RAMOM: A Reference Architecture for Manufacturing Operations Management Activities in Industry 4.0

Gonçalo Freire
INESC-ID Instituto Superior Técnico Universidade de Lisboa
Lisbon, Portugal *goncalo.b.freire@tecnico.ulisboa.pt*

André Vasconcelos
INESC-ID Instituto Superior Técnico Universidade de Lisboa
Lisbon, Portugal *andre.vasconcelos@tecnico.ulisboa.pt*

Abstract

Industry 4.0 has revolutionized manufacturing by introducing technologies such as Cyber-Physical Systems, **Internet of Things** and others that make manufacturing more efficient and dynamic. Despite these benefits, **Industry 4.0** has a high barrier to entry. The complexity of manufacturing systems will inevitably increase, and it is also necessary to redesign existing manufacturing processes to take advantage of **Industry 4.0**. For these reasons, we looked at **Enterprise Architecture**, as this discipline can help companies to deal with the increasing complexity as they adopt **Industry 4.0**. In our research, we found that many solutions have been developed to help companies make the technological transition to **Industry 4.0**, but none helps companies align their newly acquired technological capabilities with their production processes. To address this knowledge gap, we developed **RAMOM**, a reference architecture for manufacturing operation management activities in **Industry 4.0**. **RAMOM** is composed of several views, developed in the Archimate language, that provide information on the actors, functions, data types and how these relate to manufacturing operation management activities, thus guiding organizations in their implementation. To confirm its validity, we conducted an evaluation of **RAMOM** based on expert knowledge and an application of **RAMOM** in a Portuguese industry case study. We concluded is useful to use **RAMOM** to help organizations adapt their processes to **Industry 4.0**.

Keywords: Industry 4.0, Enterprise Architecture, Job profiles, Reference Architecture and Manufacturing operation management activities

1. Introduction

The introduction of the **Industry 4.0** concept in the manufacturing industry has created new challenges for companies. Industry 4.0 introduces new key technologies that enable more efficient, personalized and dynamic production [11, 18]. The introduction of **Industry 4.0** in a company entails updating technology, production and support systems, which leads to an increase in complexity and is one of the main obstacles in the transition to **Industry 4.0** [12]. We have found that one possible way to overcome this obstacle is to study **Enterprise Architecture (EA)** in the context of **Industry 4.0**, as this discipline can help organizations align people, processes, and technology with their business goals and provide methods for dealing with increasing complexity. **EA** can provide the aforementioned values by presenting already proven models that provide organizations with recommendations on how to structure themselves [5]. During the development of this work, we were part of an **Industry 4.0** transition project in a company. In this project, we found that many problems resulted from a lack of adaptation of production and support processes to the introduced **Industry 4.0** technologies. Although we noted this difficulty in our research on **EA** in **Industry 4.0** as part of the project, little information was found on this topic. For this reason, we decided to develop a **Reference Architecture (RA)** that can help companies adapt their processes in the transition to **Industry 4.0**. After researching the topic of **Industry 4.0** production processes, the only source of information we found was a comprehensive list of production processes in the **IEC 62264-3** standard, which only covers management processes. The decision was made to cover only these types of operations, as these are the majority of production processes in **Industry 4.0**. This paper is organized in six sections. First we present the theoretical basis of our proposal; next we described how we realized a Systematic literature review on the topic of **Industry 4.0 job profiles**; then we present our proposal addressing the problems that we identified **RAMOM**; after we apply **RAMOM** in Portuguese industry case study; after we provide a theoretical evaluation of **RAMOM**; finally we conclude our work and provide a glimpse of future work that remains to be done.

2. Background

This section presents all the research and analysis performed that corresponds to all the knowledge obtained to reach the solution definition. We start by introducing the topics of **Industry 4.0** and **Enterprise Architecture**. Then we discuss the topic of **Reference Architectures** and how these have been used in **Industry 4.0**. Finally we introduce the standard **IEC 62264** which will be used in our proposal.

