object describing the temperature of the coil. The coil temperature is realized by the steel coil, as well as a data object that stores the information. The structure of the temperature data, while currently not yet determined, might be as follows:

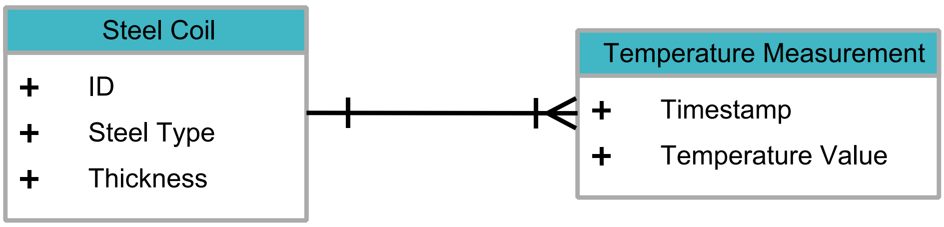
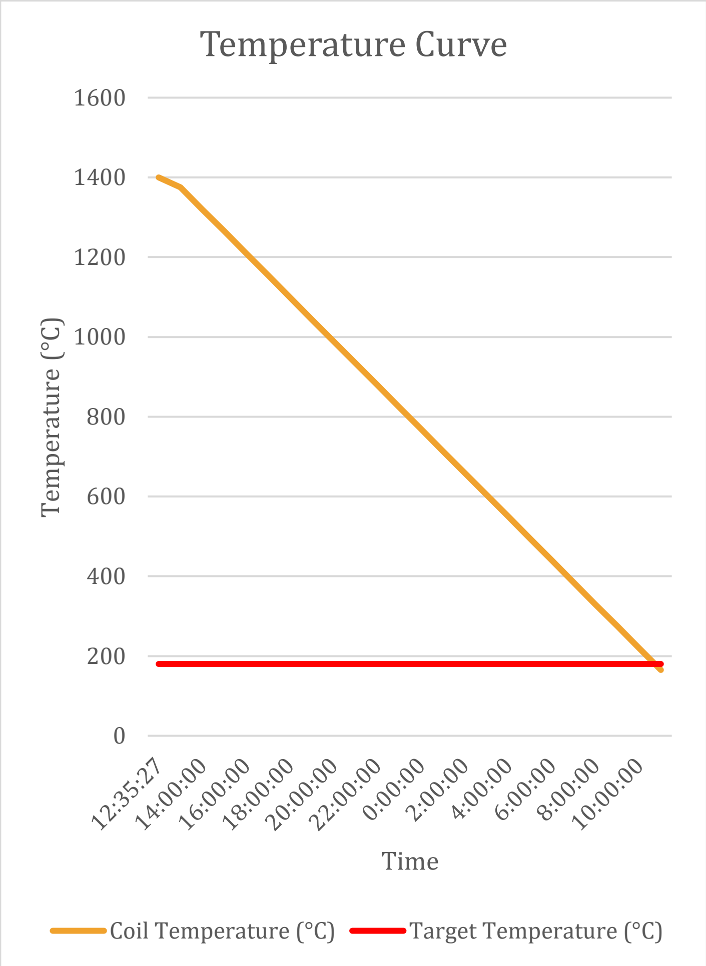


Figure 35: Cooling Down Temperature Data Structure

Using the temperature data, a cooling down curve can be derived (see below). This example uses mocked up historical data to illustrate how this might work. The example assumes a sample of the current temperature will be recorded every hour. Temperature may also be monitored in real-time for more accuracy.

Table 13: Cooling Down Temperature Curve Data Example

Timestamp	Coil Temperature (°C)
12:35:27	1400
13:00:00	1375
14:00:00	1320
15:00:00	1265
16:00:00	1210
17:00:00	1155
18:00:00	1100
19:00:00	1045
20:00:00	990
21:00:00	935
22:00:00	880
23:00:00	825
00:00:00	770
01:00:00	715
02:00:00	660
03:00:00	605
04:00:00	550
05:00:00	495
06:00:00	440
07:00:00	385
08:00:00	330
09:00:00	275
10:00:00	220
11:00:00	165



The above temperature curve shows how a fictional coil cools down over a period of time. The coil enters the warehouse at 12:35:27. At that time, the coil temperature is 1400 degrees Celsius. Over time, the coil cools down at a linear rate of 55 degrees per hour. The target temperature of 180 degrees Celsius is reached at approximately 10:45:00. This means the coil has had a cooling down period of around 22 hours and 10 minutes. This is one hour and fifty minutes less than the normally allotted time of 24 hours.

Using the actual cooling down times of coils, certain patterns may be revealed regarding the cooling down time of a type of coil. This way, rather than reactively moving a coil out of the warehouse as soon as it is cool enough, planning can take into account the expected cooling down time of a coil.

8.5.4 Score calculation

Taking the above temperature curve as the expected temperature curve for this type of coil indicates that the current process is inefficient in terms of both availability and utilization by 7,6%. Assuming every other aspect of the process to be perfect, the operational excellence score calculation for the as-is situation is as follows:

Table 14: Operational Excellence Score (No data use)

Factor	**Score**
Quality	10
Availability	9,24
Utilization	9,24
Operational Excellence Score	8,53

In the to-be situation, availability and utilization will be improved. The magnitude of improvement will depend on how the data is used. If the temperature data is used reactively, notifying operators that a coil is ready based on the hourly measurement, the actual gains will be somewhat variable based on what time a coil has entered the warehouse. At most, the time wasted will be an hour. Based on the most pessimistic scenario, this means an improvement to availability and utilization of 3,4%, leading to the following scores:

Table 15: Operational Excellence Score (Reactive data use)

Factor	**Score**
Quality	10
Availability	9,58
Utilization	9,58
Operational Excellence Score	9,18

Finally, if the temperature data is used to its fullest, by using the data to compute average cooling down times based on a coil's cooling down temperature curve, the amount of time wasted can be minimized, leading to a perfect operational excellence score (of course, assuming every other task is performed fully efficiently as well):

Table 16: Operational Excellence Score (Temperature curve use)

Factor	**Score**
Quality	10
Availability	10
Utilization	10
Operational Excellence Score	10

8.6 Conclusion

The batch annealing process at the SteelCorp steel manufacturing facility in Krefeld was modeled in ArchiMate 3.0 using the patterns discussed. Using the constructs readily available in ArchiMate, as well as the patterns introduced that make use of just these, it is possible to model a large portion of the OTK case. However, some aspects of the case could not be modeled and required the use of patterns that make use of new elements. For example, the current utilization of the oven (and the discrepancy between the perceived state of the oven and its actual state) could not be modeled. This will require a realization relation to a business object. Another example of this is the temperature data related to a coil. Furthermore, a socket (in which coils are placed before they enter the oven) consists of three convector plates; one for each coil. However, the model only shows one. Since these convector plates do not differ from one another from an architectural standpoint, it would have been more meaningful to model this quantity as a parameter instead. Finally, usefulness of the model was successfully demonstrated through an impact of change, as well as an operational excellence analysis.

9 Discussion

This chapter reflects on the research and discusses opportunities for future work.

9.1 Results

Based on the ISA-95 standard for the integration of enterprise systems and control systems in the manufacturing industry, this research has presented an analysis of ArchiMate 3.0 in terms of its coverage of the manufacturing domain. The conclusions from previous chapters now lead to the following answers to the main research questions:

RQ1. To what extent can ArchiMate 3.0 express the enterprise architecture of any smart manufacturer per ISA-95?

The first part of this question asks what constitutes the enterprise architecture of a smart manufacturer per ISA-95. Since ISA-95 was written on a different abstraction level from ArchiMate, not all of its concepts may be architectural. To determine which concepts are architectural, the ISA-95 concepts were normalized using the criteria used to determine which concepts should be part of the ArchiMate language (Lankhorst et al., n.d.). The normalization reveals that only 66% of ISA-95 concepts may be classified as such.

Given the set of architectural concepts identified, a mapping was made of each architectural ISA-95 concept to ArchiMate 3.0. To be able to express the enterprise architecture of any smart manufacturer, ArchiMate should be able to express each architectural ISA-95 concept. The mapping analysis revealed that, while 8% of concepts can be mapped one-to-one, either construct overload or construct deficit occurs in the remaining 56% of cases. Solving these issues will require the use of a pattern based on either an indirect relation or a new construct.

To review which specific ISA-95 concepts are architectural, as well as how each of the architectural concepts relates to ArchiMate, please refer to the separately provided Excel spreadsheet[3] containing the analysis.

RQ2. If ArchiMate 3.0 cannot fully express the enterprise architecture of any smart manufacturer per ISA-95, how can the meta-model of ArchiMate 3.0 be adapted such that the enterprise architecture of any smart manufacturer can be modeled?

When a concept from the manufacturing domain cannot be mapped to ArchiMate, this will invariably cause issues when attempting to model the architecture of a manufacturing enterprise. Thus, this second question asks for a solution to the mapping difficulties uncovered as part of the mapping analysis.

For each issue identified, a pattern is introduced that resolves the problem by either following an indirect relation (thus using some combination of ArchiMate concepts to express the intended meaning of the ISA-95 concept) and/or by introducing some new construct if ArchiMate's meta-model does not prove sufficiently expressive.

