Computers in Industry 115 (2020) 103178

Contents lists available at ScienceDirect

Computers in Industry

journal homepage: www.elsevier.com/locate/compind

Incorporating process and data heterogeneity in enterprise architecture: Extended AMA4EA in an international manufacturing company

Marco Nardello[a,*], Shengnan Han[b], Charles Møller[a], John Gøtze[c,d]

[a] Aalborg University, Department of Materials and Production, Fibigerstræde 16, DK-9220, Aalborg East, Denmark
[b] Stockholm University, Department of Computer and Systems Sciences, Borgarfjordsgatan 12, 164 07, Kista, Sweden
[c] IT University of Copenhagen, Rued Langgaards Vej 7, DK-2300, Copenhagen, Denmark
[d] QualiWare aps, Ryttermarken 15, 3520, Farum, Denmark

ARTICLE INFO

Article history:
Received 24 June 2019
Received in revised form
25 November 2019
Accepted 2 December 2019

Keywords:
Enterprise architecture
Enterprise modelling
Automated modelling
AMA4EA
Manufacturing

ABSTRACT

The heterogeneity of production processes is a serious problem faced by international manufacturing companies. The transformation towards Industry 4.0 and the adoption of Internet-of-Things (IoT) have produced huge amounts of heterogeneous data. The production processes and data from sites across the world cannot be shared and compared at the enterprise level. Therefore, companies cannot improve their production processes and the current state-of-the-art of enterprise architecture (EA) cannot address this heterogeneity problem. To mitigate and address this heterogeneity problem, we extend the automated modelling with abstraction for EA (AMA4EA). We demonstrate the extension using the processes and data of an international manufacturing company in Denmark. The results show that the extended AMA4EA addresses the process heterogeneity problem by automatically creating EA models that relate and compare production processes from different sites. In addition, the extended AMA4EA extracts value from heterogeneous data and visualizes them in EA models. The extended AMA4EA exhibits a novel method in EA to incorporate process and data heterogeneity. This is a significant advance to EA research because it supports EA in modelling the different realities of companies. In addition, the extended AMA4EA demonstrates how production managers can jointly analyse production processes from different sites. As a result, managers can identify potential opportunities for improvement across production sites. Through EA models, they can access data and documentation stored on different enterprise systems. These contributions pave the foundation for understanding and improving the performance of heterogeneous production processes for international manufacturing companies.

1. Introduction

Enterprise architecture (EA) models define enterprises' elements and relationships (Lankhorst et al., 2017). They are helpful both for analysing enterprises and implementing enterprise systems. They are generally focused on three aspects (Lankhorst et al., 2017, p. 76): business, application and technology. Various EA modelling methods exist to created EA models. Historically, these methods require extensive manual activities which resulted in inefficient, time-consuming and error-prone practices (Hauder et al., 2012; Buschle et al., 2012; Hauder et al., 2013; Holm et al., 2014). To address these limitations, new automated EA modelling methods, which are based on data and information, have emerged (Hauder et al., 2012; Buschle et al., 2012; Hauder et al., 2013; Holm et al., 2014). However, most of the automated EA modelling methods have been focusing on EA models related to the application and technology aspects (Nardello et al., 2019). To leverage the automated EA modelling method also for business aspects, automated modelling with abstraction for enterprise architecture (AMA4EA) was proposed (Nardello et al., 2019).

AMA4EA is a method that abstracts data to create EA models (Nardello et al., 2019). We evaluated AMA4EA at the Industry 4.0 laboratory at Aalborg University, in Denmark. We demonstrated that AMA4EA can abstract detailed data from an enterprise resource planning (ERP) system and a manufacturing execution system (MES) to be relevant for creating a business process model (Nardello et al., 2019). This EA model provided a useful and simpli-

* Corresponding author.
E-mail addresses: man@mp.aau.dk (M. Nardello), shengnan@dsv.su.se (S. Han), charles@mp.aau.dk (C. Møller), jogo@itu.dk (J. Gøtze).

https://doi.org/10.1016/j.compind.2019.103178
0166-3615/

fied visualization of production processes (Nardello et al., 2019). In this demonstration, only homogeneous data and production process were feed to the AMA4EA.

International manufacturing companies are usually constituted of subsidiaries that operate in heterogeneous environments (Ghoshal and Nahria, 1989). Heterogeneous environments are due to different historical and environmental conditions (Ghoshal and Nahria, 1989). These different conditions lead to heterogeneous processes and IT systems across different subsidiaries. Different processes, IT systems, environmental and historical conditions lead to the problem of process and data heterogeneity. In our case company, in the ERP system, the production process of the same component was specified differently depending on the production site, 26 activities in one site and over 200 in another. Process and data heterogeneity hinders international manufacturing companies in comparing their production processes. Furthermore, it is problematic for production managers in sharing data from heterogeneous processes to achieve process efficiency. In addition, the heterogeneity problem hampers companies from leveraging the increased data availability of Industry 4.0 technologies to support improving production processes. To address the process and data heterogeneity problem and support companies adopting Industry 4.0 technologies, new EA approaches that create EA models based on data and information are needed (Tambo and Bækgaard, 2013, p. 293; Gampfer et al., 2018). Therefore, in this article, we contribute to EA and automated EA modelling methods by addressing the following research question:

> How to further develop automated EA modelling methods that model business aspects to cope with process and data heterogeneity?

In this article, we evaluate AMA4EA with data from an international manufacturing company. The heterogeneity problem can be addressed using AMA4EA because the method is able to abstract heterogeneous data from enterprise systems (ESs) and visualize them in EA models. However, AMA4EA was developed in an environment with homogeneous processes and data (Nardello et al., 2019). Two extensions to the method are necessary to fully address the heterogeneity problem. The first extension is to create EA models at two levels of detail, i.e. at the subsidiary/site level and enterprise level. The second is to include data from production processes in EA models and provide access to other external resources through EA models.

The extended AMA4EA contributes to EA research in three main ways. First, it demonstrates how automated EA modelling approaches can be adapted to address the heterogeneity problem. Second, it supports holistic approaches in EA by automatically creating EA models that represent the different realities of companies (i.e. production processes of multiple production sites). Third, it enables the comparison of production processes and data and accesses external resources through EA models. The extended AMA4EA contributes to practice, especially to production managers at international manufacturing companies. The three main contributions are: (1) identify the activities that the production sites execute in the same sub-process, (2) identify the potential for improvement across production sites, and (3) provide access to data and documentation stored on different ESs using EA models.

Our study follows an explorative research approach that "involves the construction and incremental extensions of problem statements and associated solutions" (Corne et al., 1994; Lou Maher et al., 1996). In (Nardello et al., 2019), the problem was the inability to use business data to generate EA models. AMA4EA solved the problem by abstracting data and automatically creating an EA model. Afterwards, AMA4EA was applied in an industrial context and this refocused the problem to process and data heterogeneity. This problem is addressed by the extensions of AMA4EA presented in this article. This article is organized as follows. In the next section, we present in more detail the process and data heterogeneity problem. Section 3 summarizes the original AMA4EA method and the background literature used to extend AMA4EA. Section 4 describes the extended AMA4EA and Section 5 presents the application of the extended AMA4EA to a Danish international manufacturing company. Section 6 discusses the implications of our research for the EA research field and practitioners in manufacturing companies. In the last section, we present the conclusions and future work.

2. Process and data heterogeneity problem

This section explains the process and data heterogeneity problem. International manufacturing companies are very heterogeneous because production sites are embedded in different environmental conditions (Ghoshal and Nahria, 1989, p. 323). For example, international manufacturing companies have production sites that operate in countries with different regulations and cultures. These companies have very heterogeneous processes and data because each production site has developed under different historical conditions (Ghoshal and Nahria, 1989, p. 323). For example, some sites have been part of the enterprise from its origin – and operate with similar production processes – while other sites have been acquired during the years – and operate with production processes different from the rest of the enterprise.