2.1. Industry 4.0

Industry 4.0 is a term used to describe the 4th industrial revolution that brings digitization forwards within factories by integrating information and communication technologies with industrial technology [11, 18]. This is accomplished by creating a network among people, products, and devices, making it possible to constantly capture relevant information during the production and use of the product. The new information captured allows a highly flexible, personalized production model to compute changes to the product and the production process on the fly [11, 18]. This is allowed through the use of new emerging technologies.

2.2. Enterprise Architecture

ISO 42010:2011 describes architecture as the "process of conceiving, defining, expressing, documenting, communicating, certifying proper implementation of, maintaining and improving an architecture throughout a system's life cycle" [1]. Architecture applied at the level of an entire organization is referred to as **EA**.

Architectural description

ISO 42010:2011 [1] describes an architectural description as the "work product expressing the architecture of a system from the perspective of specific system concerns". "An architecture description shall identify the system of interest and include supplementary information as determined by the project and/or organisation" [1] and can consist of at least one architectural view or (view).

Architectural Views and Viewpoints

An architectural view frames one or more concerns from one of the system's stakeholders, and the view can frame one or more architectural viewpoints (or viewpoints). A viewpoint is described as a "work product establishing the conventions for the construction, interpretation and use of architecture views to frame specific system concerns" [1]. The use of views and viewpoints provides many advantages to the architecture definition process, including the proposed solution. Separating the solution into distinct descriptions will aid its design, analysis, and communication process by making it possible to approach different parts of the system individually, reducing the complexity of the architecture definition process

2.3. Reference Architectures

”A Reference Architecture is, in essence, a predefined architectural pattern, or set of patterns, possibly partially or completely instantiated, designed and proven for use, in particular, business and technical contexts, together with supporting artifacts to enable their use. Often, these artifacts are harvested from previous projects” [10]. Due to their usefulness and high coverage of **RAs**, this tool has been studied and applied in a variety of fields resulting in several different definitions and an increased number of **RAs** for other domains [14]. **RAs** can be classified as research-driven or practical-driven.“Practice-driven reference architectures are defined when sufficient knowledge has been accumulated in a domain to propose the “best of best-practices” architecture. Research-driven reference architectures provide a “futuristic” view on a class of systems that are expected to become important in the future, but by the time of the architecture definition are seen as hard to build. These architectures aim at facilitating the design of the first systems from a class of systems” [4].

2.4. Reference Architectures in Industry 4.0

Since **Industry 4.0** is a new phenomenon, **RAs** has an increased value in this area, since it hasn’t reached a maturity level where widely practiced standards exist, for the same reason not many **RA** have been developed in this area. In this section, we will go through the most popular **Industry 4.0** to see how these are built and what topics they cover.

Reference Architecture Industry 4.0 (RAMI 4.0)

Reference Architecture Industry 4.0 (RAMI 4.0) is a reference architecture model developed by the German Electrical and Electronic Manufacturers’ Association (ZVEI) to support **Industry 4.0** initiatives [23]. The RAMI 4.0 Reference Architectural Model gives companies a framework for developing future products and business models. The model “consists of a three-dimensional coordinate system that describes all crucial aspects of **Industry 4.0**" [9].

Industrial Internet Reference Architecture (IIRA)

The Industrial Internet Reference Architecture (IIRA) is a reference architecture to enable the implementation of IIoT (Industrial Internet of things) architectures in a wide variety of industries [13]. For this purpose, the “architecture description and representation are generic and at a high level of abstraction to support the requisite broad industry applicability” [2]. The IIRA model consists of four viewpoints, business, usage, functional and implementation viewpoints, that frame different concerns of **Industry 4.0**.

