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A Quality 4.0 Model for architecting industry 4.0 systems

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ABSTRACT

The increasing importance of automation and smart capabilities for factories and other industrial systems has led to the concept of Industry 4.0 (I4.0). This concept aims at creating systems that improve the vertical and horizontal integration of production through (i) comprehensive and intelligent automation of industrial processes, (ii) informed and decentralized real-time decision making, and (iii) stringent quality requirements that can be monitored at any time. The I4.0 infrastructure, supported in many cases by robots, sensors, and algorithms, demands highly skilled workers able to continuously monitor the quality of both the items to be produced and the underlying production processes.

While the first attempts to develop smart factories and enhance the digital transformation of companies are under way, we need adequate methods to support the identification and specification of quality attributes that are relevant to I4.0 systems. Our main contribution is to provide a refined version of the ISO 25010 quality model specifically tailored to those qualities demanded by I4.0 needs. This model aims to provide actionable support for I4.0 software engineers that are concerned with quality issues. We developed our model based on an exhaustive analysis of similar proposals using the design science method as well as expertise from seasoned engineers in the domain. We further evaluate our model by applying it to two important I4.0 reference architectures further clarifying its application.

1. Introduction

Over the last decade the fourth industrial revolution has become a very important paradigm for the future of industrial systems. This has led to the proposal of the Industry 4.0 (I4.0) concept as a basis for building systems that address the needs of this fourth revolution. I4.0 is strongly related to the concepts of the Internet of Things (IoT) and Cyber–Physical Systems (CPS), among others, it creates a vision of the future of industrial production. It was initially created as a motto for an industry trade fair in Hanover (Germany), but quickly evolved into a full-fledged vision, bringing together developments like Artificial Intelligence, Big Data, additive manufacturing, and simulation, as well as other technological advances. By 2013, a working group had developed a set of recommendations and principles for I4.0 in the form of a platform and the "Reference Architectural Model Industrie 4.0" (RAMI 4.0) [1]. This provided a reference framework for further developments, both in industry and in research.

I4.0 aims at a technical basis for creating systems that address the needs of the fourth industrial revolution [1–3] and aims at the end-to-end digitalization and the flexibility of manufacturing and supply chains require revisiting concepts like Service Oriented Architectures (SOA) and Digital Twins, which have been used as key concepts in the design of I4.0 systems, as well as developing new software and system architecture concepts.

So far, research has mainly focused on functional and technical capabilities for I4.0-based systems, while the quality aspect has received significantly less attention [2]. To address this shortcoming, in this paper we propose a quality model, called *Quality 4.0 Model to Architect I4.0 Systems*, which refines quality aspects of the widely used ISO 25010 [4] software and systems engineering quality standard. The model was defined taking into account specific recommendations of existing I4.0 systems standards, which, in turn, focus mainly on functional and operational aspects. The systematic understanding of I4.0 quality aspects is fundamental to support the proper balancing of quality aspects while designing I4.0 systems.

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This work is not completely without precedent as some attempts do already exist to systematically address quality in I4.0 systems. For example, the company *LNS Research* presented a model, structured around process, technology, and people to characterize qualities in I4.0.[1] What differentiates our approach from models like these is that we focus on bridging widely used software and systems engineering quality standards like the ISO/IEC 25010 [4], and existing specific I4.0 standards that focus on operationalization of production plants. Beyond the organization of this body of knowledge, our main contribution is to provide this model in a way that is applicable to a broad range of different systems in line with the I4.0 concept and also in an actionable form, i.e., in a way that aims to provide concrete support to (software) engineers. After a careful analysis of scientific publications, grey literature and standards we develop a refined version of the ISO 25010 quality model specifically customized to include the most relevant qualities demanded by I4.0 needs. We also provide an initial evaluation of our model using two well-known I4.0 software architectures used by our industrial partners.