2.1. Process heterogeneity

Different environmental and historical conditions caused the development of heterogeneous processes across production sites in international manufacturing companies. To address the process heterogeneity problem of international manufacturing companies, previous research defined production processes at two levels of detail, enterprise and site levels (Netland, 2013; Netland and Aspelund, 2014, p. 393). At the enterprise level, the outline of the production process is defined. Usually, this process is created during the development of a new product and it specifies the production process in an "ideal" site. At the site level, the production process at the enterprise level was further adapted to comply with the environmental and historical conditions of the production site. This activity is performed by managers and engineers at each production site by further specifying the production process from the enterprise level to the site level. Therefore, the latter is context-specific and accounts for environmental conditions like the site's physical limitations and national regulations. The benefits of the two-level approach are that there is a certain amount of process standardisation across the enterprise as well as room for production site adaptation to not neglect local advantages (Netland, 2013; Netland and Aspelund, 2014, p. 393). However, the production process at the enterprise and local levels are often stored in different ESs and are managed differently. As a result, the relationship between a process at the enterprise and site level is often lost because the first is usually stored in a product lifecycle management system and is seldom updated, while the second is stored in an ERP system and MES and is continuously updated for process efficiency. Consequently, production managers are missing a system that provides an overview of production processes (i.e. at an enterprise level) with a relationship to the production processes specific to each site (i.e. site level). Currently, production managers have access only to isolated production processes at the site level. Therefore, the heterogeneity of the process hinders international manufacturing companies in directly comparing production processes across sites and improving the processes' efficiency.

2.2. Data heterogeneity

Different environmental and historical conditions and the process heterogeneity problem often lead to storing process data on different ESs. We refer to this as the data heterogeneity problem. Since production process data and external resources—for example, performance measurements and assembly documentation—are heterogeneous across production sites and are stored on different ESs, it is problematic to share and compare. This problem has been partially addressed with the implementation of ESs like ERP and ME systems to store the enterprise's production process data at the site level. However, the ERP and ME systems do not store either the production process at the enterprise level or a connection between the production process at the site level and the one at the enterprise level. When managers and engineers at the production site specify the production process from the enterprise level to the site level, they decide which data to collect and how to structure the external resources and the level of detail of these data and external resources. As a result, data and external resources at the site level are heterogeneous across production sites and develop differently over time. Consequently, production managers are missing a system that collects production process data and external resources in a system that relates these data with an overview of production processes and the detailed production processes (i.e. at the site level). Currently, data is stored on different systems and production managers access it separately. Fragmented data hinders international manufacturing companies from using this data effectively and efficiently to improve production processes.

3. Background literature

This section presents the state-of-the-art EA literature (i.e. including AMA4EA method) related to address the process and data heterogeneity problem.

3.1. State-of-the-art EA literature

EA as a discipline uses EA frameworks (e.g. Zachman framework (Zachman, 1987)) to define EA models and structure their content and relationships. For instance, the *how* interrogative in (Zachman, 1987) is concerned with the design and execution of processes within the enterprise (Lapalme et al., 2016). The *what* interrogative in (Zachman, 1987) is concerned products and products components (Lapalme et al., 2016). In large manufacturing companies, there are hundreds of processes and products to be modelled. To support the development of these models, process mining and automated EA modelling methods have been developed.

Process mining is used to establish relationships between a process, its data and its process model (Van Der Aalst, 2016). Process discovery technique is usually used in process mining to create process models by using event logs without any prior information (Van Der Aalst, 2016). It is useful to discover "real" processes on the bases of process event logs (Van Der Aalst, 2016). Process abstraction, a part of process discovery techniques, was proposed to address the process heterogeneity problem. It provides an overview of a process by aggregating activities and representing the process model in a compact and understandable way (Garcia et al., 2019). The "semantic-based approach to manage perspectives of process mining" (Kingsley et al., 2016) uses ontologies to enrich event logs (Karray et al., 2014). Though, this technique used only for process models which are only a part of EA models for the business aspect. Other EA models for the business aspect cover product architectures, strategy and project planning. Therefore, although useful this approach is not developed to create EA models for business aspects.

In EA research, two methods are developed in the field of automated EA modelling. First, automated EA documentation (Farwick et al., 2016) is a method for the collection of data to create EA models. It includes four techniques (Farwick et al., 2016): (1) task-based reminders, (2) automated structured data collection, (3) external event triggers, and (4) internal model event triggers. Among them, the automated structured data collection technique focused on "the reuse of external structured data sources into the EA model in order to reduce or even eliminate the manual data collection effort for specific model elements in the repository" (Farwick et al., 2016, p. 408). Second, the automated EA modelling method for IT architectures (Holm et al., 2014, p. 839). This method was first presented by Buschle et al. (2011) and then further applied and developed by other researchers (Holm et al., 2014; Välja et al., 2015; Välja et al., 2016). It uses predominantly network scanner applications for collecting data about IT architectures in an enterprise (Buschle et al. (2011)). It then creates EA models related to the application and technical aspects with the data collected. The limitation of these methods is that they are not used for creating EA models related to the business aspects. In addition, the description of these methods is not very exhaustive and therefore we cannot replicate them.

3.2. Automated modelling with abstraction for enterprise architecture (AMA4EA)

AMA4EA is the method to "automatically abstract detailed data from ESs to concepts. The abstraction is achieved through the use of AMA4EA environment" (Nardello et al., 2019). In the AMA4EA environment data abstraction occurs. Data, for instance from ESs, is related to predefined concepts in abstraction hierarchies. "AMA4EA also instantiates the relevant information in an EA repository and creates EA models automatically" (Nardello et al., 2019). AMA4EA is meant to be applied to create EA models for which data is available. For instance, product architecture models can be created abstracting data from product lifecycle management with the standard on industrial products (International Electrotechnical Commission, 2019). Similarly, business process models can be created leveraging a production process classification (Sorensen et al., 2018) and software application landscape models using classifications provided by EA vendors. AMA4EA requires four roles: a stakeholder (S), who initiates the modelling and sets the requirements; an enterprise architect (A), who manages the execution of AMA4EA; a data source manager (DSM), who is responsible for providing data for AMA4EA; and a subject-matter expert (SME), who collaborates with the enterprise architect by defining abstraction hierarchies and performing abstractions. The method starts with a manual preparation phase and continues with an automated execution phase. The activities of each phase are summarized in Tables 1 and 2 and represented in Figs. 1[1] and 2 .

AMA4EA (Nardello et al., 2019) was tested in a laboratory environment. The process and data were homogeneous and coherent. Although the Industry 4.0 laboratory aims at replicating industrial environments, not all industrial problems were considered—i.e. process and data heterogeneity.

4. The extended AMA4EA

In this section, we present the details of the two extensions for AMA4EA to incorporate process and data heterogeneity in EA and address the problems we discussed.

[1] If no suitable abstraction hierarchies exist, the SME and architect may search for one—e.g. industrial standards. If no satisfactory abstraction hierarchies are found, they develop a new abstraction hierarchy.

Table 1
The four activities in the preparation phase of AMA4EA (Nardello et al., 2019).

Activity	Description of AMA4EA
1. Define the desired EA model	An architect and a stakeholder define the desired EA model's purpose, scope and concepts. They decide the desired EA model's abstraction level—business, application, or technology (Lankhorst et al., 2017). The architect then chooses the desired EA model's type—e.g. business process model, product architecture model, or strategy model—and the modelling notation—e.g. ArchiMate, BPMN, UML, or industry- or enterprise-specific notation.
2. Identify data sources	The architect and DSM specify which ES handles the data related to the desired EA model's concepts. They locate the relevant data in the ES and identify the data's structural metadata. The architect and DSM choose from the structural metadata the fields relevant for the desired EA model. In addition, they indicate the interfaces available for extracting data from the ES.
3. Identify abstraction hierarchy	The architect selects an abstraction hierarchy aligned with the desired EA model's purpose, scope and concepts. If no suitable abstraction hierarchies exist, the SME and architect may search for one—e.g. industrial standards. If no satisfactory abstraction hierarchies are found, they develop a new abstraction hierarchy. In the last two cases, the architect imports the abstraction hierarchy into the AMA4EA environment and into an EA repository.
4. Set-up the AMA4EA environment	This activity is structured in two tasks. The architect creates a storage area in the AMA4EA environment, replicating the ES's structural metadata. In this way, data from ESs can be automatically imported into the AMA4EA environment. In the second task, the architect defines the structural metadata of the AMA4EA environment's interface. The first section of the interface relates to fields from the dedicated data storage area. The second contains information for performing abstractions. It includes the concepts and relationships in the abstraction hierarchy. The third includes the information for mapping fields from the ES structural metadata to the metamodel of the elements in the EA repository.

Table 2
The three activities in the execution phase of AMA4EA (Nardello et al., 2019).