2.5. The "human element" in Reference Architectures for Industry 4.0

From our research into reference architectures in **Industry 4.0**, we could observe there isn’t enough detail regarding the human component of **Industry 4.0** [17]. In the current literature relating to **Industry 4.0** and automation, there is a consensus that despite the technological advances in the manufacturing industry, humans will still maintain a relevant role in this industry [17]. So these should also be considered in system modeling regarding **Industry 4.0** since the human element is a factor that can also benefit from the advantages brought by **RAs**. In RAMI 4.0, personnel is part of the Asset layer, which is then seen as physical components by

RAMI 4.0, such as linear axes, metal parts, documents, circuit diagrams, ideas, and archives [3]. While this might be sufficient for some scenarios, this isn't enough, as proven by the article An industrial evaluation of an **Industry 4.0 RA** demonstrating the need for the inclusion of security and human components. In this article, the authors try to model three scenarios from the manufacturing industry that include the human element using RAMI 4.0 [17]. The authors found that all scenarios showed uncertainties when modeling the human part. The authors then conclude that a more significant focus is on the human element in the future of RAMI 4.0 [17]. IIRA acknowledges that humans can play a role in the several domains of IIoT systems, briefly describing what role these can have in the operations, information, application, and business domains. Despite knowing that it is crucial and challenging to understand "what capabilities a given person will provide, how those capabilities fit into the system design as a whole and assuring that person is actually providing those capabilities when needed" [2] IIRA, other than what was already mentioned, doesn't provide much more details regarding the human element in IIoT.

2.6. IEC 62264

IEC 62264, is the international standard for integrating enterprise and control systems. This standard was developed to provide a model that end-users, integrators, and vendors can use when integrating new applications in the enterprise. **IEC 62264** defines five different levels with their respective problems and challenges when implementing applications using an SOA-based approach [8]. This work will mainly focus on **IEC 62264-3**, which corresponds to the third part of this standard. This part defines activity models of manufacturing operations management that enable enterprise systems to control system integration and includes a model of the activities associated with manufacturing operations management, Level 3 functions, and an identification of some of the data exchanged between Level 3 activities [6].

3. Systematic literature review

The introduction of **Industry 4.0** technologies means that the complexity of the shop floor will increase, and the organization's manufacturing operations will change. This, coupled with the organizational changes, means there is a need for new actors with new roles and the revamp of old ones in **Industry 4.0** able organizations. Throughout the research realized in Enterprise architecture in **Industry 4.0**, it is possible to observe that this was a subject not covered by the current literature. In order to fully explore these topics an Systematic Literature Review (SLR) was conducted. For this purpose, the following Research questions were developed.

- **Research Question 1:** What are the main traits of **Industry 4.0 job profiles** ?
- **Research Question 2:** What new or updated job profiles were developed for **Industry 4.0**?
- **Research Question 3:** What standards or proposals exist connecting organizational structure, **job profiles**, and the activities they perform in the context of **Industry 4.0**?

To ensure that our research is conducted properly we defined a review protocol with the research strings, the databases used for the research and inclusion criteria such as papers with titles related to our research strings, with a publishing date after 2011, written in English and free to access. From our research we recovered 774 papers that fit the proposed criteria. Then we further reviewed these papers and selected 24 to utilize in the SLR.

From our research, we were able to take the following conclusions.

- The key traits that **Industry 4.0 job profiles** have are High IT skills, Improved soft skills, More focus on cognitive skills, and a High focus on multidisciplinary skills.
- There has already been some research done in creating and updating **job profiles** in **Industry 4.0**. Although research on **job profiles** in **Industry 4.0** hasn't reached maturity, this should be comprehensive enough to start architecture, how these should be organized, and the task these should carry out.
- We found only two proposals regarding **job profiles** and their roles and activities, and these don't show much potential of being useful for our thesis.

4. Towards a Reference Architecture for Manufacturing Operations Management Activities in Industry 4.0

Considenting the open issues identified in the SLR we propose a research-driven RA, focused on manufacturing operation management activities and its actors: **RAMOM**. In this work, the choice was made to only focus on level 3 activities, since this was the only level where we explicitly found a set of activities (**IEC 62264-3**). The focus of this **RA** is to provide organizations a tool to adapt their business side, to be more in line with Industry 4.0 ways of operating. To guide the development of **RAMOM** we followed a methodology for the development of **RAs** named ProSA-RA [14]. This is divided into four stages, Information Source Investigation, Architectural Analysis, Architectural Synthesis, and Architectural Evaluation, which we will follow.