To raise the concept coverage from 8% to 62% (92% of all architectural concepts), eight distinct modeling patterns are introduced, as well as several new concstructs that extend the ArchiMate 3.0 meta-model (which are used in the patterns). These patterns were validated successfully as part of a case study at SteelCorp, a large European steel manufacturer.

[3] http://bit.ly/2amGJqi

9.2 Limitations

This research compares ISA-95 and ArchiMate to arrive at an architecture modeling language for smart manufacturers. ArchiMate's criteria for enterprise architecture concepts were used for the normalization process of concepts, which ended up in a distinction between architectural and non-architectural concepts. This list may, however, not be applicable to all architecture frameworks and languages if they use different criteria from ArchiMate. Furthermore, the patterns introduced are applicable to ArchiMate only.

This research assumes that ISA-95 describes the manufacturing domain perfectly at the process level. However, being a model of itself, ISA-95 also makes abstractions of the real world. It may be that ISA-95 has abstracted architectural concepts from the manufacturing domain that would have been meaningful to ArchiMate.

Finally, the validation for this research covers one case at one company. While the patterns introduced have proven useful, not all could be tested since not all patterns were meaningful in the context of this particular scenario.

9.3 Future work

Since this research was limited to ArchiMate, an investigation of other architecture frameworks and/or languages in conjuncture with ISA-95 may reveal other architectural concepts that are relevant to the manufacturing domain. Further, the patterns identified for ArchiMate should be applied to more cases, particularly discrete and continuous processes since the SteelCorp case concerns only a batch process (and not also a discrete or continuous one).

10 Conclusion

With the introduction of smart manufacturing (or industry 4.0), information technology and operations technology increasingly overlap. For large manufacturers, this means increasing digitization of the shop floor and, consequently, the need to control the information flowing from the physical domain as well as the need to manage changes from a multidisciplinary (IT and OT) perspective. This is where enterprise architecture helps, but existing frameworks and languages were not designed specifically with their requirements in mind. This research aims to provide enterprise architecture modeling support for smart manufacturing companies.

The enterprise architecture language of choice for this research is ArchiMate. First, the suitability of ArchiMate for modeling an enterprise architecture in the manufacturing domain needed to be assessed. Next, if ArchiMate was found insufficiently expressive to model such an architecture, a way needed to be found to extend the meta-model such that a sufficient level of expressiveness is reached.

To this end, ArchiMate 3.0 was mapped to ISA-95, a standard for enterprise systems and control systems integration. Based on the deficiencies uncovered as a result of this analysis, patterns are introduced to achieve full coverage of the manufacturing domain for ArchiMate. To realize some of these patterns, this research introduces several new constructs to ArchiMate. The patterns introduced achieve a coverage of 92% of all architectural concepts in ISA-95. The extension of the meta-model was validated by modeling the architecture of a production process at a large European steel manufacturer. Furthermore, two common manufacturing use cases (an impact of change analysis and an operational excellence analysis) were applied successfully to the model.

11 References

Boucharas, V., van Steenbergen, M., Jansen, S., & Brinkkemper, S. (2010). The Contribution of Enterprise Architecture to the Achievement of Organizational Goals: A Review of the Evidence. In *TEAR 2010* (pp. 1–15). Berlin: Springer-Verlag.

Caminiti, S. (2011). Manufacturing Intelligence. *NYSE Magazine*.

Chand, S., & Davis, J. (2010a, July). What is smart manufacturing? *Time Magazine*.

Chand, S., & Davis, J. (2010b, November). The smart manufacturing revolution. *Manufacturing Executive Leadership Journal*.

Davis, J., Edgar, T., Graybill, R., Korambath, P., Schott, B., Swink, D., … Wetzel, J. (2015). Smart Manufacturing. *Annual Review of Chemical and Biomolecular Engineering*, *6*, 141–160. http://doi.org/10.1146/annurev-chembioeng-061114-123255

Davis, J., Edgar, T., Porter, J., Bernaden, J., & Sarli, M. (2012). Smart manufacturing, manufacturing intelligence and demand-dynamic performance. *Computers and Chemical Engineering*, *47*, 145–156. http://doi.org/10.1016/j.compchemeng.2012.06.037

Department of Defense. (2010). DoDAF Architecture Framework Version 2.2. Retrieved from http://dodcio.defense.gov/dodaf20.aspx

EABOK. (2016). Enterprise Architecture Book of Knowledge, Planning an EA - Purpose. Retrieved March 4, 2016, from http://www2.mitre.org/public/eabok/planning_an_ea/purpose.html

Federal government of the United States. (2013). Federal Enterprise Architecture Framework Version 2. Retrieved from https://www.whitehouse.gov/sites/default/files/omb/assets/egov_docs/fea_v2.pdf

Henderson, J. C., & Venkatraman, H. (1993). Strategic alignment: Leveraging information technology for transforming organizations. *IBM Systems Journal*, *32*(1), 472–484. http://doi.org/10.1147/sj.382.0472

Hermann, M., Pentek, T., & Otto, B. (2015). Design Principles for Industrie 4.0 Scenarios: A Literature Review. *Technische Universitat Dortmund*, *01*(01), 4–16. Retrieved from http://www.leorobotics.nl/sites/leorobotics.nl/files/bestanden/2015 - Hermann Pentek & Otto - Design Principles for Industrie 4 Scenarios.pdf

International Society of Automation. (2010). ANSI/ISA-95.00.01-2010. In *Enterprise-Control System Integration*. Retrieved from http://www.isa.org/Template.cfm?Section=Standards2&template=/Ecommerce/ProductDisplay.cfm&ProductID=11225

Lankhorst, M. M., Proper, H. A., Jonkers, H., Novay, Radboud University Nijmegen, Capgemini, & BiZZdesign. (n.d.). *The Anatomy of the ArchiMate Language*.

Lee, E. a. (2008). Cyber Physical Systems: Design Challenges. *2008 11th IEEE International Symposium on Object and Component-Oriented Real-Time Distributed Computing (ISORC)*, 363–369. http://doi.org/10.1109/ISORC.2008.25

Mazak, A., & Huemer, C. (2015). A standards framework for value networks in the context of Industry 4.0. *Industrial Engineering and Engineering Management (IEEM), 2015 IEEE International Conference on*, 1342–1346. http://doi.org/10.1109/IEEM.2015.7385866

Panetto, H., Baïna, S., & Morel, G. (2007). Mapping the IEC 62264 models onto the Zachman framework for analysing products information traceability: A case study. *Journal of Intelligent Manufacturing*, *18*(6), 679–698. http://doi.org/10.1007/s10845-007-0040-x

Sacala, I. S., & Moisescu, M. A. (2014). The Development of Enterprise Systems based on Cyber-Physical Systems Principles. *Romanian Statistical Review*, *4*, 29–39.

Smart Manufacturing Leadership Coalition, & United States Department of Energy. (2011). *Implementing 21st century smart manufacturing*. Washington, DC.

The Open Group. (2016). *ArchiMate 3.0 Specification*. The Open Group.

U.S. Department of Defense. (2016). DM2 - DoDAF Meta-Model. Retrieved June 2, 2016, from http://dodcio.defense.gov/Library/DoDArchitectureFramework/dodaf20_conceptual.aspx

Urbaczewski, L., & Mrdalj, S. (2006). A comparison of enterprise architecture frameworks. *Issues in Information Systems*, *7*(2), 18–23. http://doi.org/10.1227/01.neu.0000410082.42657.aa

Wagner, H.-T., & Weitzel, T. (2006). Operational IT Business Alignment as the Missing Link from IT Strategy to Firm Success as the Missing Link from IT Strategy to Firm Success. *AMCIS 2006 Proceedings*.

Wand, Y., & Weber, R. (2002). Research commentary: Information systems and conceptual modeling - A research agenda. *Information Systems Research*, *13*(4), 363–376. http://doi.org/10.1287/isre.13.4.363.69

WonderWare. (n.d.). Wonderware's ArchestrA™ technology and the ISA-95 standard are helping SA companies ease successfully into MES.

12 Appendix A

12.1 ISA-95 Common Object Model

The following sections each discuss an information model and its related concepts. Each table of definitions is a summary of that section of the standard specification. Every UML diagram is taken directly from the specification document as well.