In order to connect the ISO 25010 quality model with the standards used in I4.0 and the engineering and operational aspects I4.0 solutions need, we aim to address three research questions in this paper, which build on each other. These are:

RQ1: What are adequate software and systems engineering quality and I4.0 standards for reasoning on the architectural quality of I4.0 systems?

Rationale: We aim to identify and analyze existing software and systems engineering quality standards and I4.0 standards to identify those that are adequate for reasoning about and evaluating the architectural qualities of I4.0 systems.

RQ2: Which quality attributes are relevant to I4.0 systems?

Rationale: By exploiting the findings for RQ1, in particular, we aim to identify the quality attributes that are required and appropriate for I4.0 systems. Therefore, we refine the results of RQ2 to identify the most relevant qualities that pertain to I4.0 systems.

RQ3: How can we relate relevant qualities to I4.0 standards and scenarios?

Rationale: With this research question, we aim to propose a quality model for evaluating the quality of I4.0 systems. We will use the relevant qualities found in RQ2 to relate them to map them in I4.0 and come up with a list of scenarios addressing those qualities.

The remainder of this paper is structured as follows. Section 2 describes some background and related work on smart factories and the notion of Quality 4.0. We introduce our research approach and steps guiding the rest of the paper in Section 3. Section 4 presents quality attributes, quality standards, and architecture drivers for I4.0, thus answering RQ1 and RQ2. Section 5 describes our Quality 4.0 model, thus answering research question RQ3. In Section 6, we then describe our validation by applying our model to two major reference architectures for I4.0 and discuss the findings and limitations of our research. Finally, in Section 7 we conclude and discuss potential directions for future work.

2. Background and related work

Enabling efficient manufacturing of small lot sizes and even lot size 1 is a key motivator for the fourth industrial revolution and hence for the creation of I4.0 systems [3]. To enable such efficient manufacturing, key capabilities that are not new to other domains, like plug and play and intelligent monitoring of processes, must be tailored to the demands of smart production systems. We first describe the need of defining requirements in cyber–physical systems (CPS) and then we discuss some related work about reconfigurable manufacturing systems (RMS) and their qualities demanded by these. Finally, we discuss specific quality properties in CPS.

2.1. Requirements for cyber–physical systems

In order to support such capabilities, I4.0 solutions have stringent requirements in order to cope with the automation and quality of the production process. The use of concepts like digital twins demand certain requirements for handling I4.0 Cyber–Physical Systems (CPS), such as described in [5], where the authors provide a list of 25 requirements and quality properties imposed on I4.0 systems. Other works like [6] propose a framework to assess the preparation of supply chain organizations and meet the expected requirements demanded by the fourth industrial revolution in response to the dynamic changes demanded by the supply chains and market needs. The authors suggest a list of I4.0 design principles aimed to support six different qualities guiding the design of sustainable supply chains using Internet of Things (IoT) technology. Finally, a recent work [7] describes a requirements engineering model for Industrial Internet of Things (IIoT) and CPS systems and how to elicit IIoT requirements effectively. Although the authors suggest a taxonomy of requirements they do not provide ways how to use this and it is not driven by concrete I4.0 scenarios.

For I4.0 systems, system-level requirements may induce software-level requirements. For example, system-level reliability induces recoverability or dynamic reconfiguration capabilities on the software level. Plant modifiability itself induces either configurability requirements (especially for foreseeable changes), self-organization capabilities that go beyond these, and – only for major changes – maintainability requirements. In addition, digital twins on the system level induce performance and resource requirements for the software.