4.1. Information source investigation

In this phase, the primary sources for constructing the RA are selected. These sources can come from people, publications, reference models, RA, and domain ontologies. The chosen sources must provide information about processes and activities supporting a system of the target domain [16]. This was already done in the **Background and Related Work** chapter, so instead in this section, we will organize the recovered information in a more digestible way.

Industry 4.0 job profiles

During the SLR, we discovered several works that identified or adapted existing **job profiles** for **Industry 4.0**. In this section, we look at the **job profiles** that we discovered in our research and organize them into our own **job profiles** so we are able to more easily use them in **RAMOM**. From the **job profiles** recovered in the SLR, we derived and introduced in **RAMOM** the following **job profiles**: Data Scientist, Maintenance Operator, Production Operator, Production Manager, Logistics Operator, Supply Chain manager, Production manager, Environmental technician, Quality manager, and Quality operator.

4.2. Architectural Analysis

Following the ProSA-RA methodology, after realizing an Information Source Investigation an architectural analysis is made. In this the system requirements are identified, then based on these the architectural requirements of the **RA** are identified and finally we established the set of concepts that must be considered in this reference architecture.

Table 1. Architectural Analysis

System Requirements	Architectural Requirements	Domain concept
Be able to identify the manufacturing operation management activities realized in a smart factory	Capture and display relevant information pertaining to the tasks/activities	Architectural requirements related to activities/tasks
Show what tasks composed the operation management activities	Capture and display relevant information pertaining to the tasks/activities	Architectural requirements related to activities/tasks
Be able to identify what data/artifacts are necessary to execute these activities	Capture and display relevant information pertaining to the data/artifacts related with the tasks/activities	Architectural requirements related to data/artifacts
Be able to identify data/artifacts that result from these activities	Capture and display relevant information pertaining to the data/artifacts related to the tasks/activities	Architectural requirements related to data/artifacts
Be able to identify what actors are required to execute the manufacturing operation management activities in a smart factory	Capture and display relevant information related to the actors and tasks/activities	Architectural requirements related to actors
Be able to identify what actors are responsible for each task/activity	Capture and display the relationship between the actors and the tasks/activities	Architectural requirements related to actors
Be able to identify what is the minimum amount of data/artifacts that the actors should have access to be able to fulfill the tasks/activities they are responsible	Capture and display relevant information pertaining to the data/artifacts related to the actors	Architectural requirements related to data/artifacts

4.3. Architectural Synthesis

In this step, following the ProSA-RA methodology, the architectural description of the reference architecture is built by describing the goals of **RAMOM**, its stakeholders, its concerns and the viewpoints and view that are present in **RAMOM**.

Goals of the **RAMOM**: 1. Support the implementation of Industry 4.0 systems in organizations; 2. Reduce the entry barrier for the implementation of Industry 4.0 systems by providing a baseline model of activities and resources; 3. Allow to detect points of failure in Industry 4.0 systems; 4. Increase the success and effectiveness of the implementation of Industry 4.0 components in organizations;

Stakeholders: Operation managers, Process architects, Data architects, Domain architects and Recruiters.

Concerns from the stakeholders: 1.What are the main manufacturing operation management activities to support smart factories; 2.What tasks composed the manufacturing operation management activities; 3.What actors should be responsible for the manufacturing operation management activities; 4.What characteristics should the actors possess to effectively realize the activities they are responsible for; 5.What data/artifacts are required for the realization of the manufacturing operation management activities; 6.What data/artifacts result from the realization of the activities; 7.What are the required artifacts/data that the different actors must have access to effectively realize their responsibilities;

Architectural viewpoints and views

In this section, we present the viewpoints and views that will compose **RAMOM**.

Capability Map Viewpoint: The capability map viewpoint allows the Business Architect to create a structured overview of the capabilities of the enterprise. A capability map typically shows two or three levels of capabilities across the entire enterprise. It can, for example, be used as a heat map to identify investment areas. In some cases, a capability map may also show specific outcomes delivered by these capabilities.