12.1.1 Personnel

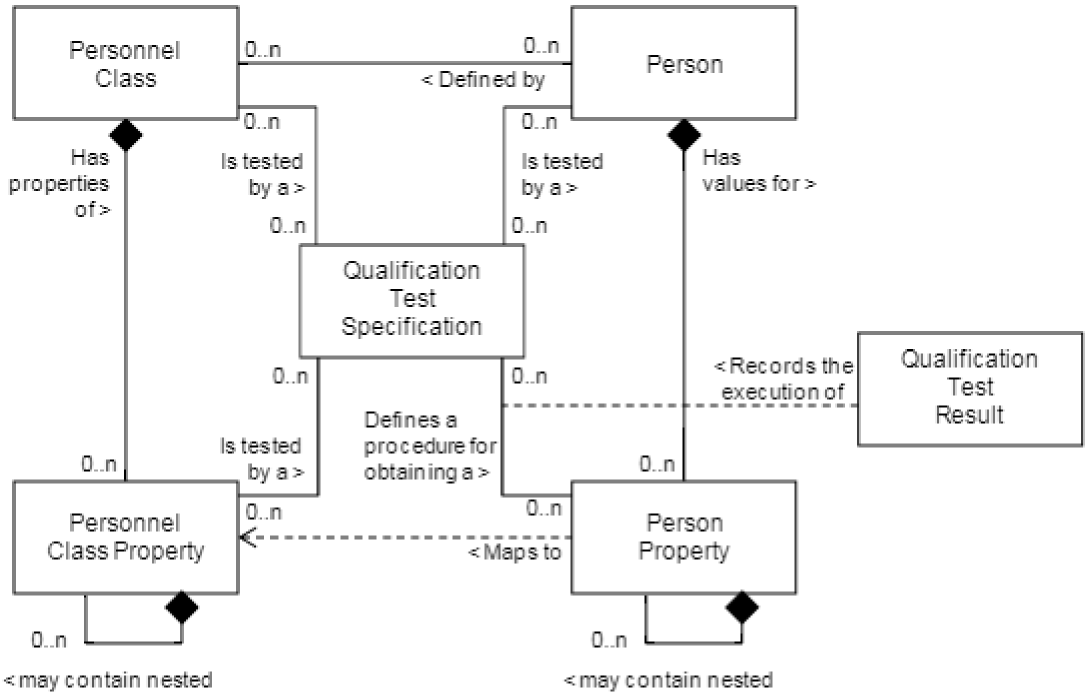


Figure 36: ISA-95 Personnel Model

Table 17: Related Concepts

Concept Name	**Definition**
Personnel Class	A personnel class is a representation of a grouping of persons with similar characteristics such as manufacturing operations definition, scheduling, capability and performance. Any person may be a member of zero or more personnel classes. A personnel class may be tested by the execution of a qualification test specification.
Personnel Class Property	Properties of a personnel class shall be shown as personnel class properties. Each personnel class shall have zero or more recognized properties. Production requests may specify required personnel class property requirements for a product segment. A personnel class property may be tested by the execution of a qualification test specification. Personnel class properties may contain nested personnel class properties.
Person	A person is a representation of a specifically identified individual. A person may be a member of zero or more personnel classes. A person may be tested by the execution of a qualification test specification.
Person Property	Properties of a person shall be listed as person properties. Each person shall have zero or more person properties. These specify the current property values of the person for the associated personnel class property. Person properties may include the current availability of a person and other current information, such as location and assigned activity and the unit of

	measure of the current information. A person property may be tested by the execution of a qualification test specification with test results exchanged in a qualification test result. Person properties may contain nested person properties.
Qualification Test Specification	A representation of a qualification test shall be presented as a qualification test specification. A qualification test specification may be associated with a personnel class, a personnel class property, a person or person property. This is typically used where a qualification test or properly demonstrated competency is required to ensure that a person has the correct training and/or experience for specific operations.
Qualification Test Result	The results from a qualification test for a specific person shall be given as a qualification test result.

12.1.2 Role Based Equipment

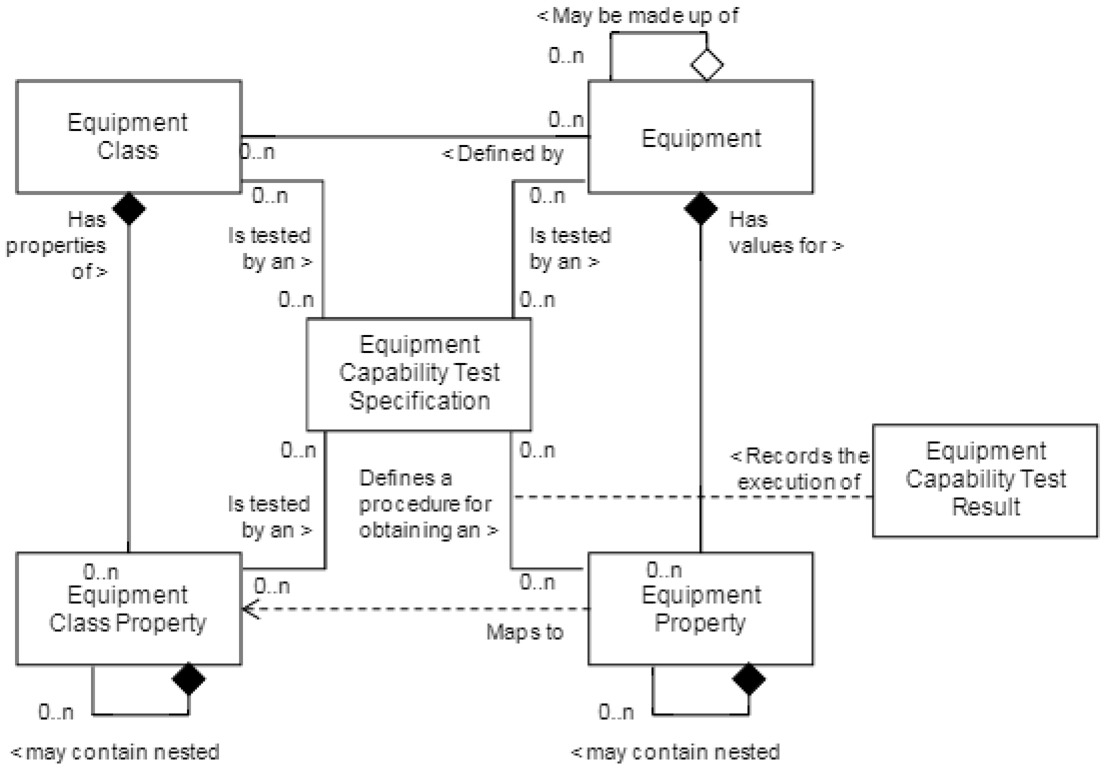


Figure 37: ISA-95 Role Based Equipment Model

Table 18: Related Concepts

Concept Name	**Definition**
Equipment Class	An equipment class is a representation of a grouping of equipment with similar characteristics for a definite purpose such as manufacturing operations definition, scheduling, capability and performance. Any piece of equipment may be a member of zero or more equipment classes. An equipment class may be tested by the execution of an equipment capability test specification.
Equipment Class Property	Properties of an equipment class shall be listed as equipment class properties. Each may have zero or more recognized properties. An equipment class property may be tested by the execution of an equipment capability test specification. Equipment class properties may contain nested equipment class properties.
Equipment	A representation of the elements of the equipment hierarchy model shall be known as equipment. Equipment may be a listing of sites, areas, production units, production lines, work cells, process cells, units, storage zones or storage units. Equipment may be tested by the execution of an equipment capability test specification. Equipment may be made up of other equipment.
Equipment Property	Properties of equipment shall be listed as equipment properties. An equipment shall have zero or more equipment properties. These specify the current property values of the equipment for the associated equipment class property. Equipment properties may include a unit of measure. An equipment property may be tested by the execution of an equipment capability test specification with results exchanged in an equipment capability test result.

Equipment Capability Test Specification	A representation of a capability test shall be presented as an equipment capability test specification. An equipment capability test specification may be associated with an equipment class, equipment class property, equipment or equipment property. This is typically used where a test is required to ensure that the equipment has the necessary capability and capacity. An equipment capability test may test for one or more equipment properties.
Equipment Capability Test Result	The results from an equipment capability test for a specific piece of equipment shall be shown as an equipment capability test result.