Based on current runtime quality needs required by manufacturing systems, we can identify a number of quality aspects that should be defined to address I4.0 systems, demands like changeability, portability, and adaptability. These demands on I4.0 systems result from the paradigm shift from traditional PLCs to logical artifacts. These quality properties are crucial for enabling a production plant to cope with unforeseeable situations like machine failure or system unresponsiveness, and to ensure predictability of plant behavior, which demands the use of predictive strategies (e.g., predictive maintenance). Beyond these quality properties, ensuring specific levels of reliability, efficiency, and efficacy of the production plant is mandatory to ensure reliable operation of I4.0-based production plants. The work from [2] describes architecture drivers and decision blueprints for I4.0 shop-floor systems identified in the context of the BaSys 4.0 project[2] with major players of the German production industry. More specifically, this work details five quality attributes (i.e., compatibility, maintainability, portability, reliability (as Fault Tolerance), and security) as major architecture drivers to achieve different degrees of automation of I4.0 solutions.

These architecture drivers and decision blueprints for I4.0 shop-floor systems are used as input for the engineering of I4.0 systems and operational aspects of the quality 4.0 model proposed, such as we describe in Section 4.

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[1] https://blog.lnsresearch.com/top-4-reasons-to-update-to-quality-4.0

[2] http://www.basys40.de/

Example. Consider a typical factory shop-floor consisting of machines comprising electromechanical components, hardware, and specialized embedded software controlling them, specialized information systems like Manufacturing Execution System (MES), and personnel operating this multitude of systems. As the idea of I4.0 systems centers around the notion of intelligent and autonomous flexibility of the production, one important quality aspect observed is *adaptability*. This is defined, according to the ISO 25010 [4], as the "*degree to which a product or system can effectively and efficiently be adapted for different or evolving hardware, software or other operational or usage environments*". Adaptability of a typical factory shop-floor is required to allow flexible reconfiguration of the factory to new needs, perhaps even on the basis of lot size 1. Depending on the specific adaptability needs, such a change might vary, from reconfiguration of the existing electromechanical, hardware, and software set-up to the refactoring of specific software components and the replacement of specific controllers, among others.

2.2. Reconfigurable manufacturing systems

Reconfigurable manufacturing systems combine machines and software to produce finished products. The development of smart RMS is challenging because they need to adapt their capacity and functionality to varying demand and, at the same time, achieve certain quality levels. Hence, important quality attributes like performance, flexibility, adaptability, or scalability must be attainable in order to satisfy unforeseen changes in production planning [8,9]. The competition between flexibility and productivity in dynamic manufacturing environments must be estimated using adequate simulators and digital twins [10].

Some authors suggest assessment criteria defining several qualities for reconfigurable manufacturing systems in the automotive domain in order to ensure the quality of the assembled products [11]. Thereby, controlling the quality of products improves productivity of the manufacturing process and at the same time improves the detection of quality defects [12]. Thus, a quality management system for flexible manufacturing systems is important [13]. One recent work [14] highlights up to eight quality attributes of major interest for I4.0 smart manufacturing systems. Nevertheless, the proposed works fail to provide more concrete guidance on how to use the desired qualities for smart manufacturing systems based on concrete I4.0 scenarios. We have witnessed a shift to estimate these qualities from a software engineering perspective rather than from the purely mechanical aspects. Also, most of these approaches lack of a proper description on how these qualities should be defined in a software architecture.

2.3. Qualities demanded by cyber–physical systems

In I4.0, systems require specific qualities also from the software side. For example, as the systems may actually be easily and frequently changed, the software typically needs to support ease of customization, usually based on a plug-and-play approach. Often, high-performance data feeds also need to be taken into account, processed, and reacted upon (typically in real time), which leads to very demanding performance requirements.

Because of these particularities, I4.0 systems demand a tailoring of a specific subset of the qualities defined in the ISO 25010 standard [4]. The company *LNS Research* proposed a Quality 4.0 model,[3] based on the dimensions of people, processes and technology. This model identifies eleven axes or key components (e.g. analytics, data, connectivity, collaboration, etc.), supported by different processes and technologies. Other works like [15] put the focus on cybersecurity aspects to assess data quality models based on the ISO 25012 standard. Thereby, approaches like [16] highlight the role of security aspects to integrate risk-based testing and open quality models. However, these approaches do not consider how these qualities can be used in industrial automation activities where the quality of processes must be ensured dynamically.