- **Stakeholders:** Business managers, enterprise, business architects, recruiters
- **Concerns:** Architecture strategy and tactics, motivation
- **Purpose:** Designing, deciding
- **Scope:** Strategy
- **Archimate elements:** Resources, Capabilities and Outcome

Business function, objects, and actors/roles viewpoint: The Business function, objects, and actors/roles viewpoint focus on identifying the actors/roles that are responsible for executing the business functions of the organization as well as the business objects that are inputted into the function and that result from it.

- **Stakeholders:** Operation managers, Process architects, Data architects, and Domain architects
- **Concerns:** Identification of execution responsibility and artifacts input and output
- **Purpose:** Designing, deciding, informing
- **Scope:** Single layer/Single aspect
- **Archimate elements:** Actor, Function and Business object

Actor's business objects viewpoint: The actor data and artifacts viewpoint focuses on what data/artifacts inside an organization should be available to the actors for them to be able to effectively exercise their tasks.

- **Stakeholders:** Data architects, Domain architects, and Operation managers
- **Concerns:** Data architecture, security and management
- **Purpose:** Designing, deciding, informing
- **Scope:** Single layer/Single aspect
- **Archimate elements:** Actor and Business object

From the viewpoints presented before we derived five views that adequately represent **RAMOM**. Each of the selected views addresses the concerns of the stakeholders that were raised earlier.

Job profiles capabilities view: This view is derived from the Capability map viewpoint. This view will display the different **job profiles** necessary to effectively run manufacturing operation management activities in a smart factory as well as the capabilities that these must have to execute the functions that will be attributed to them. These **job profiles** will serve as the source of information for the actors presented in the **RA**. This view will address the fourth raised concern "What characteristics should the actors possess to effectively realize the activities they are responsible for".

Actor's data/artifacts view: This view is derived from the Actor's business objects Viewpoint. This view will display the different data/artifacts that should be made available to the actors responsible for the manufacturing operation management activities, this will facilitate both data and security architecture. This view will address the seventh raised concern "What are the required data/artifacts that the different actors must have access to effectively realize their responsibilities".

Business function's data/artifact view: This view is derived from the Business function, objects, and actors viewpoint. This view identifies both the data/artifacts that are inputted into the function as well as the data/artifacts that result from it. This view addresses the fifth and sixth raised concerns "What data/artifacts are required for the realization of the manufacturing operation management activities" and "What data/artifacts result from the realization of the activities".

Business function responsibility view: This view is derived from the Business function, objects, and actors viewpoint. This view identifies what actors are responsible for manufacturing operation management activities. The objective of this actor is to indicate which activities are mainly the responsibility of the information system inside organizations instead of the **job profiles** that have been identified in this work.

Business function general view: This view is derived from the Business function, objects, and actors' viewpoint. This view has the objective of providing a more general vision of the system by combining both data/artifacts and actors of the manufacturing operation management activities in the same view, facilitating the overall communication of the architecture with stakeholders. This view addresses the first and second raised concerns "What are the main manufacturing operation management activities to support smart factories" and "What tasks composed the manufacturing operation management activities."

5. RAMOM in a Portuguese industry case study

In this section, we described how a use case as used to show how **RAMOM** can be used in a real project. Through this use case, we aim to prove that **RAMOM** can be used in a real scenario and has a practical use.

During the development of **RAMOM**, one of the possible use cases that we envisioned for it is to validate the architecture of a manufacturing area that has converted to Industry 4.0. This might be necessary to evaluate if the architecture meets industry best practices or to identify why the manufacturing area is not functioning as intended after the transition. To perform this validation a trusted architecture in this topic is necessary to recognise if the best industry practices are followed or to pinpoint the issues faced by the current architecture. **RAMOM** would serve as the trusted architecture that would guide this analysis. The demonstration will be similar to the case we mentioned before. The architecture chosen for this analysis belongs to a Democorp, which we know that it faces some issues after starting its transition to Industry 4.0. The demonstration has two main phases. First, we modelled the Democorp architecture following the **RAMOM** views and viewpoints enabling its analysis using **RAMOM**. After this, we start comparing the Democorp and **RAMOM** view by view identifying factors that contribute to the challenges that Democorp is facing in its transition to Industry 4.0.