Activity	Description of AMA4EA
1. Extract data from ES to the AMA4EA environment	The DSM exports data from an ES. Then, the data is automatically imported into AMA4EA using the *data import algorithm*. The algorithm stores the data in the dedicated storage area in the AMA4EA environment.
2. Abstract data in the AMA4EA environment	The *abstraction algorithm* retrieves previous abstractions in the AMA4EA environment and applies them to the data under analysis. If data cannot be automatically abstracted, the SME is requested to manually abstract them. This includes the mapping of the fields from the ES to the corresponding fields of the elements in the EA repository. The *abstraction algorithm* saves the manual abstractions in the AMA4EA environment.
3. Create the desired EA model	The *instantiate and position algorithm* is responsible for importing data and their abstractions from the AMA4EA environment into the EA repository. This algorithm instantiates new elements in the EA repository, storing the abstractions in the elements' fields. The algorithm also creates the desired EA model and positions the instantiated elements in the desired EA model.

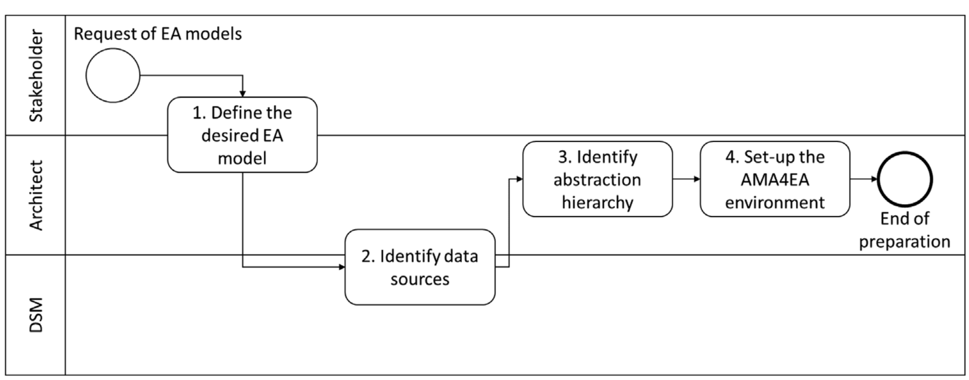


Fig. 1. The preparation phase of AMA4EA method.

4.1. The extended AMA4EA: incorporating process heterogeneity

To address this problem of process heterogeneity, we extended AMA4EA to create EA models at a site level alongside with EA models at an enterprise level. In this way, heterogeneous production processes at a site level are related to the overview of the production processes at an enterprise level. To develop this extension, we analysed contributions related to business process models, which are a core artefact of EA (Winter and Fischer, 2007, p. 5). Researchers developed business process models for production processes that allow the modelling at two levels of detail (Desbiens and Chaabane, 2014; Erasmus et al., 2018). These articles use business process model and notation (BPMN) and follow the integration model proposed by the ISA-95 standard (International Electrotechnical Commission, 2013). We included part of the research from Desbiens and Chaabane (2014) and Erasmus et al. (2018) in the extended AMA4EA as follows. The process model at the enterprise level provides an overview of production processes (ISA-95 level 4) using sub-processes, see Fig. 3. The process model at the site level (ISA-95 level 3) specifies the activities performed at the production sites for each sub-process, see Fig. 3. It also provides a detailed breakdown of the sub-processes included in the overview model. Process models at a site level are linked to the sub-processes at the enterprise level. As a result, production processes at both levels are easily accessible by the users. A similar approach for service maintenance processes was developed by Rondini et al. (2018). As Desbiens and Chaabane pointed out, manual development of these production process models required a considerable amount of time and extensive manipulation and interpretation of input data (Desbiens and Chaabane, 2014, p. 330). We address the process heterogeneity

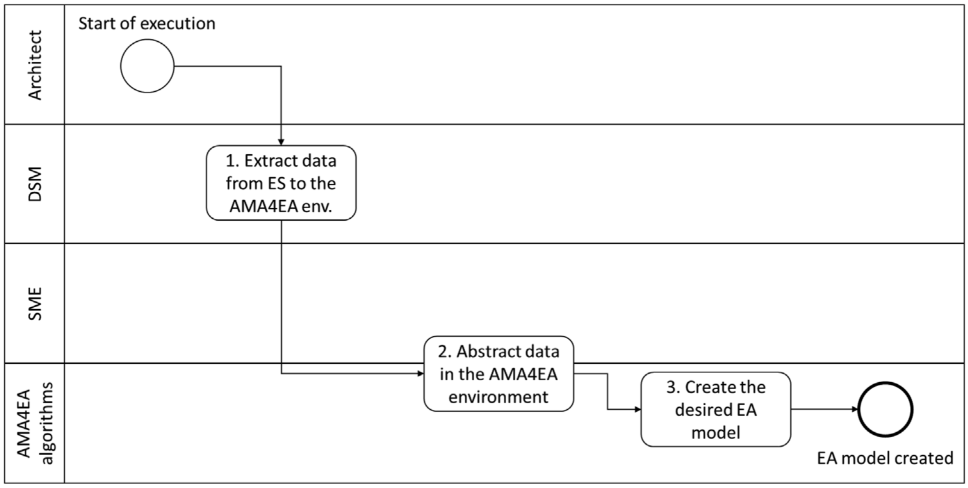


Fig. 2. The execution phase of AMA4EA method.

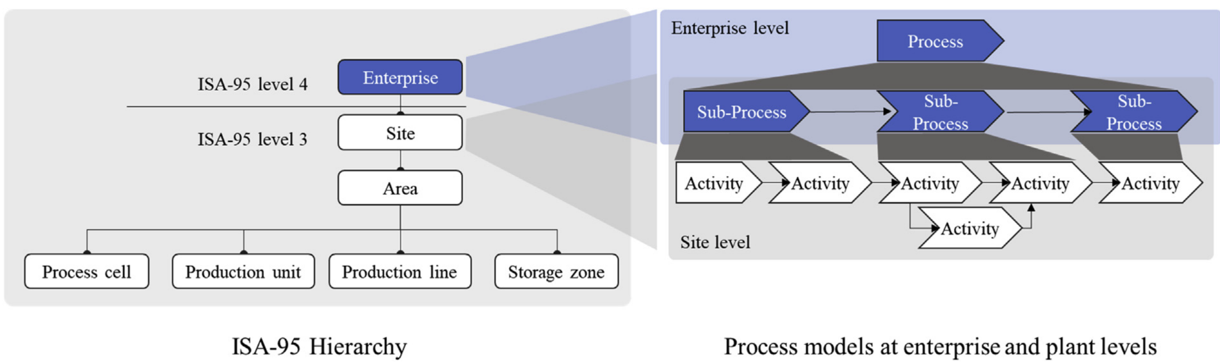


Fig. 3. Hierarchical levels of ISA-95 adapted from (International Electrotechnical Commission, 2017; Nardello et al., 2017) and the relationship between process models at enterprise and site levels.

problem and this limitation by extending AMA4EA to automatically create EA models (i.e. business process models) at two levels of detail.

In more detail, EA models at the site level are related to the sub-processes at the enterprise level. This is achieved in the extended AMA4EA by importing a production process at the enterprise level and then mapping the production processes at the site level to the production process at the enterprise level. The activities of AMA4EA (Nardello et al., 2019) are extended as follows. The extensions of the activities in the preparation and execution phase are explained respectively in Tables 3 and 4.

To clarify, the second activity includes *abstracting* data to concepts in the abstraction hierarchy and *mapping* concepts from the site level to concepts at the enterprise level. The abstraction of data is stored in the AMA4EA environment and can be automatically applied through the *abstraction algorithm* to new data that has similar properties (e.g. ID or description field) to the data already abstracted. For instance, all the activities from a production site have a description field that is used following a predetermined structure. Therefore, based on this field activities of different processes with the same description field are referring to the same concepts and can be abstracted to these concepts in the abstraction hierarchy. The mapping of concepts from site level to enterprise level is also stored in the AMA4EA environment and can be automatically applied through the *abstraction algorithm* to the same data. For instance, when a process at a site level is mapped to an enterprise level, the EA models are created. If afterwards the EA models are deleted, the same data from the ES can be imported in the AMA4EA environment then the old mapping will be automatically applied. If necessary, the SME can still make adjustments and corrections to the mapping.