I4.0 CPS require to achieve specific levels of qualities to support manufacturing performance, agile decision-making, efficiency, and scalability of cloud and service-based platforms among others. Moreover, as the quality levels in I4.0 projects might be stringent according to the automation goals, application domains and types of companies, such as reported in a recent SAS report,[4] it is important to understand which are the most relevant quality properties and how these can be evaluated in different I4.0 contexts.

Example. In the case of a plant that is connected only by static conveyors, no software will enable this plant to be fully changeable like a plant that uses separated manufacturing islands and connects them via Autonomous Transport Vehicles (ATV). Or to put it the other way around: Software running on Programmable Logic Controllers (PLCs) is unable to provide a service interface, and a manufacturing island design will not automatically introduce the needed changeability. Nevertheless, changing PLC software is a much easier task than changing a plant setup. In other cases, the capability to connect a new device to a computer and use it without the need to perform manual installation steps is crucial. *Plug*'n'*Produce* describes the capability of a production system to integrate a new manufacturing device[5] within a certain time frame. In the optimal case, no human intervention is needed. However, to achieve this automatic integration, both the system and the device have to fulfill certain requirements. Thus, Some scenarios motivating I4.0 qualities are the following:

- **Reliability (Recoverability/Fault Tolerance)**: Industrial plants should be able to recover from electromechanical failures. This depends heavily on the means used to connect the different devices. For instance, if the plant uses ATVs, these can simply be rerouted, but if a human has to come and pick up work pieces and transport them to a different conveyor, it may get complicated.
- **Maintainability (Modifiability)**: Plants should allow introducing new production capabilities and products on the fly. In a service-based production, for instance, this may be an easy task, but when there is a more Industry 3.0-oriented production setup, these changes will consume a lot of time and money to achieve the expected modifiability level.
- **Maintainability (Testability)**: Digital factories using digital twins must accurately reflect the status of the physical twins. One big use case of Industry 4.0 are "what-if" simulations to determine the impact of a change before actually performing it. If, for example, the communication infrastructure is not suitable for transporting the amount of data needed for an accurate digital twin, these "what-if" simulations will be hard to realize for some use cases.

2.4. Related work

To the best of our knowledge, only few scientific papers have been published about experiences in developing I4.0 systems that address quality aspects. As quality drives the development of the systems and architectures of I4.0 solutions, the diversity of I4.0 systems and architectures and the relevant qualities can be very large. The work in [17] focuses on Internet of Things (IoT), which is a relevant area of I4.0 solutions. This work highlights the importance of quality

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[3] https://blog.lnsresearch.com/quality40

[4] https://www.sas.com/content/dam/SAS/en_us/doc/whitepaper2/quality-4-0-impact-strategy-109087.pdf

[5] https://www.plattform-i40.de/PI40/Redaktion/EN/Downloads/Publikation/Industrie-40-Plug-and-Produce.pdf

properties in the industrial automation of IoT. Specifically, the authors discuss quality attribute constraints relevant to industrial automation and IoT challenges and they come up with a list of relevant qualities and the technical solutions to cope with these challenges. Also, in [18] the authors discuss challenges regarding the standardization of I4.0 processes and certain quality needs of industrial IoT systems (IIoT). The authors highlight the role of IIoT reference architectures to support strict quality requirements such as interoperability, real-time performance, availability, and reliability. The work in [19] presents an experience of using quality dimensions in the IIoT domain and captures the voice of the developers via a satisfaction survey using the Critical Incident Technique (CIT) in order to identify which boundary resources for IIoT platforms cause more satisfaction.