Where we only present the analysis made to the job profiles capabilities view of the Democorp. Similar analysis were done to remaining views.

In job profiles capabilities view two main challenges were found. The first is the lack of profiles specialized in handling data. During our research on **Industry 4.0**, we have found that many of the benefits can only be achieved by handling and processing the large amounts of data obtained from production equipment so that it is possible to draw conclusions from this data and make the production process more efficient [7]. This process is very complex and difficult due to the large amounts of data output by the system, the complexity of the data models used to organize the data and make it coherent, and the complexity of analyzing the results and presenting workable solutions based on the results. In the current Democorp architecture, no profile can perform these tasks, which means that the transition to **Industry 4.0** is not possible. The clear solution to this problem is to create a profile identical to the **RAMOM** data scientist to fulfill the activities of this profile. The second problem is the lack of capabilities of the operations profiles in dealing with technologically advanced equipment. In both the maintenance and production operator profiles in **RAMOM**, the emphasis is that they should be able to interact with digital tools, and the production operator should be able to use software to monitor activities and program and interact with automated systems. Currently, profiles similar to those in Democorp do not have these skills, which keeps them from iterating with **Industry 4.0** equipment and makes the transition more difficult. One possible solution would be to train operators in these areas so they can handle high-tech systems, or hire employees with these skills. These were the two biggest challenges we identified in our analysis. In addition, we identified two other issues that, while not as relevant as those previously mentioned, Democorp should also be aware of, namely the lack of maintenance profiles equipped to deal with automation and the fact that they use a more vertical hierarchical structure. In the **RAMOM**, maintenance operators should be able to deal with automation challenges, while in the Democorp nothing is mentioned about automation, which may become a challenge in the transition to Industry 4.0 as it relies heavily on automation. The use of a more vertical hierarchical structure can be problematic in the transition to Industry 4.0, as it makes it difficult to implement various Industry 4.0 values such as decentralization, personalization of the product, and flexibility [15].

From this type of analysis on all of **RAMOM** views, we were able to identify the several factors that will present difficulties for the transition of Democorp to Industry 4.0 demonstrating how **RAMOM** has practical utility since we were able to successfully identify important elements that were lacking in the Democorp architecture for this to be able to transition to Industry 4.0. The challenges identified are resumed in the table below.

Table 2. Main issues identified in Democorp

View	Possible challenges detected in Democorp
Job profiles capabilities view	Lack of profiles specialized in data usage; Lack of capabilities in operational profiles; Lack of maintenance profiles equipped to deal with automation; More vertical hierarchical structure;
Actor's data/artifacts view	Non found

Business function's data/artifact view	Analysis activities missing and not systematically performed; Maintenance and Inventory tracking activities not performed;
Business function responsibility view	Lack of automatization of activities; Unhelpful separation of activities; Performance analysis activities are not realized by profiles proficient in data;
Business function general view	Non found

6. Evaluation

This section describes how we evaluate **RAMOM** followed by ther conclusions that we took from this process. For a RA to be considered fit for purpose it must be proven that it is built correctly (this means without any architectural flaws) and that its content must be theoretically correct. For these reasons, there is an inherent need of evaluating **RAs** [4]. To evaluate RAMOM we opted to used FERA methodology as this is a suitable evaluation methodology for **RAs**. FERA was developed as a way to evaluate RAs for embedded systems but that could be personalized to fit other subjects. For this purpose, a questionnaire was built based on current literature available on embedded systems, reference architectures, and software architecture and already developed research on this topic [16]. Because FERA focuses on **RAs** for embedded systems, some changes were done to the base questionnaire of FERA to better fit the needs of our project. We only removed the questions specific to embedded systems, since this is out of the context of our project, the remaining questions were deemed relevant to evaluating the developed **RA**. We saw no need to add questions to the base questionnaire, since the remaining questions already covered all relevant topics to our project, since these cover the completeness of the **RA**, if its construction is correct, and if the contents presented in the **RA** are valid. The inspection of **RAMOM** was done by 3 roles, one specialist in industry 4.0, project management and familiar with Enterprise Architecture, an industrial engineer working on Industry 4.0 projects, and an IoT project manager working on Industry 4.0 projects that did not have previous involvement with **RAMOM**. This evaluation aims to validate 3 main concerns: Completeness of general information related to the construction and content of the architectural views, adequacy for releasing the architectural description of **RAMOM** and iability and change possibilities of **RAMOM**. For this purpose, 71 question questionnaire was answered by the participants. From the results, we conclude that the main problems identified are related to the lack of guidelines when it comes to implementing concrete instances of the architecture described in **RAMOM**, some details in **RAMOM** that do not comply with international standards, best practices, and guidelines, and some information that was missing in the architectural description of **RAMOM**.