12.1.3 Physical Asset

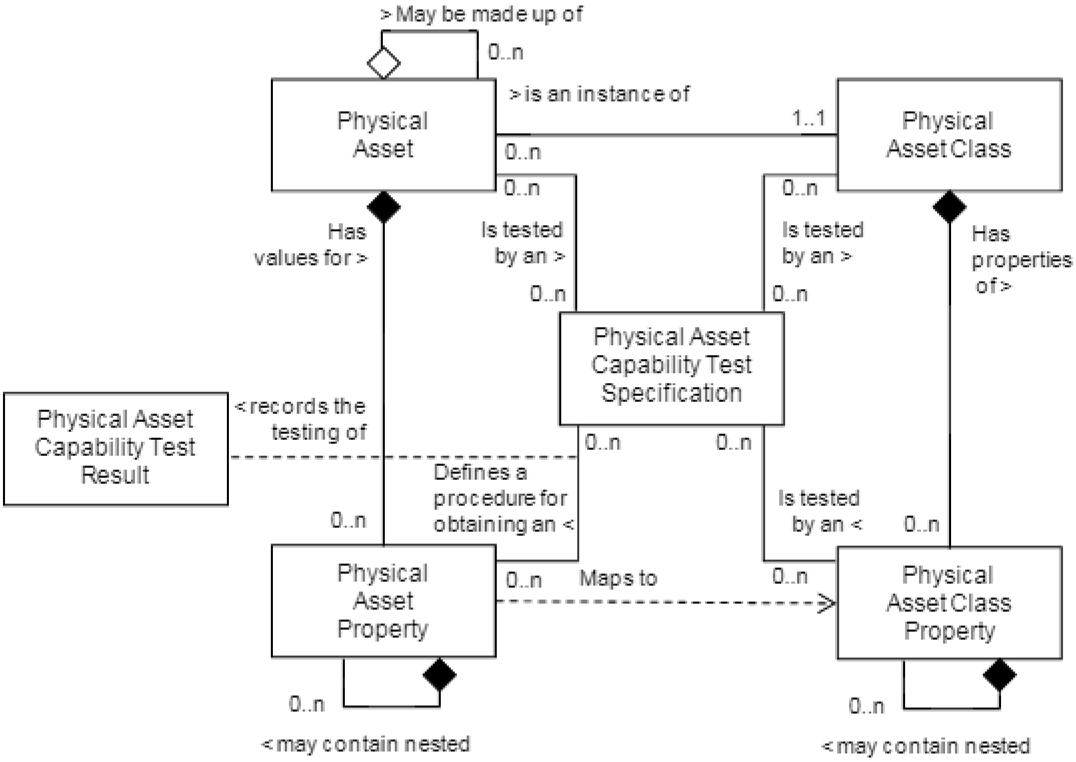


Figure 38: ISA-95 Physical Asset Model

Table 19: Related Concepts

Concept Name	**Definition**
Physical Asset	A physical asset represents a physical piece of equipment. A physical asset may be tested by the execution of a physical asset capability test specification. Physical assets may be made up of other physical assets.
Physical Asset Property	Properties of physical assets shall be listed as physical asset properties. A physical asset shall have zero or more physical asset properties. These specify the current property values of the physical asset for the associated physical asset class property. Physical asset properties may include a unit of measurement. A physical asset property may be tested by the execution of a physical asset capability test specification with results exchanged using a physical asset capability test result.
Physical Asset Class	A representation of a grouping of physical assets with similar characteristics for purposes of repair and replacement shall be used as a physical asset class. Any physical assets shall be a member of one physical asset class. A physical asset class may be tested by the execution of a physical asset capability test specification.
Physical Asset Class Property	Properties of physical assets shall be listed as physical asset class properties. Each may have zero or more recognized properties. A physical asset class property may be tested by the execution of a physical asset capability test specification. Physical asset class properties may contain nested physical asset class properties.
Physical Asset Capability Test Specification	A representation of a capability test for a physical asset shall be represented as a physical asset capability test specification. A physical asset capability test specification may be associated with a physical asset property. This is typically used where a test is required to ensure that the physical asset has

	the rated capability and capacity. A physical asset capability test specification may test for one or more physical asset properties.
Physical Asset Capability Test Result	The results from a qualification test for a specific physical asset shall be represented as a physical capability test result.

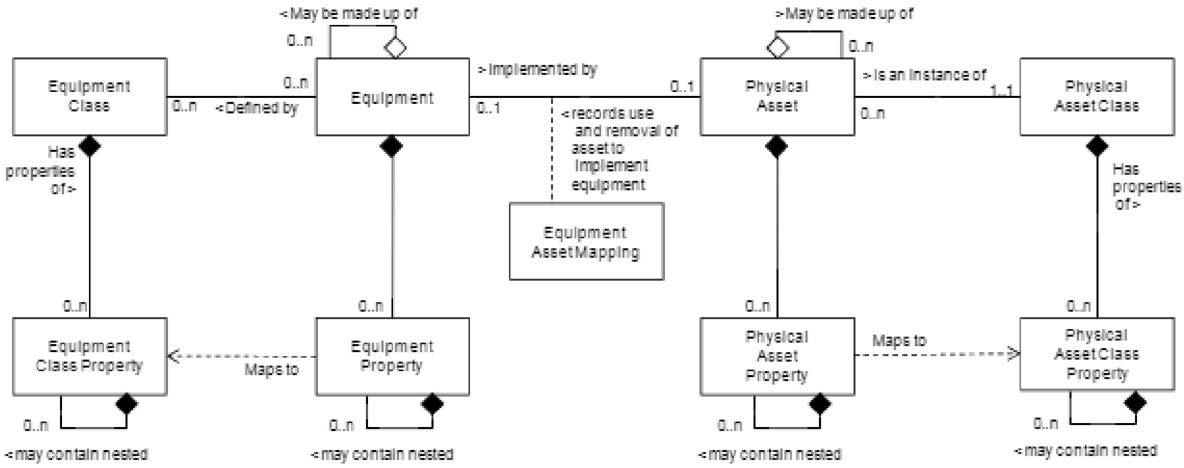


Figure 39: ISA-95 Physical Asset and Equipment Relationship

The relationship between a physical asset and an equipment shall be represented as an equipment asset mapping. The equipment asset mapping records the time period when one equipment object and one physical asset object were associated.

12.1.3.1.1 Containers

A container for material shall be represented as role based equipment, physical asset or both of type storage zone or storage unit. In a refinery, bulk storage tanks would be represented as a Storage Units and as containers for specific materials.

12.1.3.1.2 Tools

A tool shall be represented as a role based equipment, physical asset or both. For example, in a pharmaceutical plant, a tablet die used to compress and shape tables would be represented as a Work Unit. The tablet die work unit may have properties that identified the expected u se time and the actual use time. In semiconductor manufacturing, a multi-pattern CMP tool would be represented as a Work Cell. A micrometer used for measuring sheet metal thickness in a general purpose machine shop may be recorded as equipment but not tracked as a physical asset.

12.1.3.1.3 Software

Software shall be represented as a role based equipment, physical asset or both. Level 3 applications may have responsibility for keeping the actual software up to date. In the context of ISA-95, information about the software may need to be specified, required, reported or synchronized with level 4 systems.

12.1.4 Material

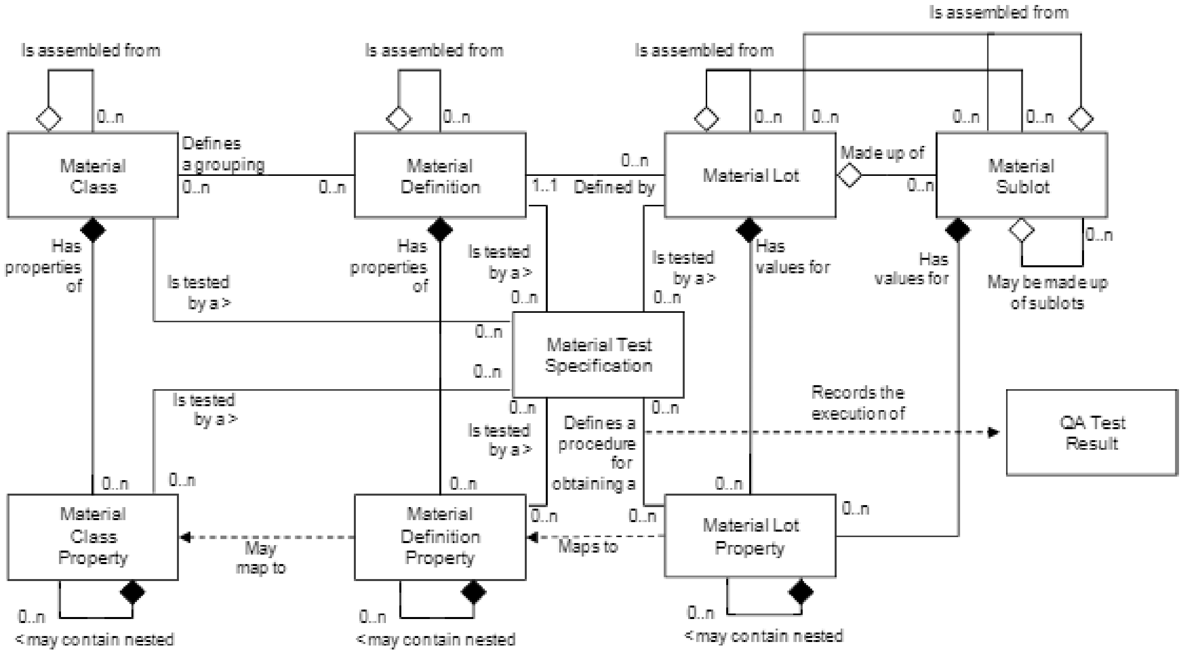


Figure 40: ISA-95 Material Model

Table 20: Related Concepts

Concept Name	**Definition**
Material Class	A material class is a representation of groupings of material definitions for a definite purpose such as manufacturing operations definition, scheduling, capability and performance. A material class may be tested by the execution of a material test specification. Examples include: sweetener, with members of fructose, corn syrup and sugar cane syrup, or; water, with members of city water, recycled water and spring water.
Material Class Property	Properties of a material class shall be presented as material class properties
Material Definition	A representation of goods with similar name characteristics for the purpose of manufacturing operations definition, scheduling, capability and performance shall be shown as a material definition. Examples include: city water, hydrochloric acid and grade B aluminum.
Material Definition Property	Properties of a material definition shall be defined as material definition properties.
Material Lot	A representation of a uniquely identified specific amount of material, either countable or weighable shall be named as a material lot. A material lot describes the planned or actual total quantity of material available, its current state, and its specific property values. A material lot may be tested by the execution of a material test specification. A material lot may be made up of material sublots. Material lots and sublots may be used for traceability when they contain unique identifiers. A material lot may be tested by the execution of a material test specification with results exchanged in a QA test specification result.
Material Lot Property	Each material can have unique values for zero or more material lot properties. A material lot property may be tested by the execution of a material test specification with results exchanged in a QA test specification result.

Material Sublot	A material lot may be stored in separately identifiable quantities. Each separately identifiable quantity of the same material lot shall be presented as a material sublot. All material sublots are part of the same material lot, sof they have the material lot's property values. A material sublot may be just a single item. Material sublots may contain other sublots.
Material Test Specification	A representation of a material test shall be shown as a material test specification. A material test specification shall be associated with one or more material definition properties. This is typically used when a test is required to ensure that the material has the required property value. A material test specification may identify a test for one or more material definition properties. Not all properties need to have a defined material test specification. Material test specifications may also be related to a production request. The same material may have different specifications for different production requests, depending on specific customer requirements.
Material Test Result	A representation of the results from the execution of a quality assurance test shall be presented as a material test result.
Assemblies	Assemblies are collections or sets of related elements. Assemblies are represented as relationships between elements and attributes of elements. Each assembly element has its own identity and properties, such as a material lot which has its own identity and properties. An object with an assembly contains the list of other elements that make up the assembly.