Today, many I4.0 solutions follow the so-called Reference Architectural Model Industrie 4.0 (a.k.a. RAMI 4.0) [1]. RAMI 4.0 is a three-dimensional service-oriented reference model that defines six different layers (e.g., business, functions, data, etc.) of a production process for I4.0 products in order to transition from the real world to the digital world, and different hierarchical levels going from product to a connected world. A recent contribution [12] discusses an extension of the RAMI 4.0 architecture to include security and human components in support of industrial scenarios. The authors suggest three different industrial scenarios and discuss how RAMI 4.0 does not adequately model humans within I4.0 systems. The authors, then propose adding a new layer for supporting security concerns and some recommendations to include humans in the loop during the interaction with the physical assets.

Regarding the role of quality properties in I4.0, some works [20] describe a process-centric approach to improve the quality of IoT data and data quality management for Smart Connected Product (SCP) operations. The concept of SCP embodies the concept of IoT, as one of the trending technologies supporting I4.0. The authors describe the different types of IoT data and the role of quality management for SCP operations. As a result, some relevant qualities such as reliability and safety are identified for preventive maintenance of smart connected product families. In [21], the authors present a software architecture for an agent-based fault diagnostic engine for industrial cyber–physical systems and they evaluate a set of quality requirements using the Architectural Trade-off Analysis Method (ATAM) in order to mitigate early risks detected in the construction of agents.

Other works such as [22] report on the state of the art of quality models for I4.0 and suggest a set of metrics for the evaluation of data quality in industrial processes. The authors propose a quality model composed of several data quality characteristics (e.g., accuracy, availability, completeness, etc.) that they evaluated in two use cases. The recent research in [23] reports on a systematic mapping study on the use of quality attributes in industrial cloud computing systems, but the authors do not provide any quality model applicable to I4.0 systems.

Although previous works motivate the need for qualities in CPS and RMS systems, there is no quality model able to support the architecting of software-based I4.0 systems that considers I4.0 standards, recommendations of certification authorities, and the body of knowledge and operational aspects of practitioners. Also, there is a need to define which of the existing qualities need to be better represented and used by I4.0 approaches. To address this challenge, we propose a customization of the ISO 25010 [4] standard focusing on the most relevant qualities for architecting I4.0 systems.

3. Research method

In this work, we aim at defining a model to guide I4.0 software engineers in the selection and use of quality attributes when developing their I4.0 solutions, taking into account their specific needs and combining technologies used by the I4.0 industry. To define our framework we followed the design research method [24], which is mainly used for creating new knowledge and artifacts that are required to address a particular phenomenon or problem (see Fig. 1). .

Our quality model was developed in three iterations, where each iteration consisted of three phases:

1. Awareness of the problem:

1.1 First Iteration: In the first iteration, we explored the literature using Google Scholar to find evidence of the use of quality attributes in I4.0 approaches [25]. In I4.0, many approaches have been proposed by companies and are often not documented in peer-reviewed publications. Consequently, we analyzed the existing literature, combining academic and gray literature on quality approaches for I4.0 topics and following the spirit of Multi-vocal Literature Reviews (MLRs) described in [26]. This was complemented by snowballing to achieve a higher level of completeness.

1.2 Second Iteration: We collected quality standards for I4.0 by exploiting our solid experience with quality models and I4.0 standards. We complemented this knowledge with a dedicated search activity through the use of search engines.

1.3 Third Iteration: We identified scenarios of quality aspect monitoring and usage in different contexts by exploiting our experience acquired in different research and industrial I4.0 projects.

2. Solution development:

2.1 First Iteration: We analyzed the data collected for the literature review and we identified quality attributes for I4.0.

2.2 Second Iteration: We selected and analyzed quality standards for I4.0.

2.3 Third Iteration: We defined the quality model by exploiting the knowledge acquired in the previous two iterations, as well as the knowledge acquired in step 1.3 about different research and industrial I4.0 projects.

3. Evaluation:

3.1 First Iteration: The validation consisted of an internal validation performed by two of the authors (LR — Literature review evaluators) who did not participate in the literature review. The LR evaluators independently checked the protocol of the literature review as well as a sample of the primary studies. The LR evaluators then met with the author who had performed the literature review and discussed it. The objective of this validation was to reduce the threats to validity of the process leading to the identification of the quality attributes for I4.0.