4.2. The extended AMA4EA: incorporating data heterogeneity

To address the data heterogeneity problem, we extended AMA4EA in two ways. First, we included performance measurements for EA and business process models in AMA4EA models (Cardoso, 2013) and facilitated access to assembly documentation through the use of uniform resource locators (URL). Cardoso's research addressed the problem of including performance measurements in EA models representing processes. From his research, we included instance and aggregated measurements in AMA4EA. For example, measuring the number of errors reported by the operator during the execution of an activity at the site level. An aggregated measurement "uses a set of process instances to calculate the KPI's values (aggregating single process instances)" [Cardoso, 2013, p. 331]. For example, aggregating the number of errors in its activities for each sub-process during a week. Another example is aggregating the number of errors reported for related sub-processes at a site level for each sub-process of a production process at an enterprise level. Second, we linked external resources in the EA models created by AMA4EA. Once the measurements and external resources from different processes are included in EA models, it is possible to compare and improve the performances and operations at different sites. In more detail, we extended the AMA4EA method to include elements in the EA models, URLs and database queries to link external resources and visualize pro-

Table 3
The extensions of the four activities in the preparation phase of AMA4EA for incorporating process heterogeneity.

Activity	Description of AMA4EA
1. Define the desired EA model	The stakeholder and the architect acknowledge the need for managing EA models at two levels of detail. This requires defining the purpose, scope and concepts at each level. In addition to choosing the type of EA model, the stakeholder and the architect decide the modelling notation for each level. They can be different. *Input:* The stakeholder presents his understanding of the problem addressed with the EA models. *Output:* Definition of the desired EA models, the scope of the models and the notation to be used.
2. Identify data sources	The DSM identifies the ESs storing data related to the concepts to be included in the desired EA model and the location of data in the ESs. For instance, production routing data in the ERP system is related to production processes. *Input:* Purpose, scope and concepts to be included in the EA models. *Output:* Name of the ESs with the relevant data and the location for extracting the data.
3. Identify abstraction hierarchy	The architect selects the abstraction hierarchies relevant to abstract the data from the ESs to the concepts in the EA model at the enterprise and site level. If no suitable abstraction hierarchies exist, the SME and architect may search for one — e.g. industrial standards. If no satisfactory abstraction hierarchies are found, they develop a new abstraction hierarchy. If this is the first application of the abstraction hierarchies, the architect imports them into the AMA4EA environment and into an EA repository. *Input:* Modelling notation selected in the first activity. *Output:* Abstraction hierarchy with the concepts that will be represented in the EA models.
4. Set-up the AMA4EA environment	For the EA model at the enterprise level, this activity does not change. For the EA model at the site level, this activity needs to duplicate the “main” interface to create a “site” interface. The architect needs to extend the structural metadata of the AMA4EA environment’s šiteïnterface adding the columns for the fields and abstractions of the data for the EA model at the enterprise level. In this way, in the “site” interface it will be possible to specify the mapping from the data for the EA models at the site level to the EA model at the enterprise level. *Input:* AMA4EA environment with only the “main” interface. *Output:* AMA4EA environment with “main” and “site” interfaces, with the site interface that allows mapping the data and abstraction from the site level to the enterprise level.

Table 4
The extensions of the three activities in the execution phase of AMA4EA for incorporating process heterogeneity.

Activity	Description of AMA4EA
1. Extract data from ES to the AMA4EA environment	An enterprise integration software or the DSM extracts data from the ESs for creating the EA models previously identified. The data is imported in the dedicated storage area in the AMA4EA environment using the *data import algorithm*. *Input:* Name of the ESs with the data for the EA models and the location for extracting the data. *Output:* AMA4EA environment with data from the ESs in the “main” and “site” interfaces.
2. Abstract data in the AMA4EA environment	This extension is executed after the abstraction from data to concepts using the abstraction hierarchy. In the šiteïnterface, the *abstraction algorithm* or SME map concepts at the site level to the concepts at the enterprise level. For instance, each activity in the production process at the site level is mapped to a sub-process of the process at the enterprise level. *Input:* AMA4EA environment with data from the ESs in the “main” and “site” interfaces. *Output:* AMA4EA environment with an abstraction of the data to concepts for both the enterprise and site level. In addition, the “site” interface maps the concepts at the site level to the concepts at the enterprise level.
3. Create the desired EA model	The *instantiate and position algorithm* imports all the data, abstractions and mappings in the m̈ainänd šiteïnterfaces of the AMA4EA environment to the EA repository. The algorithm instantiates an EA model at the enterprise level using the data and abstractions from the m̈ainïnterface. The algorithm instantiates an EA model for each concept at the enterprise level with the concepts at a site level mapped in the šiteïnterface. For instance, the algorithm instantiates one EA model for the process at the enterprise level with the sub-processes, as well as EA models that specify the activities for each of the sub-processes at the site level. *Input:* The output of the previous activity. *Output:* An EA model with the concepts at the enterprise level, and EA models that map these concepts at the site level.

duction process measurements. To fulfil these requirements, we extended the activities of AMA4EA specified in (Nardello et al., 2019) as follows. The extensions of the activities in the preparation and execution phase are explained respectively in Tables 5 and 6.

5. Industrial case application

The extended AMA4EA was applied using data from an engineer to order company in discrete manufacturing with production sites located in more than seven countries. The company has the goal to share internally knowledge about their different production processes to improve them. Some of these sites produce the same product specification. The product is a large metal product with electrical engines, electronic and mechanical components. These components are installed on the product during the production process. Due to historical and environmental differences, the sites are managed differently, therefore, causing the process and data heterogeneity problem. Related to process heterogeneity, the production processes in different sites are specified at different levels of detail. In a production site, the production process of a component is structured in 26 sub-processes. While in another production site, the production process of the same component is divided into more than 200 sub-processes. Related to data heterogeneity, the production process data is collected and stored in different sites on different ESs and at different levels of detail. Production data—i.e. timestamps and error data—and assembly documentation—i.e. manuals for production site employees—are available for each activity in the sites at very different levels of detail (i.e. 20 activities vs. over 200 activities). The process and data heterogeneity hinder international manufacturing companies in directly comparing production processes across sites and improving the processes' efficiency. Consequently, production managers are missing a system that collects and relates production process data and external resources with the overview of production processes (i.e. at the enterprise level) and the detailed production processes (i.e. at the site level).

Process and data heterogeneity hinder companies from comparing and sharing data across different sites. This creates three main

Table 5
The extensions of the four activities in the preparation phase of AMA4EA for incorporating data heterogeneity.

Activity	Description of AMA4EA
1. Define the desired EA model	The stakeholder and the architect acknowledge the need for including external resources in the EA models at two levels of detail. This requires defining the external resources relevant for the purpose, scope and concepts at each level. For instance, KPIs or documentation. In addition to choosing the type of EA model, the stakeholder and the architect decide how the external will be visualized for each level. For instance, KPIs can be visualized with different colour coding and different documentation can have different icons on the EA models. These visualizations can be different for the two levels. *Input:* The stakeholder presents how the problem can be addressed with the EA models that include external resources. *Output:* Definition of the desired EA models including the external resources and their visualization.
2. Identify data sources	The DSM identifies the ESs used for managing the external resources to be included in the desired EA model and the location of data in the ESs. For instance, the assembly documentation can be accessed through URL and the data for the KPIs can be accessed through a database query. *Input:* Definition of the desired EA models including the external resources. *Output:* Name of the ESs with the relevant data and the URL or query for extracting the data.
3. Identify abstraction hierarchy	(No extension is necessary)
4. Set-up the AMA4EA environment	For both m̈ainänd s̈iteïnterfaces, the structural metadata of the AMA4EA environments' is extended with one column for each external resource. This column stores the URL or query for accessing the external resource. For instance, one column can store URLs to access assembly documentation and another column can store database queries to retrieve performance measurements. *Input:* AMA4EA environment with "main" and "site" interfaces *Output:* AMA4EA environment with "main" and "site" interfaces, with the columns for storing the URLs and queries to access external information.

Table 6
The extensions of the three activities in the execution phase of AMA4EA for incorporating data heterogeneity.

Activity	Description of AMA4EA
1. Extract data from ES to the AMA4EA environment	Following the extraction of data from ESs to the AMA4EA environment, the DSM inserts the queries and URLs necessary to access external resources in the dedicated columns created in the set-up the AMA4EA environment activity. *Input:* Name of the ESs with the relevant data and the URL or query for extracting the data. *Output:* AMA4EA environment with the URLs and queries in the "main" and "site" interfaces to access external resources.
2. Abstract data in the AMA4EA environment	(No extension is necessary)
3. Create the desired EA model	The *instantiate and position algorithm* stores queries and URLs to external resources in elements in the EA repository. During the instantiation of the elements in the EA models, URL visualized for each element with a predefined symbol. In addition, if the queries return numerical results they are visualized for each element. This visualization can be enhanced by predefined colour schemes. *Input:* AMA4EA environment with data from the ESs in the "main" and "site" interfaces including URLs and queries to access external resources. *Output:* EA models with elements that provide access to external resources and visualize performance measurements.