12.1.5 Process Segment

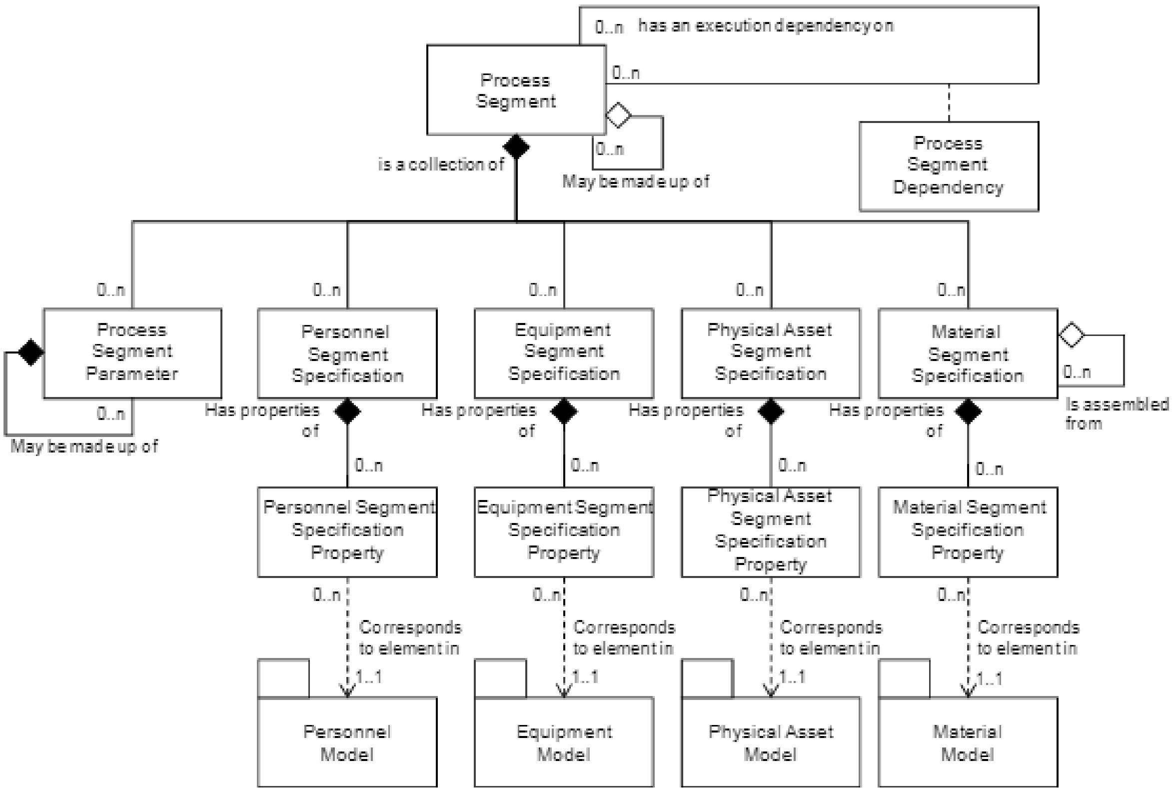


Figure 41: ISA-95 Process Segment Model

A process segment is something that occurs or can occur during manufacturing operations. It lists the classes of personnel, equipment, physical assets and material needed, and/or it may present specific resources, such as specific equipment or resources needed for the process segment. A process segment may list the quantity of the resource needed. It may also identify the time duration associated with the resources and constraint rules associated with ordering or sequencing of segments. A process segment may be made up of other process segments, in a hierarchy of definitions.

Table 21: Related Concepts

Concept Name	**Definition**
Personnel Segment Specification	Personnel resources that are required for a process segment shall be presented as personnel segment specifications.
Personnel Segment Specification Property	Specific properties that are required are specified in personnel segment specification properties. Personnel segment specification properties may contain nested personnel segment specification properties.
Equipment Segment Specification	Equipment resources that are required for a process segment shall be presented as equipment segment specifications.
Equipment Segment Specification Property	Specific properties that are required are specified in equipment segment specification properties. Equipment segment specification properties may contain nested equipment segment specification properties.
Material Segment Specification	Material resources that are required for a process segment shall be presented as material segment specifications. A material segment specification may be defined as containing an assembly of material segment specifications.

Material Segment Specification Property	Specific properties that are required are specified in material segment specification properties. Material segment specification properties may contain nested material segment specification properties.
Physical Asset Segment Specification	Physical asset resources that are required for a process segment shall be presented as physical asset segment specifications.
Physical Asset Segment Specification Property	Specific properties that are required are specified in physical asset segment specification properties. Physical asset segment specification properties may contain nested physical asset segment specification properties.
Process Segment Parameter	Specific parameters required for a segment shall be shown as process segment parameters. Process segment parameters may contain nested process segment parameters.
Process Segment Dependency	Process segment dependencies can be used to describe process dependencies that are independent of any particular product or operations task.

12.1.6 Operations Definition

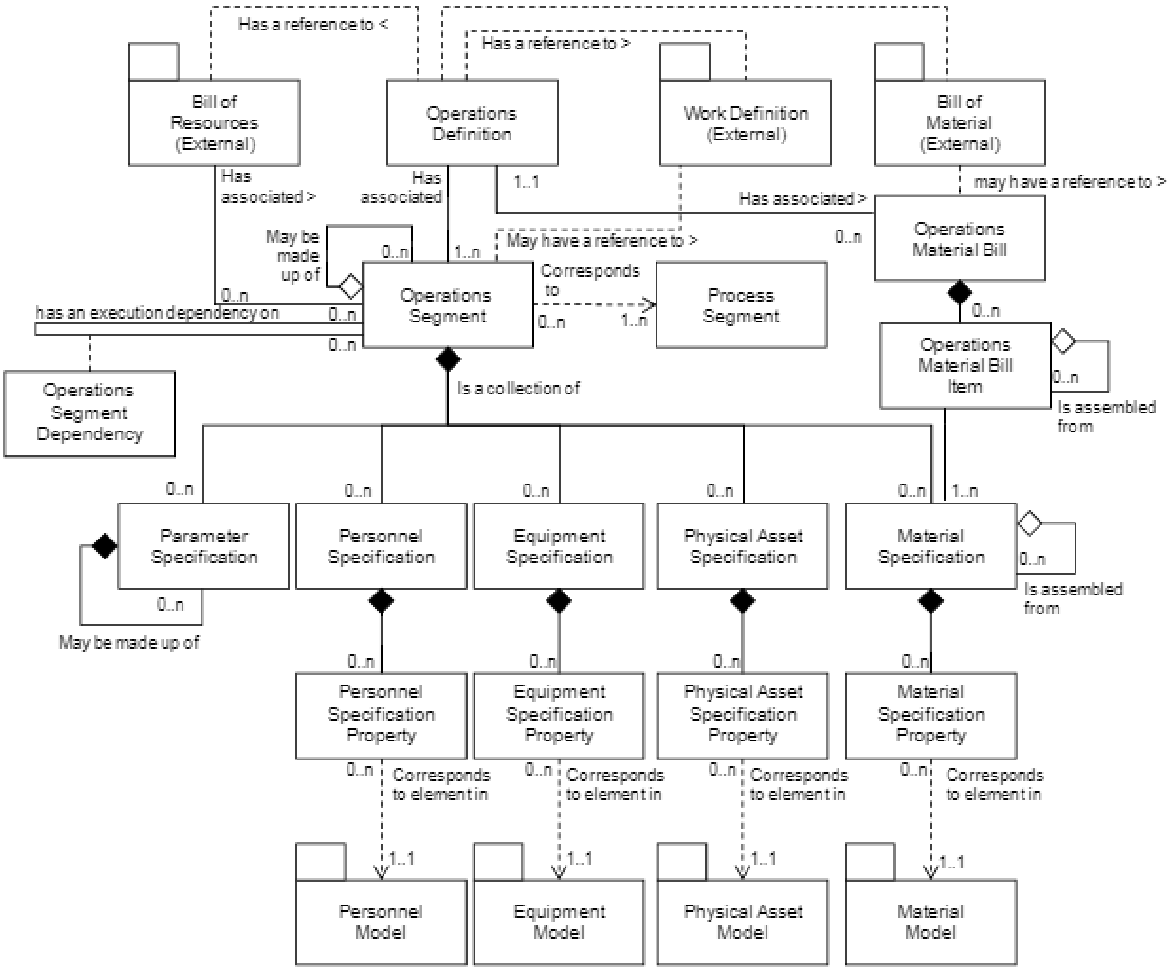


Figure 42: Operations Definition Model

Operations definition shall be used to specify the resources required to perform a specified operation. The operations definition may apply to defining production, maintenance, quality test and inventory operations.

The actual definition of how to perform the operation is not included in the object model. Operations instructions are defined as the information used to instruct a manufacturing operation how to perform the operation. Production operations specific operations instructions may be called a general, site or master recipe (IEC-61512-1 and ANSI/ISA-88.01-1995 definition), standard operating procedure (SOP), standard operating conditions (SOC), master or product routing, or assembly steps based on the production strategy used.