The criticism of the lack of guidelines is to be expected due to the fact that **RAMOM** is a research-driven RA, i.e., it was developed based on research done on these topics and not on a concrete architecture, so the lack of concepts such as guidelines for its implementation, knowledge of how the variable part interacts with the non-variable part in because of the architecture, or how to implement the architecture in instances is normal, since this knowledge is gained only after implementing a concrete instance of **RAMOM**. The non-compliance with international standards, best practices, and guidelines was discussed with the experts involved in the evaluation and based on their feedback and further research, changes were made to **RAMOM** to correct these non-compliances. Finally, we also received feedback that certain aspects of **RAMOM** lacked information, such as a version identifier in each model or the lack of articulation of open decisions. Based on these results, we improved the architectural views to provide

Table 3. FERA questionnaire results

	Completely satisfactory	Partially satisfactory	Not satisfactory
Participant nº1	83%	7%	10%
Participant nº2	71%	19%	10%
Participant nº3	79%	11%	10%
Total	78%	12%	10%

a more consistent and complete architectural description of **RAMOM** and facilitate its dissemination.

Based on the evaluation carried out and the further discussion and treatment of the problems encountered, we can conclude that RAMOM is theoretically sound.

7. Conclusions

In this work, we explored how **EA** is used in the field of **Industry 4.0** and contributed to this research topic in several forms. First, we identified a gap in this research topic, by identifying a lack of **EA** resources on how organizations could adapt their operational processes to the technological innovations originated by Industry 4.0. We reached this conclusion by looking at the most popular **Industry 4.0 RAs'** and how these dealt with this topic. After determining this we decided to approach this topic with the development of a **RA** that supports organization's transition to **Industry 4.0**, leading to the development of **RAMOM**. **RAMOM** is a **RA** focused on manufacturing operations management in **Industry 4.0** that aids organization's adjustment to **Industry 4.0** by providing a set of generic actors, functions and data required for manufacturing operations management activities. For this purpose, RAMOM is composed of five views developed to answer the shareholder's concerns, which we mentioned before, as well as to improve the communication of these concerns between shareholders. The information present in the views was obtained through an SLR on **Industry 4.0 job profiles** and the study of the standard **IEC 62264-3**. **RAMOM** has proven theoretically correct by being evaluated by three industry professionals with the FERA method and was demonstrated in a use case on a Democorp to prove its practical use accomplishing our objective of developing an EA resource capable of helping organizations adapt their operational processes to the changes brought by **Industry 4.0**. **RAMOM** enables this by providing a trusted source of information that indicates to shareholders the most fundamental components that an organization must have when transitioning to **Industry 4.0** lowering the risk of the transition and the resources necessary to enable it. Despite considering this work a success there are several limitations of this work that should be considered. The first is limitation is that **Industry 4.0** is a relatively new phenomenon, meaning that **RAMOM** should be qualified as a research-driven **RA**, meaning that the best practices described in **RAMOM** might change in the future with further developments in the area. The other relevant limitation is the limited scope of **RAMOM** since it only deals with manufacturing operation management activities meaning that the topic of levels two and four activities aren't covered. To deal with this research should be conducted to identify what activities belong to levels two and four activities and then conduct a similar work as the one done in **RAMOM**. Finally, further research should be done on identifying the challenges companies face in moving to **Industry 4.0** in terms of their operating and business models and how **EA** can help companies solve these challenges since the main aspiration of this work are to demonstrate that this is a real challenge that is impeding organizations of adopting **Industry 4.0** and to contribute to this challenge by expanding our current understanding of this topic.