Table 7
Problems of the company in the industrial case application and solutions of the extended AMA4EA.

Problems of the international manufacturing company	The extended AMA4EA
Production processes of the same component are specified at different levels of detail based on the site: • 26 activities in one site • Over 200 activities in another site Therefore, it is problematic to identify which activities from one site correspond to those at another site.	Automated creation of EA models of production processes at two levels of detail: enterprise and site. From the production process at the enterprise level, it is possible to access the specification of the production processes at different sites, and vice-versa.
Performance improvement analysis is independent for each site. It is problematic to identify potential opportunities for improvement across sites.	The EA models at both levels aggregate performance measurements to identify potential opportunities for improvement across plans.
Assembly documentation is available on different platforms and at different levels of detail based on the site.	Link external resources to the elements in the EA models.

problems for companies. First, it is problematic to identify how the sub-process is executed at each site. Second, data analysis for performance improvement is independent for each site, even for sites that are manufacturing the same product specification. Therefore, it is not possible to identify which sub-process has the biggest potential for improvement among all sites. Third, the lack of relations for assembly documentation for similar processes hinders managers from different sites in learning about practices at other sites. The problems and the solutions provided by the extended AMA4EA are summarized in Table 7.

In this industrial case application of the extended AMA4EA, we abstracted data from the enterprise's ERP system. The extended AMA4EA automatically created the EA models in QualiWare's EA repository. These models included measurements and links to external resources and the process at the enterprise and site levels. The stakeholders from the enterprise were a production manager, a production engineer and the head of business intelligence. The DSM was a system administrator from the enterprise. The first author acted as architect and SME. The production engineer acted as additional SME. The ESs used were SAP ERP system, a manufacturing operations management (MOM) software, a data analytics platform, QualiWare's EA repository (QualiWare, 2018) (QLM version 6.6) and a Microsoft Excel file as the AMA4EA environment.

Op.	Description	Process category	Process family	Process class	Process subclass	Name in QualiWare	Next Op.	Performance Measurements	Assembly documentation
001	Initial Allocation of Component A	MaterialHandlin	Handling	ChangeQuantit	Allocate	Initial Allocation	201		
201	02 - Cleaning Component A	Manufacturing	SurfaceTreatment			02 - Cleaning Co	202		
202	10 - Preparing Component A	MaterialHandlin	Handling	Movement		10 - Preparing Cc	203		
203	20 - Mounting of Component B	Manufacturing	Joining	Assembly		20 - Mounting of	204		
204	30 - Mounting of additional equipment	Manufacturing	Joining	Assembly		30 - Mounting of	205		
205	40 - Mounting of Component C	Manufacturing	Joining	Assembly		40 - Mounting of	206		
206	50 - Last assembly	Manufacturing	Joining	Assembly		50 - Last assembl	207		
207	60 - Placing Component A	MaterialHandlin	Handling	Movement		60 - Placing Com	208		
208	70 - Placing Component C	MaterialHandlin	Handling	Movement		70 - Placing Com	310		
310	WC 1 - Component D Mounted on Compon	Manufacturing	Joining	Assembly		WC 1 - Compone	320		
320	WC 2 - Mounting of lights	Manufacturing	Joining	Assembly		WC 2 - Mounting	321		

Fig. 4. “Main” interface of AMA4EA with the production process at the enterprise level. The blue columns contain the data from the ERP system, the green columns are used for the abstractions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Op.	Description	Process category	Process family	Process class	Process subclass	Name in QualiWare	Next Op.	Op. in enterprise process	Description in enterprise process
0072	Prepare electrical equipmen	MaterialHandlin	Handling	Movement	Position	Prepare electrica	080	204	30 - Mounting of additional equipme
0080	Prepare cable guides and pip	MaterialHandlin	Handling	Movement	Position	Prepare cable gu	083	204	30 - Mounting of additional equipme
0083	Prepare cables	MaterialHandlin	Handling	Movement	Position	Prepare cables	090	204	30 - Mounting of additional equipme
0090	Prepare protection hose	MaterialHandlin	Handling	Movement	Position	Prepare protecti	093	204	30 - Mounting of additional equipme
0093	Sign off material used	MaterialHandlin	Handling			Sign off material	100	204	30 - Mounting of additional equipme
0100	Install electrical equipment	Manufacturing	Joining	Assembly	Insert&PutIn	Install electrical	103	204	30 - Mounting of additional equipme
0103	Install cable guides and pipe	Manufacturing	Joining	Assembly	Insert&PutIn	Install cable guic	110	204	30 - Mounting of additional equipme
0110	Install cables	Manufacturing	Joining	Assembly	Insert&PutIn	Install cables	111	204	30 - Mounting of additional equipme
0111	Install protection hose	Manufacturing	Joining	Assembly	Insert&PutIn	Install protectioı	112	204	30 - Mounting of additional equipme
0112	Prepare Component C	Manufacturing	Joining	Assembly		Prepare Compor	115	205	40 - Mounting of Component C
0115	Clean Component C	Manufacturing	Joining	Assembly		Clean Componeı	124	205	40 - Mounting of Component C

Fig. 5. “Site” interface of AMA4EA with the mapping of the production process at the site level to the production process at the enterprise level. The external resource columns have been omitted in the figure.

5.1. Preparation phase

Define the desired EA model is the first activity of the extended AMA4EA. The stakeholders agreed that the desired EA model should provide a unified visual representation of production processes using the modelling notation of the production process classification. Alternatively, BPMN extensions for the manufacturing domain (Zor et al., 2011) could have been used, but the stakeholders preferred not to use them. The scope was restricted to two production processes for a specific component at different sites. At the enterprise level, the selected production process was composed of 26 activities. In addition, the stakeholders decided to use the “number of errors reported in a week” as a performance measurement. Although better operations management performance measurements are available (ISO, 2014), the stakeholders defined themselves a performance measurement that could be easily implemented. Furthermore, the stakeholders requested to link the assembly documentation in the EA models at the site level.

The DSM and architect jointly performed the *identify data sources* activity. They selected SAP ERP for the production processes, the enterprise’s data analytics platform for the performance measurements, and their MOM software for assembly documentation.

In the *identify abstraction hierarchy* activity, the production process classification was chosen as the abstraction hierarchy. This hierarchy classifies production processes in discrete manufacturing at four levels (Sorensen et al., 2018): category, family, class and subclass. The abstraction hierarchy was already available in the AMA4EA environment and QualiWare’s EA repository.

In the *set-up AMA4EA environment* activity, the architect prepared the AMA4EA environment as follows. The structural metadata of the interface for the production process at the enterprise level was the following:

- Three columns for the production process from the ERP system: Operation ID, Work center ID, Description of the Operation;
- Four columns for the production process classification, one for each hierarchy level;
- A column to specify the name displayed in the EA model;
- The “Next Operation” column.

In addition to the structural metadata above, the structural metadata of the “site” interface for the production process at the site level included the following columns:

- Three columns for mapping each sub-process at a site level to the sub-process at the enterprise level: Operation ID of the enterprise process, Work center ID of the enterprise process, Description of the Operation in reference process;
- Two columns for including the query to the data analytics platform with the performance measurements and a URL to the production work instructions in the MOM software.

In this industrial case application, the mapping between the structural metadata from the ESs and the structural metadata of the elements in the EA repository was included in the *instantiate and position algorithm*.