Table 22: Related Concepts

Concept Name	Definition
Operations Material Bill	Operations material bill objects define the collection of all material used in the operation independent of the segment the material is used in. There may be multiple operations material bills, with different uses.
Operations Material Bill Item	Operations material bill item objects identify the items that make up the complete operations material bill.

Operations Segment	The information needed to quantify a segment for a specific operation shall be an operations segment. An operations segment identifies, references or corresponds to a process segment.
Parameter Specification	An operations segment may have an associated set of zero or more parameter specifications. The parameter specification contains the names and types of the values that may be sent to the Level 3 systems to parameterize the operation. Parameter specifications may contain nested parameter specifications.
Personnel Specification	An identification, reference or correspondence to a personnel capability shall be presented as a personnel specification. A personnel specification usually specifies personnel class but may specify a person. This identifies the specific personnel capability that is associated with the identified operations segment or product segment. Specific elements associated with a personnel specification may be included in one or more personnel specifications.
Personnel Specification Property	Personnel specification properties may contain nested personnel specification properties.
Equipment Specification	An identification, reference or correspondence to an equipment capability shall be used as an equipment specification. An equipment specification may specify either an equipment class or a piece of equipment. This identifies the specific equipment capability that is associated with the segment. Specific elements associated with an equipment specification may be included in one or more equipment specification properties.
Equipment Specification Property	Equipment specification properties may contain nested equipment specification properties.
Physical asset specification	An identification, reference or correspondence to a physical asset shall be used as a physical asset specification. A physical asset specification may specify either a physical asset or a physical asset class. This identifies the specific physical asset capability that is associated with the segment. Specific elements associated with a physical asset specification may be included in one or more physical asset specification properties.
Physical asset specification property	Physical asset specification properties may contain nested physical asset specification properties.
Material Specification	An identification or correspondence to a material capability shall be presented as a material specification. A material specification specifies a material or a material class. This identifies the specific material specification that is associated with the identified product segment. Specific elements associated with a material specification may be included in one or more material specification properties.
Material Specification Property	Material specification properties may contain nested material specification properties.
Operations Segment Dependency	The operations segment dependencies can be used to describe dependencies that are operation or product specific.

12.1.7 Operations Schedule

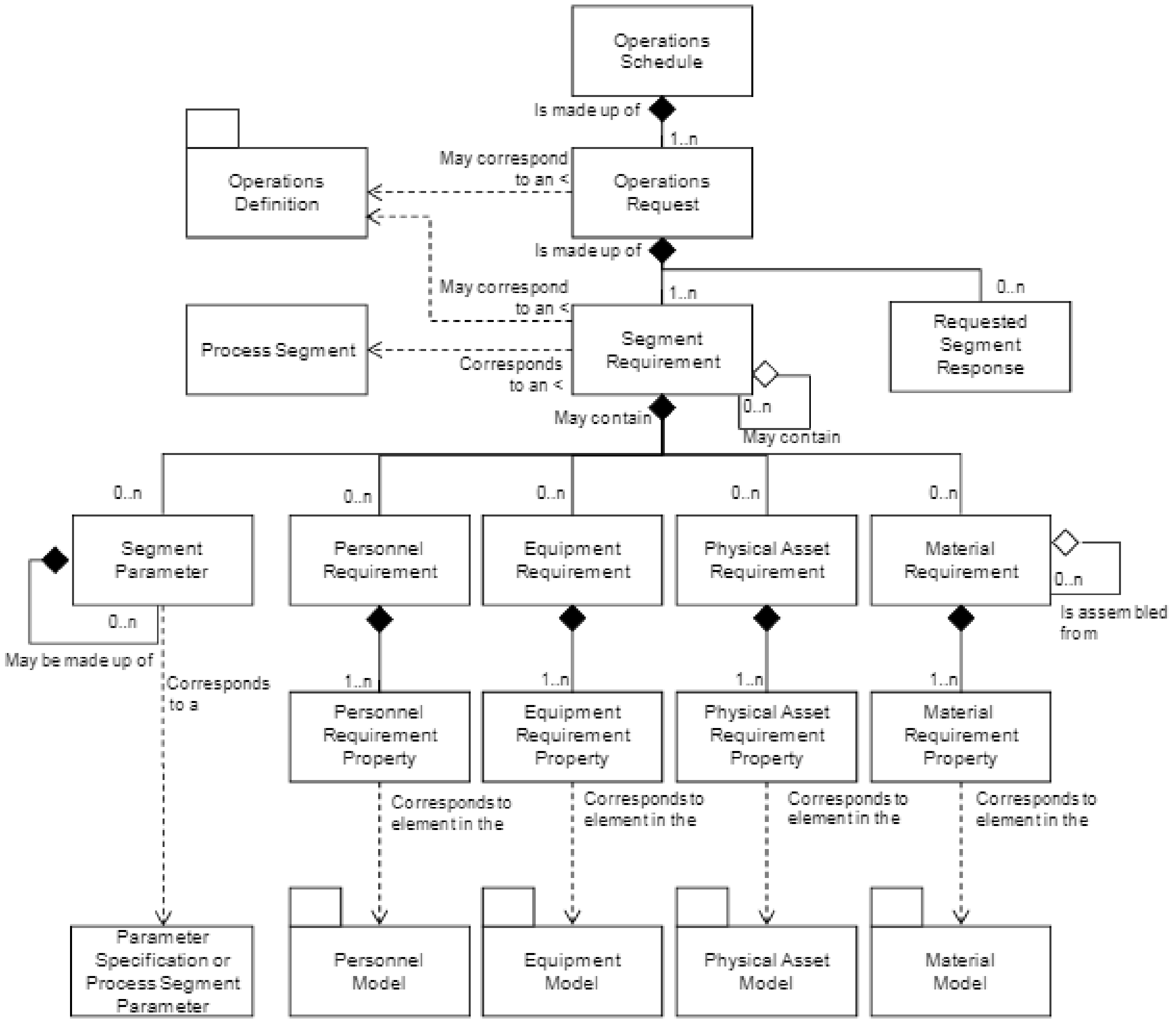


Figure 43: Operations Schedule Model

A request for operations to be performed shall be listed as an operations schedule. An operations schedule shall be made up of one or more operations requests. An operations schedule may be defined for any specific category or operations; production, maintenance, quality or inventory, or it may be defined for a combination of categories. When a combination is selected, then the operations requests or segment requirement specifies the category of the operation.

Table 23: Related Concepts

Concept Name	**Definition**
Operations Request	A request for an element of an operation schedule shall be known as an operations request. An operations request contains the information required by manufacturing to fulfill the scheduled operation. This may be a subset of the business information, or it may contain additional information not normally used by the business system. An operations request may identify or reference the associated operations instructions. An operations request shall contain at least one segment requirement, even if it spans all of the operation. An operations request may be reported on by one or more operations responses. Additional information may be described in the production parameters, personnel requirements, equipment requirements and material requirements.

Segment Requirement	A process segment and a production request shall be made up of one or more segment requirements. Each segment requirement shall correspond to, or reference, an identified operations segment or process segment. The segment requirement identifies or references the segment capability to which the associated personnel, equipment, materials and segment parameters correspond. The personnel requirement property, equipment requirement property and product parameter shall align with the personnel property, equipment property and product parameters sent as part of a production request. If the scheduling function sends information that is not understood by the receiving control function, then that information cannot be used within the control function. Likewise, the scheduling function has to be able to determine what information can be accepted by the control function.
Segment Parameter	Information contained in the enterprise system that is required by the operation system for correct manufacturing shall be known as segment parameters. A segment parameter should include a set of limits that apply to any change to the value, such as quality limits and safety limits. Segment parameters may contain nested segment parameters.
Personnel Requirement	The identification of the number, type, duration and scheduling of specific certifications and job classifications needed to support the current operations request shall be identified as a personnel requirement. Properties of the personnel requirement shall be identified as personnel requirement properties. Specific elements associated with each personnel requirement may be included on one or more personnel requirement properties.
Personnel Requirement Property	Personnel requirement properties may contain nested personnel requirement properties.
Equipment Requirement	The identification of the number, type, duration and scheduling of specific equipment and equipment classifications or equipment constraints needed to support the current operations request shall be used as an equipment requirement. Properties of the equipment requirement shall be identified as equipment requirement properties. The operations request may include one or more equipment requirements. Requirements can be as generic as materials of construction, or as specific as a particular piece of equipment. Each of these requirements shall be an instance of the equipment requirement class. Each equipment requirement identifies a general class of equipment, a specific class of equipment or a piece or set of equipment. The specific requirements on the equipment or equipment class are listed as equipment requirement property objects. Specific elements associated with each equipment requirement may be included in one or more equipment requirement properties.
Equipment Requirement Property	Equipment requirement properties may contain nested equipment requirement properties.
Physical Asset Requirement	The identification of the number, type, duration and scheduling of specific physical assets and physical asset class constraints needed to support the current operations request shall be used as a physical asset requirement. Properties of the physical asset requirement shall be identified as physical asset requirement properties. The operations request may

	include one or more physical asset requirements. Requirements can be as generic as materials of construction or as specific as a particular piece of physical asset. Each of these requirements shall be an instance of the physical asset requirement class. Specific elements associated with each physical asset requirement may be included in one or more physical asset requirement properties.
Physical Asset Requirement Property	Physical asset requirements properties may contain nested physical asset requirement properties.
Material Requirement	An identification of a material that is expected to be used in the operations request shall be presented as a material requirement. Material requirements contain definitions of materials that may be consumed, produced, replaced or otherwise used in manufacturing. A material requirement may be defined as containing an assembly of material requirements and as part of an assembly of material requirements.
Material Requirement Property	Properties of the material requirement shall be identified as material requirement properties. Specific elements associated with each material requirement may be included in one or more material requirement properties. Material requirement properties may contain nested material requirement properties.
Requested Segment Response	The identification of the information sent back as a result of the production request is a requested segment response. This information is of the same form as a segment response, but without actual values. A requested segment response may include required information, which presents information reported on from production, such as the actual amount of material consumed. A requested segment response may also include optional information, which presents information that may be reported on from production, such as operator-entered comments.