3.2 Second Iteration: The validation consisted of an internal validation performed by two of the authors (SR — Standard review evaluators) who did not participate in the analysis of the standards. The SR evaluators independently checked the process for identifying the standards as well as the outcome of the activity. The SR evaluators then met with the author who had performed the standards identification and discussed it. The objective of this validation was to reduce the threats to validity of the relevant (for I4.0) standards identification.

3.3 Third Iteration: We validated the proposed quality model through the help of engineers with more than three years of experience in the design and implementation of I4.0 solutions.

Fig. 2 summarizes the various steps of the research methodology and connects them to research questions and sections of the paper where the research questions are answered.

4. Quality attributes, quality standards, and architecture drivers for I4.0

In this section we identify the quality attributes and standards that are relevant for I4.0. We also describe how we enacted the steps of the design research method to derive our results.

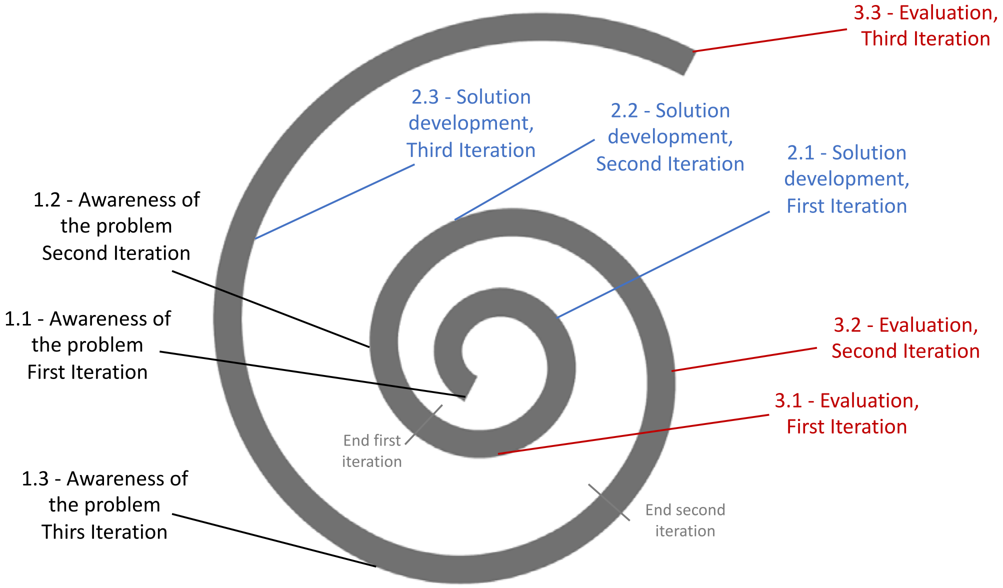

Fig. 1. Research methodology.

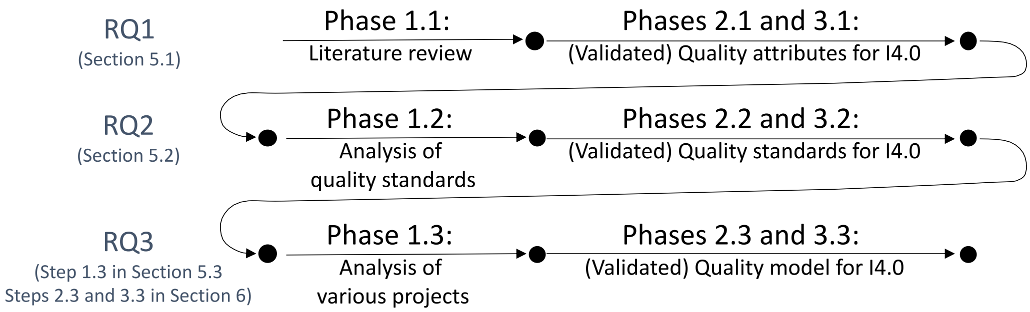

Fig. 2. Overview of the research methodology mapped to RQs and results.