5.2. Execution phase

Continuing with the extended AMA4EA method, the *extract data from ES to the AMA4EA environment* activity was executed. The production process data in SAP ERP, data analytics platform and MOM were imported into the AMA4EA environment. Fig. 4 presents the “main” interface of AMA4EA with the data from the ERP system about the process at the enterprise level (in blue and white) and its abstractions with the production process classification (in green). Fig. 5 shows the “site” interface of AMA4EA with the data from the ERP system about the process at the site “BBBB” (in blue and white), the abstractions with the production process classification (in green) and the mapping to the production process at the enterprise level (in light-blue). For the same process, Fig. 6 presents the “site” interface the data from the ERP system, the abstraction and the external resource columns, one for the SQL query for the

Op.	Description	Process category	Process family	Process class	Process subclass	Name in QualiWare	Next Op.		Performance Measurements	Assembly documentation
0072	Prepare electrical equipment	MaterialHandling	Handling	Movement	Position	Prepare electrical	080		select count(*) from tb	https://man-my.sharep
0080	Prepare cable guides and pipes	MaterialHandling	Handling	Movement	Position	Prepare cable guic	083		select count(*) from tb	https://man-my.sharep
0083	Prepare cables	MaterialHandling	Handling	Movement	Position	Prepare cables	090		select count(*) from tb	https://man-my.sharep
0090	Prepare protection hose	MaterialHandling	Handling	Movement	Position	Prepare protectio	093		select count(*) from tb	https://man-my.sharep
0093	Sign off material used	MaterialHandling	Handling			Sign off material u	100		select count(*) from tb	https://man-my.sharep
0100	Install electrical equipment	Manufacturing	Joining	Assembly	Insert&PutIn	Install electrical e	103		select count(*) from tb	https://man-my.sharep
0103	Install cable guides and pipes	Manufacturing	Joining	Assembly	Insert&PutIn	Install cable guide	110		select count(*) from tb	https://man-my.sharep
0110	Install cables	Manufacturing	Joining	Assembly	Insert&PutIn	Install cables	111		select count(*) from tb	https://man-my.sharep
0111	Install protection hose	Manufacturing	Joining	Assembly	Insert&PutIn	Install protection	112		select count(*) from tb	https://man-my.sharep
0112	Prepare Component C	Manufacturing	Joining	Assembly		Prepare Compone	115		select count(*) from tb	https://man-my.sharep
0115	Clean Component C	Manufacturing	Joining	Assembly		Clean Component	124		select count(*) from tb	https://man-my.sharep

Fig. 6. "Site" interface of AMA4EA with the external resource columns of the production process at the site level. The columns for the mapping of the production process to the enterprise level have been omitted in the figure.

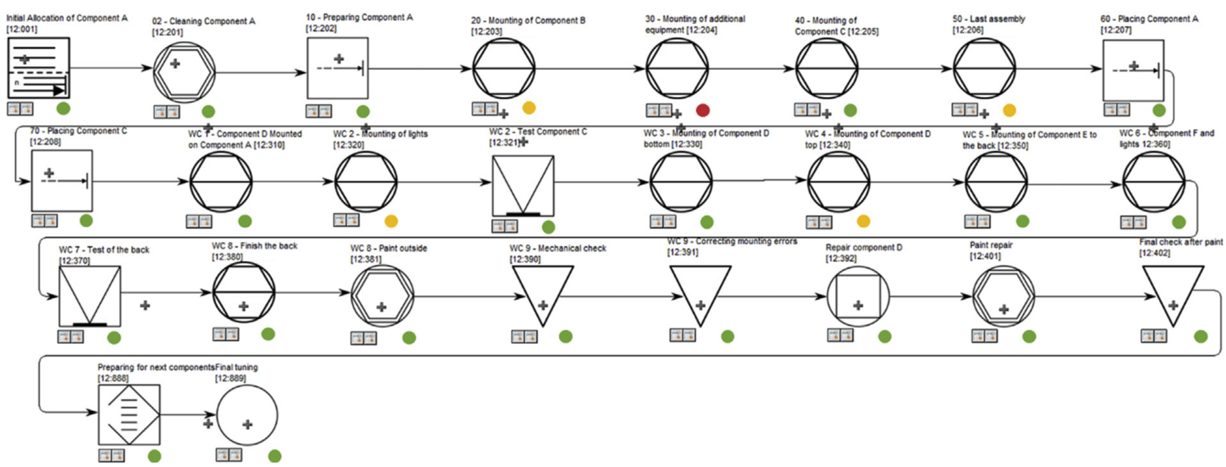


Fig. 7. The production process at the enterprise level automatically created in QualiWare's EA repository.[2]

performance measurements and one for the URL for the assembly documentation.

The extended AMA4EA was demonstrated for the first time in a real industrial context. Therefore, the AMA4EA environment did not store abstractions and the execution of the activity *abstract data in the AMA4EA environment* was performed manually. The architect abstracted the production process data at the enterprise and site levels using the production process classification. For example, Operation 100 "Install electrical equipment" was abstracted to the "Insert&PutIn" production concept, see the green columns in Fig. 5. In addition, the architect mapped the production process at the site level to the production process at the enterprise level using suggestions given by the production engineer. The last two columns in Fig. 5 include the mapping from site level production process to enterprise level. The last two columns in Fig. 6 include the query and URL to access external documentation. The queries and URLs to retrieve external resources and link them to the processes were also specified for each activity. The following is an example SQL query used to retrieve the data for measuring the number of errors reported by the operator during the execution of an activity at the site level.

```
select count(*) from BBBB.tblErrors where (Activity=0072) and (DateTimes <= Date()) and (DateTimes >= (Date() - 7));
```

The following is a simplified example of URL to retrieve the assembly documentation of an activity at the site level.

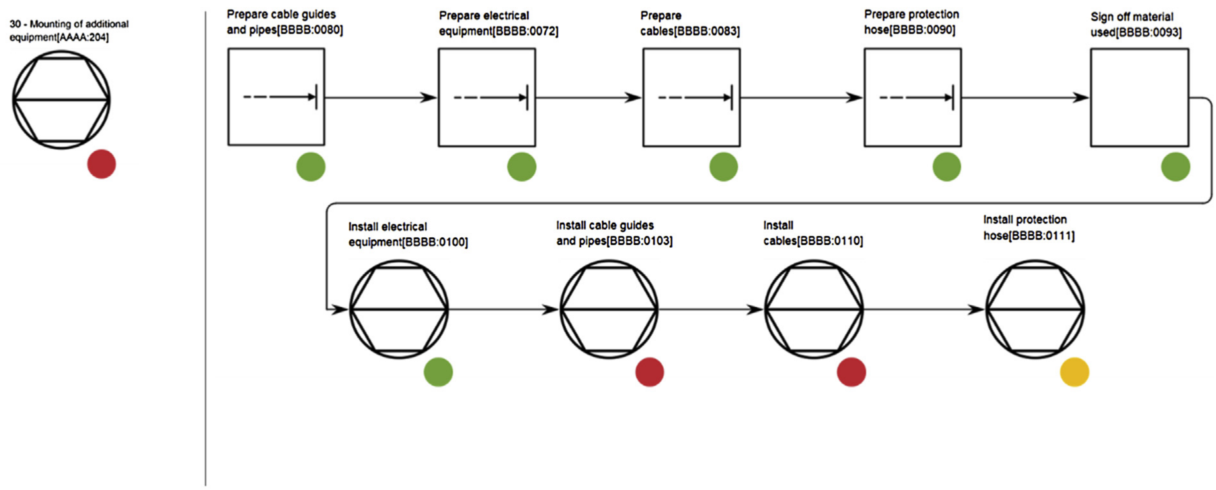
```
https://man-my.sharepoint.com/:f:/g/BBBB/0072
```

In the *create the desired EA models* activity, the *instantiate and position algorithm* imported data from the AMA4EA environment to QualiWare's EA repository. It created the EA model with the enterprise process, see Fig. 7, and then it created other EA models for specifying the site sub-processes of each enterprise sub-process, see the example in Fig. 8. The information related to the abstraction hierarchy and external resources were stored by the algorithm in the elements in the EA repository. The *instantiate and position algorithm* step also determined the position of the elements in the business process model, as shown in Fig. 7. The performance measurements were automatically aggregated from the activities at the site level to the sub-process at the enterprise level. In the example below, in both sites, the activities related to the sub-process of "Mounting of additional equipment" reported a high number of errors, see the activities with the red dot in Fig. 8. This measurement was aggregated and visualized in the production process at the enterprise level, see the sub-process with a red dot in Fig. 7.

5.3. Addressing process heterogeneity

The extended AMA4EA create an EA model at the enterprise level that provides an overview of a production process, as shown in Fig. 7. From this EA model, it is possible to access the EA models at the site level. The EA models at the site level document how a sub-process at the enterprise level is performed at different sites. As shown in Fig. 8, by opening the EA models referring to the same sub-process it is possible to compare the 1 activity at site AAAA with the 9 activities at site BBBB. In this way, the production manager of site AAAA is able to understand how the same sub-process is

[2] The aggregation of the performance measures at the enterprise level is the addition of the performance measures of the activities at the site level. The three levels of the performance measure are predefined in QualiWare's EA repository as follows: value 0 "green", values 1-3 "yellow" or values higher than 3 "red"



a. Site AAAA

b. Site BBBB

Fig. 8. The production process at the site level automatically created in QualiWare's EA repository.[2] This example visualizes the activities of sub-process 30 – Mounting of additional equipment.

executed at site BBBB. With the extended AMA4EA, we were able to compare two production processes of the same component that were specified at two different levels of detail: one 26 activities, the other over 200 activities.