12.1.8 Operations Performance

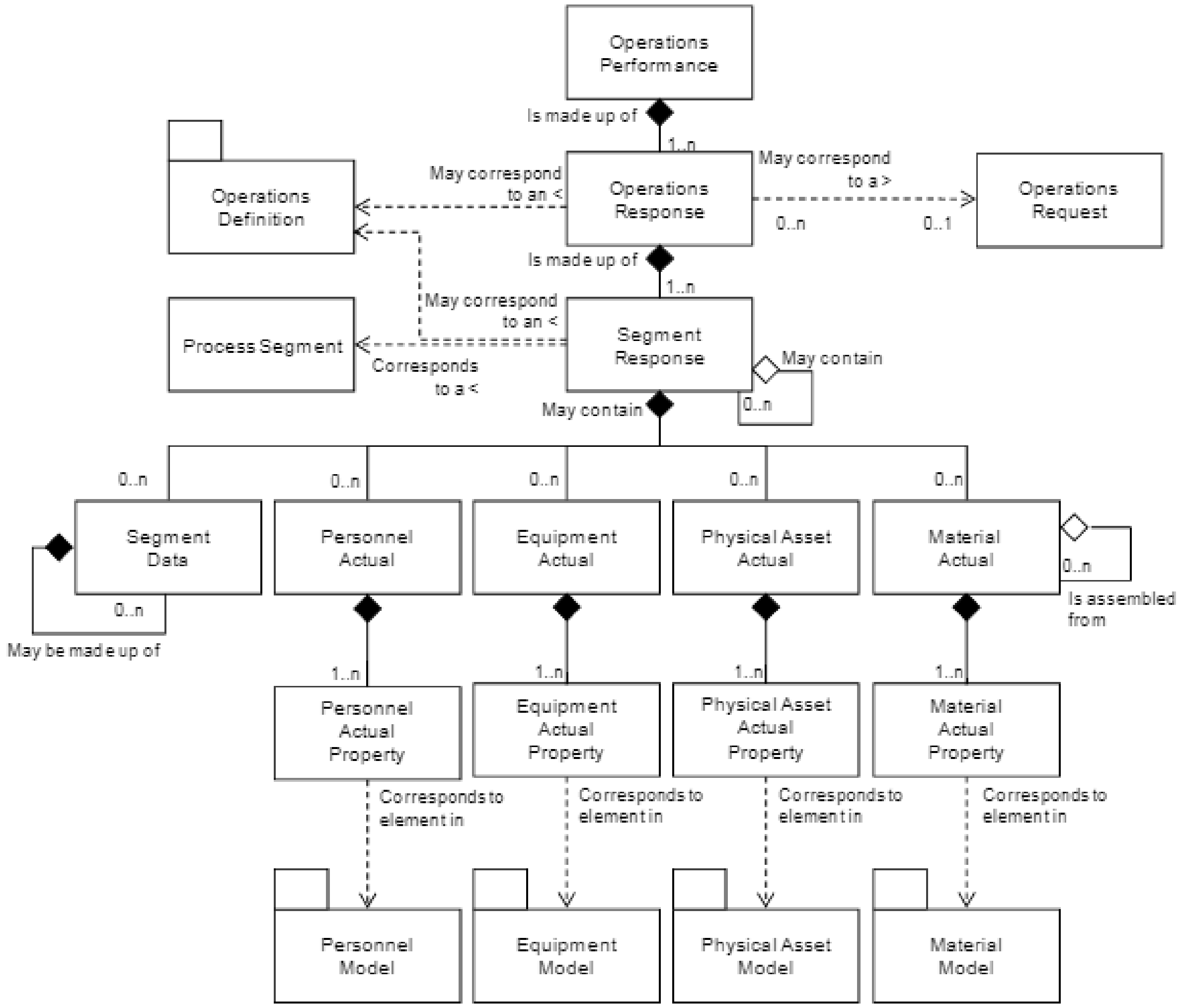


Figure 44: Operations Performance Model

The performance of the requested manufacturing requests shall be listed as operations performance.

Table 24: Related Concepts

Concept Name	**Definition**
Operations Response	The responses from manufacturing that are associated with an operations request shall be used as operations responses. There may be one or more operations responses for a single operations request if the facility needs to split the operations request into smaller elements. An operations response may include the status of the request, such as the percentage complete, a finished status or an aborted status.
Segment Response	Information on a segment of an operations response shall be used as a segment response. A segment response shall be made up of zero or more sets of information on segment data, personnel actual, equipment actual and material actual.
Segment Data	Other information related to the actual operations made shall be presented as segment data. Segment data may contain nested segment data.

Personnel Actual	An identification of a personnel capability used during a specified segment shall be used as personnel actual. Operational functions often require people as a resource to carry out tasks. Personnel actuals shall include the identification of each resource used, usually identifying a specific personnel capability or personnel class, such as end-point transmission assembly operators or personal IDs. Specific information about personnel actuals shall be listed in personnel actual properties.
Personnel Actual Property	Personnel actual properties may contain nested personnel actual properties.
Equipment Actual	An identification of an equipment capability used during a specified segment shall be identified as an equipment actual. Operations functions often require equipment as a resource to carry out tasks. Equipment actual shall include the identification of the equipment used, usually identifying a specific piece of equipment. Specific information about equipment actuals shall be listed in equipment actual properties.
Equipment Actual Property	Equipment actual properties may contain nested equipment actual properties.
Physical Asset Actual	An identification of a physical asset capability used during a specific segment shall be identified as a physical asset actual. Operations functions often require a physical asset as a resource to carry out tasks. Physical asset actual shall include the identification of the physical asset used, usually identifying a specific piece of physical asset. Specific information about physical asset actuals shall be listed in physical asset actual properties.
Physical Asset Actual Property	Physical asset actual properties may contain nested physical asset actual properties
Material Actual	An identification of a material that was used in the operations request shall be presented as a material actual. A material actual contains definitions of materials that may have been consumed, produced, replaced, sampled or otherwise used in manufacturing.
Material Actual Property	Material actual properties may contain nested material actual properties.

12.1.9 Operations Capability

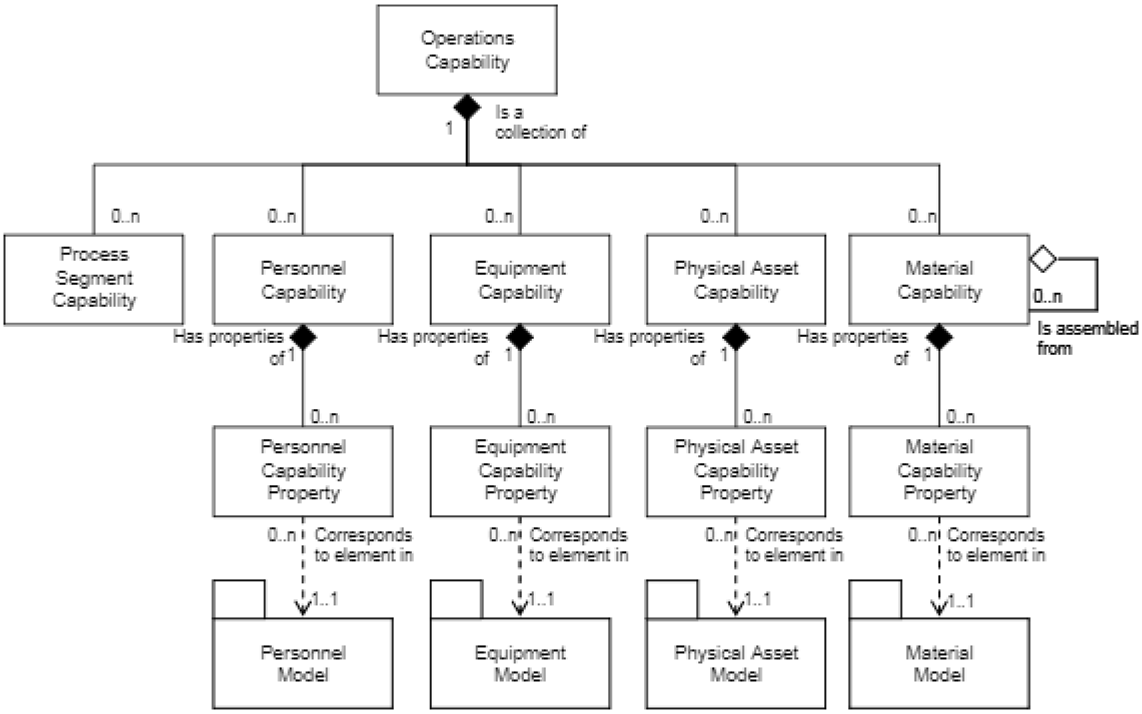


Figure 45: Operations Capability Model

Table 25: Related Concepts

Concept Name	**Definition**
Personnel Capability	A representation of the capability of persons or personnel classes that is committed, available or unattainable for a defined time shall be known as a personnel capability. Personnel capability may contain references to either persons or personnel classes. Specific personnel capabilities shall be presented in personnel capability properties. The personnel capability property may include the quantity of the resource referenced.
Personnel Capability Property	Personnel capability properties may contain nested personnel capability properties.
Equipment Capability	A representation of the capability of equipment or equipment classes that is committed, available or unattainable for a specific time shall be used as an equipment capability. Equipment capability may contain references to either equipment or equipment classes. Specific equipment capabilities shall be used in equipment capability properties. The equipment capability properties may include the quantity of the resource referenced.
Equipment Capability Property	Equipment capability properties may contain nested equipment capability properties.
Physical Asset Capability	A representation of the capability of physical assets or physical asset classes that is committed, available or unattainable for a specific time shall be used as a physical asset capability. Physical asset capability may contain references to either physical assets or physical asset classes. Specific physical asset capabilities shall be used in physical asset capability properties. The physical asset capability properties may include the quantity of the resource referenced.