4.1. Quality attributes for I4.0

To identify the quality attributes that are relevant for I4.0, we explored both the academic and the gray literature regarding works relating to quality aspects and I4.0 experiences. As our aim was not to provide a Systematic Literature Review (SLR), we adopted a straightforward strategy using Google Scholar to find evidence from both types of sources. Thus we did not query typical digital libraries like IEEE Xplore, ACM DL, or Scopus or limit our search only to scientific papers. Therefore, we used the following search string to query Google Scholar, restricting the time period to 2011 to 2021, inclusively:

`["I4.0"OR "Industrie 4.0"OR "Industrial Internet of Things" OR ‘‘Industrial Internet’’ OR ‘‘Cloud-based Manufacturing’’ OR ‘‘Smart Manufacturing’’ OR ‘‘Smart Factory’’] AND [‘‘Quality attribute’’ OR ‘‘Quality property’’ OR ‘‘Quality model’’]`

As a result, we found 1030 references. After removing entries from books, non-English links, theses, patents, and references not related to software or I4.0, we came up with 315 papers including some sources from gray literature. Our initial selection was only based on the title and abstracts of the papers found. This was done by two of the co-authors. As a result, we selected 43 sources. We analyzed these sources and carefully read each article. This resulted in a selection of 43 papers according to the following inclusion/exclusion criteria (IC/EC): IC1. Scientific papers or grey literature written in English; IC2. Approaches describing a quality model or the role of quality attributes used in an I4.0 context; EC1. Papers or sources not in English; EC2. Books, Master and PhD thesis; and EC3. Articles less than 5 pages in length.

In addition, we ran a snowballing process according to the guidelines defined in [27] to identify additional sources based on the selected 43 papers. We did one backward and one forward snowballing iteration and we found 45 and 12 papers, respectively. We reviewed the papers and we applied the IC/EC criteria and we selected 3 new papers. We will discuss a subset of the most relevant 46 papers selected, as they present quality models specific for the I4.0 domain.

Regarding the Internet of Things (IoT) domain, which is highly relevant for many I4.0 factories, the authors in [28] suggest a taxonomy of several quality attributes, such as availability, interoperability, security, and maintainability, among others. Interoperability, for instance, enables communications through the use of compatible data formats between devices from different hardware providers. Also, similar high-level requirements for IoT applications are discussed in [20]. The Industrial IoT domain (IIoT) combines the use of IoT devices with cyber–physical systems (CPS) to support I4.0 production in smart factories by covering machine-to-machine (M2M) and industrial communications. While IoT facilitates machine-to-human communications, interconnecting a plethora of devices to improve human awareness, IIoT is one of the pillars of digital manufacturing for connecting all industrial machines and information systems.

Additionally, cloud manufacturing is another I4.0 related area where stringent quality properties are demanded. For instance, the authors in [29] suggest multiple quality models to support the decentralization of machine tools, as one of the most relevant manufacturing resources. The authors highlight the role of manufacturing cloud services that require specific quality levels around certain quality properties such as performance, reliability, and safety among others. However, smart manufacturing processes require the definition of specific Key Performance Indicators (KPIs) to ensure the different qualities such as those discussed in [30] in order to quantify the system performance at different abstraction levels.

In [31] the authors provide a comprehensive survey of several quality requirements (e.g., modularity, interoperability, and responsiveness) for smart factories. The authors discuss several related surveys and investigate different aspects of smart factories ranging from qualities to systems design and digital twins. A recent work [32] reports on the use of different quality attributes in several application domains. Although the authors do not focus on I4.0 solutions, the application domains studied are closely related to I4.0. They distinguish between design and runtime qualities, the latter being quite suitable for automation goals typically used in I4.0 solutions. Other industrial approaches focusing on cloud-based control in plants supported by Programmable Logic Controllers (PLCs) [33] evaluate important quality attributes (e.g. resource sharing, scalability, elasticity, maintainability, and customizability) of an architecture used in the building automation domain.