5.4. Addressing data heterogeneity

The extended AMA4EA included in the EA models at the site level the assembly documentation for each activity. Documentation production processes at different can be accessed by production managers through the MOM. Sharing data and documentation across production sites is important to continuously improve production processes. But if the manager of site AAAA does not know how his production process is related to the one of site BBBB, he cannot access the assembly documentation for the production process at the other site. The fact that production processes can be compared with EA models and that documentation is included in these EA models enables production managers to share documentation from different sites that is structured at different levels of detail.

The extended AMA4EA included in the EA models also performance measurements. EA models at the site level include the performance measurements for each activity, as shown in Fig. 8. But since even the same production process is specified with a different number of activities, it is very difficult for production managers to compare the performance of their production lines using the performance measurements at the activity level. The EA model at the enterprise level addresses this problem and aggregates performance measurements from different sites. The performance measurements at the activity level from different sites are aggregated to a performance measurement at the sub-process level. As depicted in Fig. 7, aggregating the performance measurements enables to identify potential for improvement across sites. Fig. 7 shows that the sub-process of "Mounting of additional equipment" is the one registering most errors per week. Fig. 8 shows the specific activities at each site that are registering many errors per week. The comparison of performance measurement across sites and the identification of the cause of the error at the activity level enables the production manager to effectively and efficiently improve production processes.

6. Discussion

In this paper, we extended AMA4EA to address the process and data heterogeneity problem. The extended AMA4EA creates EA models at the site and enterprise levels and included external resources from different ESs in the EA models. We applied the extended AMA4EA to an international manufacturing company. We used data from two industrial production processes and demonstrated that the extended AMA4EA can solve the process and data heterogeneity problem of an international manufacturing company.

6.1. Contributions of the extended AMA4EA to EA research

The extended AMA4EA contributes to EA research in three main ways: (1) supports holistic EA approaches, (2) includes external heterogeneous data in EA models at both enterprise and site levels, and (3) extends the applicability of automated EA modelling approaches to heterogeneous processes and data.

The extended AMA4EA supports holistic EA approaches by automatically creating EA models that address the process heterogeneity problem of international manufacturing companies by modelling the different realities of companies. EA approaches with a reductionist stance do not model the different realities of companies and, as a result, they are often inadequate (Lapalme, 2012). Holistic EA approaches are required to model the different realities of an enterprise (Lapalme, 2012). The extended AMA4EA automatically creates an overview of the production processes (i.e. at an enterprise level), models the different implementations of the production processes at different sites, and relates production processes at the site level to the overview of the production processes (i.e. at an enterprise level). In the industrial case application, the extended AMA4EA creates an overview EA model with 26 activities and detailed EA models of two production processes with 26 and 200 activities.

The extended AMA4EA addresses the data heterogeneity problem of international manufacturing companies. Currently, data is stored on different systems and production managers access it separately. Fragmented data hinders international manufacturing companies from using this data effectively and efficiently to improve production processes. Enterprise-wide technological solutions (i.e. ERP system) are used inconsistently across the subsidiaries of International manufacturing companies. EA has traditionally not emphasized modelling different uses of enterprise-wide technological solutions. New EA approaches are required to include these different uses [Tambo and Bækgaard, 2013, p. 293]. The extended AMA4EA includes heterogeneous data and external documents from different subsidiaries in EA models, aggregates the data and allows the data to be shared and compared. In the industrial case application, the extended AMA4EA created EA models with external data and links to the documentation at the enterprise and site levels. The EA model at the enterprise level provided an overview of the production process, including aggregated production process data from the different sites, see Fig. 7. The extended AMA4EA enables EA to address the data heterogeneity problem by including production processes data and external resources in EA models, therefore, allowing the comparison of these data from different data sources.

The extended AMA4EA addresses the problem of automated EA modelling methods when using heterogeneous data to create EA models [Farwick et al., 2016, p. 421]. The extended AMA4EA demonstrates how automated EA modelling approaches can be adapted to address the heterogeneity problem. Automated EA modelling methods (Holm et al., 2014; Nardello et al., 2019; Farwick et al., 2016) did not fully address the data heterogeneity problem. In fact, existing methods maintain the same level of detail (i.e. granularity) of the data in ESs in the EA models. The extended AMA4EA addresses this shortcoming, creating EA models at the enterprise and site levels that are at two different levels of detail.

6.2. Implications of the extended AMA4EA for international manufacturing companies

The extended AMA4EA contributes to practice, especially to support the whole practice of production managers at international manufacturing companies. The three main contributions are: (1) directly identifying activities that production sites execute in the same sub-process, (2) identifying potential opportunities for improvement by cross-site analysis, and (3) accessing data and documentation stored on different ES using EA models.

The extended AMA4EA allows production managers to directly identify the activities within a sub-process that different sites execute and compare these activities—i.e. using the EA models at the site level. As reported in [Netland and Aspelund, 2014, p. 393] and confirmed by several Danish international manufacturing companies, comparing production processes for the same or similar components across subsidiaries was done manually and was problematic. Production managers were missing a solution to meet the following three requirements: (1) an overview of production processes (i.e. enterprise level), (2) the detailed representation of these production processes at the site level, and (3) the connection between processes at the enterprise and site levels. The extended AMA4EA fulfils these requirements as follows. First, it automatically creates EA models for production managers, representing the production process at the enterprise level with an overview of the production process. Second, it creates EA models representing production processes at the site level. Third, it relates the EA models at the two levels and allows production managers to easily access the production processes at both levels.

The extended AMA4EA supports production managers in identifying the sub-processes and activities that have the most potential for improvement across different production sites. This is expected to lead to an improvement in production processes and their performance that could not be obtained through independent site analysis. Comparing production processes across subsidiaries was performed manually and was problematic for production managers. The extended AMA4EA addresses data heterogeneity by including production process data (i.e. performance measurements) and access to external resources (i.e. assembly documentation) at a site level in the EA models. The extended AMA4EA allowed sharing performance measurements and documentation between different sites and aggregated data to compare them at the enterprise level. In the industrial case application, the EA model of the process at the enterprise level aggregates two "medium" problems present in both sites, enabling the managers to discover common problems across sites. A core improvement of the Industry 4.0 trend is to make this type of analysis more accurate.

The extended AMA4EA supports production managers by providing direct access to fragmented data and documentation stored on different ESs through EA models. The production process data and external resources at the site level are heterogeneous across sites and were accessible separately on different ESs. The extended AMA4EA visualizes data and documentation from different ESs in EA models. In the industrial case application, the method visualized data and provided access to documentation stored on different systems. The increased data availability brought by Industry 4.0 is mostly at a machine or activity abstraction level. Extended AMA4EA method is important in this context because it enables to relate activities at a site level to sub-processes at an enterprise level. Therefore, providing a way to aggregate and analyse the data from the machine at an enterprise level. This significantly contributes to extracting value from the data availability related to Industry 4.0.

7. Conclusions

In this article, we extended the AMA4EA method to abstract data to create EA models in two ways: (1) to create EA models at two levels, enterprise and site; and (2) to include production process data and documentation, e.g. performance measurements, in the EA models. The extended AMA4EA supports EA approaches to address the heterogeneity problem by creating EA models with both the overview and the details of production processes. These EA models represent the production process data and external resources from different subsidiaries at different levels of detail. The industrial case application using data from a Danish international manufacturing company provides sufficient evidence that the extended AMA4EA addressed the process and data heterogeneity problem. In detail, the extended AMA4EA enables production managers to access the production processes at different sites from an automatically created overview model. Furthermore, it allows sharing and comparing performance measurements and documentation from different sites and aggregates the data in an overview EA model.

The extended AMA4EA can be applied for different types of EA models. The industrial application used ERP production process data to create a business process model. Other EA models can be created if the data to create these models can be extracted from the ES and a relevant abstraction hierarchy is either identified or created. The main limitations of our research are that the extended AMA4EA was tested with only one international manufacturing company. However, the problem addressed is common for international manufacturing companies. The application was focused on one domain, production processes. The method could be applied in other domains and industries. In addition, the production process from different production sites were sequential activities in the same order. Solutions to manage branching and decisions as well as different execution order of the activities need to be developed. Finally, the method does not automatically update the EA model it creates.