Physical Asset Capability Property	Physical asset capability properties may contain nested physical asset capability properties.
Material Capability	A representation of the capability of material that is committed, available or unattainable for a specific time shall be used as a material capability. Material capability is used for material lots or sublots. This includes information that is associated with the functions of material and energy control and product inventory control. The currently available and committed material capability is the inventory. Work in progress (WIP) is a material capability currently under the control of production. Specific material capabilities shall be listed in material capability properties. The material capability properties may include the quantity of the material referenced.
Material Capability Property	Material capability properties may contain nested material capability properties.

12.1.10 Process Segment Capability

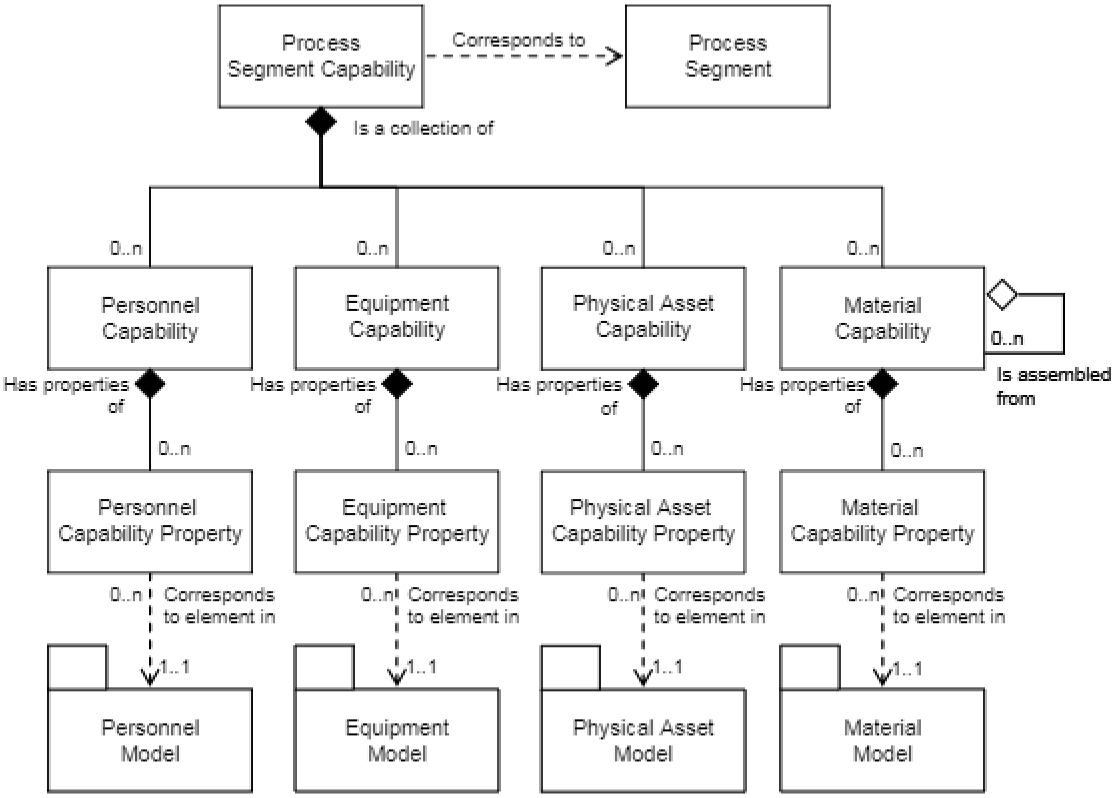


Figure 46: Process Segment Capability Model

Process Segment Capability has an equivalent structure to the personnel, equipment and material structure of operations capability, except the process segment capability is defined for a specific process segment.

12.1.11 Model Interrelationships

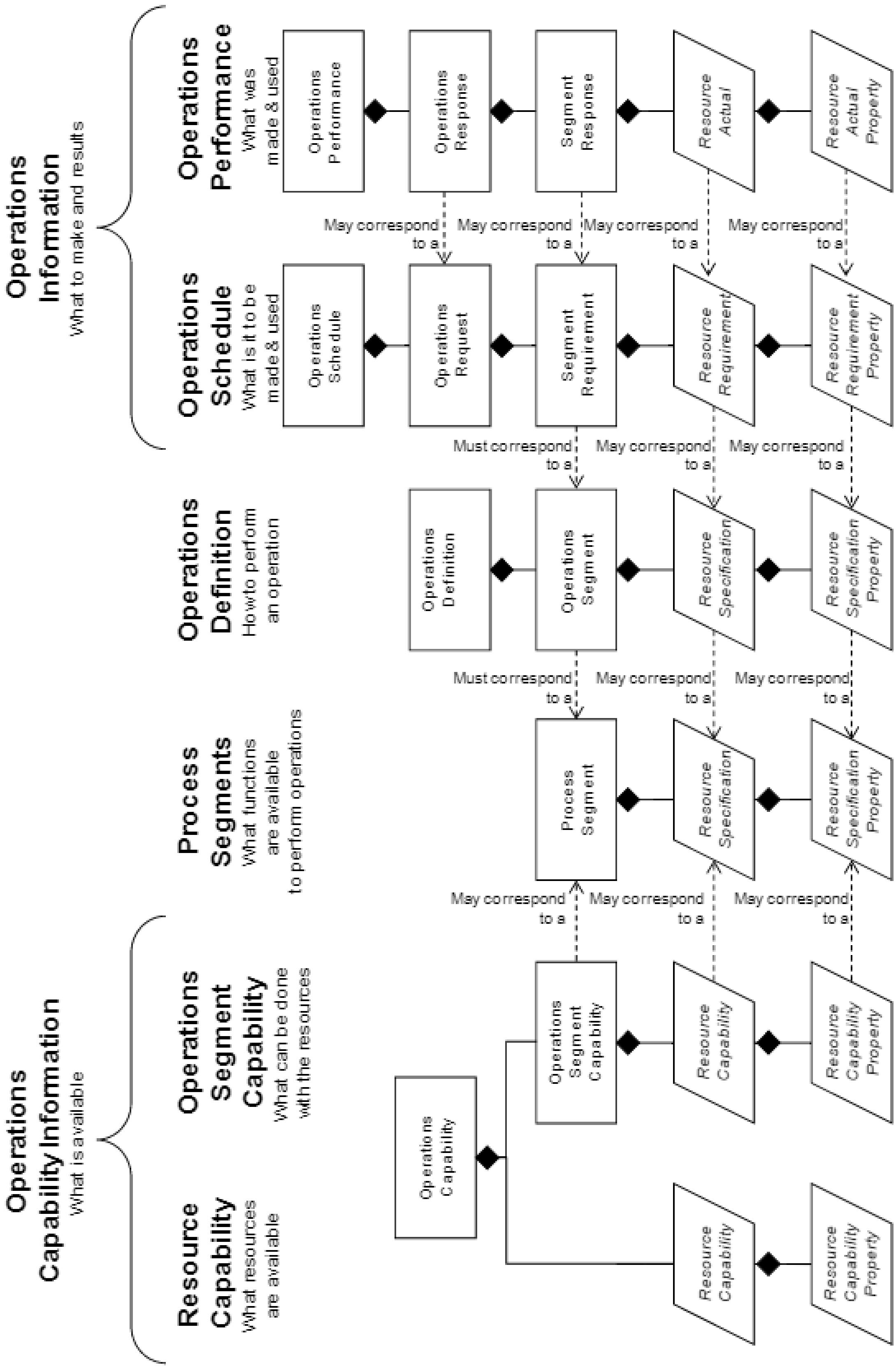


Figure 47: Model Interrelationships

Figure 47 defines the interrelationships between the concepts derived from the information models. The operations information presents what was made and what was used. Its elements correspond to information in operations scheduling that listed what to make and what to use. The operations scheduling elements correspond to information in the operations definition. The operations definition elements correspond to information in the process segment descriptions that present what can be performed with the resources. The operations capability contains what capacities exist for specified resources and for specific process segments for specific periods of time. The trapezoids represent any of the resources (personnel, equipment or material) or properties of the resources.