References

1. Iso/iec/ieee systems and software engineering – architecture description. *ISO/IEC/IEEE 42010:2011(E) (Revision of ISO/IEC 42010:2007 and IEEE Std 1471-2000)*, pages 1–46, 2011.
2. The industrial internet of things volume g1: Reference architecture. 2019.
3. P. Adolphs, H. Bedenbender, D. Dirzus, M. Ehlich, U. Epple, M. Hankel, R. Heidel, M. Hoffmeister, H. Huhle, B. Kärcher, et al. Reference architecture model industrie 4.0 (rami4. 0). *ZVEI and VDI, Status report*, 2015.
4. S. Angelov, J. J. Trienekens, and P. Grefen. Towards a method for the evaluation of reference architectures: Experiences from a case. In *European Conference on Software Architecture*, pages 225–240. Springer, 2008.
5. S. A. Bernard. *An introduction to enterprise architecture*. AuthorHouse, 2012.
6. I. E. Commission et al. Iec 62264-3 enterprise-control system integration—part 3: Activity models of manufacturing operations management. *International Electrotechnical Commission: Geneva, Switzerland*, 2016.
7. L. S. Dalenogare, G. B. Benitez, N. F. Ayala, and A. G. Frank. The expected contribution of industry 4.0 technologies for industrial performance. *International Journal of Production Economics*, 204:383–394, 2018.
8. J. Delsing, F. Rosenqvist, O. Carlsson, A. W. Colombo, and T. Bangemann. Migration of industrial process control systems into service oriented architecture. In *IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society*, pages 5786–5792, 2012.
9. M. Hankel and B. Rexroth. Industrie 4.0: The reference architectural model industrie 4.0 (rami 4.0). zvei, 2015.
10. B. Kitchenham. Procedures for performing systematic reviews. *Keele, UK, Keele University*, 33(2004):1–26, 2004.
11. H. Lasi, P. Fettke, H.-G. Kemper, T. Feld, and M. Hoffmann. Industry 4.0. *Business amp; Information Systems Engineering*, 6(4):239–242, 2014.
12. S. Luthra and S. K. Mangla. Evaluating challenges to industry 4.0 initiatives for supply chain sustainability in emerging economies. *Process Safety and Environmental Protection*, 117:168–179, 2018.
13. M. Moghaddam, M. N. Cadavid, C. R. Kenley, and A. V. Deshmukh. Reference architectures for smart manufacturing: A critical review. *Journal of manufacturing systems*, 49:215–225, 2018.
14. E. Y. Nakagawa, M. Guessi, J. C. Maldonado, D. Feitosa, and F. Oquendo. Consolidating a process for the design, representation, and evaluation of reference architectures. In *2014 IEEE/IFIP Conference on Software Architecture*, pages 143–152. IEEE, 2014.
15. M. Rüßmann, M. Lorenz, P. Gerbert, M. Waldner, J. Justus, P. Engel, and M. Harnisch. Industry 4.0: The future of productivity and growth in manufacturing industries. *Boston consulting group*, 9(1):54–89, 2015.
16. J. F. M. Santos, M. Guessi, M. Galster, D. Feitosa, and E. Y. Nakagawa. A checklist for evaluation of reference architectures of embedded systems (s). In *SEKE*, volume 13, pages 1–4, 2013.
17. R. Sharpe, K. van Lopik, A. Neal, P. Goodall, P. P. Conway, and A. A. West. An industrial evaluation of an industry 4.0 reference architecture demonstrating the need for the inclusion of security and human components. *Computers in Industry*, 108:37–44, 2019.
18. K. Zhou, T. Liu, and L. Zhou. Industry 4.0: Towards future industrial opportunities and challenges. In *2015 12th International Conference on Fuzzy Systems and Knowledge Discovery (FSKD)*, pages 2147–2152, 2015.