Future research could focus on applying the method in other companies and domains. Another research direction could be to develop a solution to manage branching and decisions, for example improving the *instantiate and position algorithm*. Based on this solution, another solution could be developed to address the problem of different order of execution of the activities. When the order of the sub-processes at the enterprise level is not constrained and the sub-processes can be executed in a different order, the EA model at the enterprise level could represent sub-processes at an enterprise level as parallel to each other and not sequential. Moreover, AMA4EA could be further extended to be able to automatically update the EA models it creates following the method presented by (Roth et al., 2013). This extension would provide constantly up-to-date EA models that are aligned with reality.

Coauthor statement

List of authors:
Marco Nardello: PhD candidate Aalborg University
Shengnan Han: Associate Professor Stockholm University
Charles Møller: Professor Aalborg University
John Gøtze: Professor IT University of Copenhagen

PhD candidate (Marco Nardello): The PhD candidate contributed to defining the overall problem and proposed the core scientific idea to solve it. The PhD candidate wrote the entire draft version of the paper and revised it according to co-authors comments. The PhD candidate identified relevant findings, which were eventually interpreted.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Buschle, M., Grunow, S., Matthes, F., Ekstedt, M., Hauder, M., Roth, S., 2012. Automating Enterprise architecture documentation using an Enterprise service bus. Americas Conference on Information Systems (AMCIS 2012), 1–14.

Buschle, M., Holm, H., Sommestad, T., Ekstedt, M., Shahzad, K., 2011. A tool for automatic enterprise architecture modeling. In: CAiSE Forum (Selected Papers)., pp. 1–15.

Cardoso, E.C.S., 2013. Challenges in performance analysis in enterprise architectures. In: Proceedings - IEEE International Enterprise Distributed Object Computing Workshop, EDOC, pp. 327–336.

Corne, D., Smithers, T., Ross, P., 1994. Solving Design Problems by Computational Exploration. IFIP WG5.2 Workshop on Formal Design Methods for CAD.

Desbiens, E., Chaabane, A., 2014. Visual notation approach for MES integration. IIE Annual Conference and Expo 2014, 321–331.

Erasmus, J., Vanderfeesten, I., Traganos, K., Grefen, P., 2018. The case for unified process management in smart manufacturing. Proceedings - 2018 IEEE 22nd International Enterprise Distributed Object Computing Conference, EDOC 2018 256, 218–227.

Farwick, M., Schweda, C.M., Breu, R., Hanschke, I., 2016. A situational method for semi-automated enterprise architecture documentation. Softw. Syst. Model. 15 (2), 397–426.

Gampfer, F., Jürgens, A., Müller, M., Buchkremer, R., 2018. Past, current and future trends in enterprise architecture—a view beyond the horizon. Comput. Ind. 100, 70–84.

Garcia, C.D.S., et al., 2019. Process mining techniques and applications – a systematic mapping study. Expert Syst. Appl. 133, 260–295.

Ghoshal, S., Nahria, N., 1989. Internal differentiation within multinational corporations. Strateg. Manage. J. 10, 323–337.

Hauder, M., Matthes, F., Roth, S., 2012. Challenges for automated enterprise architecture documentation. In: Trends in Enterprise Architecture Research and Practice-Driven Research on Enterprise Transformation. Springer, pp. 21–39.

Hauder, M., Roth, S., Pigat, S., Matthes, F., 2013. Tool support for conflict Resolution of models for automated Enterprise architecture documentation. 19th Americas Conference on Information Systems, AMCIS 2013 - Hyperconnected World: Anything, Anywhere, Anytime 3, 11–15.

Holm, H., Buschle, M., Lagerström, R., Ekstedt, M., 2014. Automatic data collection for enterprise architecture models. Softw. Syst. Model. 13 (2), 825–841.

International Electrotechnical Commission, 2019. IEC 81346 Industrial Systems, Installations and Equipment and Industrial Products – Structuring Principles and Reference Designations – Part 2: Classification of Objects and Codes for Classes. IEC.

International Electrotechnical Commission, 2013. IEC 62264-1 Enterprise-control system integration–part 1: models and terminology. Enterprise-Control System Integration, 1.

International Electrotechnical Commission, 2017. IEC PAS 63088:2017. Smart manufacturing - reference architecture model industry 4.0 (RAMI4.0). IEC, Genf, 1–35.

ISO, 2014. Automation Systems and Integration—Key Performance Indicators (KPIs) for Manufacturing Operations Management—Part 2: Definitions and Descriptions of KPIs. ISO, pp. 2011, 22400-2.

Karray, M.-H., Chebel-Morello, B., Zerhouni, N., 2014. PETRA: process evolution using a TRAce-based system on a maintenance platform. Knowl. Based Syst. 68, 21–39.

Kingsley, O., Tawil, A.-R.H., Naeem, U., Islam, S., Lamine, E., 2016. Using semantic-based approach to manage perspectives of process mining: application on improving learning process domain data. 2016 IEEE International Conference on Big Data (Big Data), 3529–3538.

Lankhorst, M., et al., 2017. Enterprise Architecture at Work: Modelling, Communication and Analysis. Springer.

Lapalme, J., 2012. Three schools of thought on enterprise architecture. IT Prof. 14 (6), 37–43.

Lapalme, J., Gerber, A., Van der Merwe, A., Zachman, J., Hinkelmann, K., De Vries, M., 2016. Exploring the future of enterprise architecture: a Zachman perspective. Comput. Ind. 79, 103–113.

Lou Maher, M., Poon, J., Boulanger, S., 1996. Formalising design exploration as co-evolution. In: Advances in Formal Design Methods for CAD. Springer, pp. 3–30.

Nardello, M., Han, S., Møller, C., Gøtze, J., 2019. Automated modeling with abstraction for enterprise architecture (AMA4EA): business process model automation in an industry 4.0 laboratory. Complex Syst. Inform. Model. Q. 19.

Nardello, M., Møller, C., Gøtze, J., 2017. Organizational learning supported by reference architecture models: industry 4.0 laboratory study. Complex Syst. Inform. Model. Q. 12, 22–38.

Netland, T.H., 2013. Exploring the phenomenon of company-specific production systems: one-best-way or own-best-way? Int. J. Prod. Res. 51 (4), 1084–1097.

Netland, T.H., Aspelund, A., 2014. Multi-plant improvement programmes: a literature review and research agenda. Int. J. Oper. Prod. Manage. 34 (3), 390–418.

QualiWare, [Online]. Available: 2018. QualiWare Enterprise Architecture. Center of Excellence. https://coe.qualiware.com/.

Rondini, A., Pezzotta, G., Cavalieri, S., Ouertani, M.-Z., Pirola, F., 2018. Standardizing delivery processes to support service transformation: a case of a multinational manufacturing firm. Comput. Ind. 100, 115–128.

Roth, S., Hauder, M., Michel, F., Münch, D., Matthes, F., 2013. Facilitating conflict resolution of models for automated enterprise architecture documentation. Proceedings of the Nineteenth Americas Conference on Information Systems.

Sorensen, D.G.H., Brunoe, T.D., Nielsen, K., 2018. A classification scheme for production system processes. 51st CIRP Conference on Manufacturing Systems.

Tambo, T., Bækgaard, L., 2013. Dilemmas in enterprise architecture research and practice from a perspective of feral information systems. 2013 17th IEEE International Enterprise Distributed Object Computing Conference Workshops, 289–295.

Välja, M., Lagerström, R., Ekstedt, M., Korman, M., 2015. A requirements based approach for automating Enterprise IT architecture modeling using multiple data sources. 2015 IEEE 19th International Enterprise Distributed Object Computing Workshop, 79–87.

Välja, M., Korman, M., Lagerström, R., Franke, U., Ekstedt, M., 2016. Automated architecture modeling for enterprise technology management using principles from data fusion: a security analysis case. Proceedings of PICMET' 16: Technology Management for Social Innovation Automated, 14–22.

Van Der Aalst, W., 2016. Process Mining: Data Science in Action.

Winter, R., Fischer, R., 2007. Essential layers, artifacts, and dependencies of enterprise architecture. J. Enterprise Archit. (May), 12.

Zachman, J.A., 1987. A framework for information systems architecture. Ibm Syst. J. 26 (3), 276–292.

Zor, S., Leymann, F., Schumm, D., 2011. A proposal of BPMN extensions for the manufacturing domain. Proceedings of 44th CIRP International Conference on Manufacturing Systems.