Currently, there are many open challenges to achieve the expected qualities in I4.0 processes. Some of these challenges are discussed in [34] with a focus on the automation hierarchy and achieving vertical and horizontal integration of value chains. In order to achieve sustainable economic success, the authors identify eight quality management research challenges to measure the effectiveness and efficiency of I4.0 processes based on the DIN ISO 9000:2015 standard [35]. Also, in [36] the authors state some shortcomings of an applicable framework for I4.0. Several cases for the application of CPS systems reveal concrete deficiencies such as how to combine sensors for intelligent application in industries, how to monitor the environment and keep safe during the operation of robots, or how to manage a resource cockpit for socio-cyber–physical systems. All in all, the authors highlight that building CPS systems is one of the biggest challenges of I4.0, but they also address IT security issues. Other experiences with industrial CPS [37] highlight the role of scalability and performance qualities for data management challenges. Finally, one recent work [38] suggests to studying the changeability of I4.0 products via quality scenarios and based on the Architecture-Level Modifiability Analysis (ALMA) method. The authors in [2,39] discuss the role of architectural drivers and its impact certain qualities for I4.0 shop-floor applications. Finally, the authors in [22] present a quality model for industrial process data.

Table 1 presents a summary excerpt of major quality attributes for I4.0 approaches found in the literature. In the first column, we show the quality attributes found in the references mentioned in the table, while the second column displays the frequency of appearance of that QA in those references. The third column shows the context of use or application domain where that quality attribute was used in an I4.0 approach. It is interesting to highlight that in the surveyed works we did not find user-friendliness and sustainability as quality attributes. Since these quality attributes seem to be relevant in Industry 4.0, we performed a dedicated search and we were able to find two papers discussing sustainability in Industry 4.0 [40,41], and one paper discussing user-friendliness in Industry 4.0 [42]. As future work we plan to refine the model when we will find stronger evidence of the importance of these or other quality attributes.

As a remark, not all the qualities shown in Table 1 will appear in our model (i.e. those labeled with “N/A"), as these are very dependent on the application domain considered and the standards used. However, Table 1 can serve as a starting guide for the selection of specific qualities to derive a customized quality model even if not all the quality attributes are addressed at the same time. We also indicate in last column of the table the section where we address the qualities.

4.2. Quality standards for I4.0

Here we analyze the following quality standards that contain important qualities for I4.0 software:

- **ISO 25010**, which is a standard whose definitions of different quality attributes are widely accepted in industry and academia. The definitions of the quality attributes from the ISO 25010 has been adopted by industries from different domains (e.g., automotive, naval, avionics, medical devices) [43,44], and lately by industries adopting technologies to move towards I4.0 concepts [2,45]. This has been observed in consultancy projects executed by some of the authors of this paper. Given the relevance and adoption in practice of the ISO 25010 definitions, the authors decided to adopt it in the Quality 4.0 model proposed in the paper.
- **I4.0 Standards and Recommendations** described in bodies of knowledge and industrial reports by industrial and public authorities, like the *ISO 13584*,[6] *The Platform Industrie 4.0* [1], *The Standardization Roadmap of Predictive Maintenance for Sino-German Industrie 4.0/Intelligent Manufacturing* [46], *The Current Standards Landscape for Smart Manufacturing Systems* [47], and the *I4.0 Semantics Interoperability*.[7] These standards have been selected because they are particular relevant to industry and or appear very often in literature.

This step required solid experience of the authors with the ISO 25010, with I4.0 standards, engineering and operational particularities, and with certification processes. This analysis generated a first group of elements for the categories *ISO 25010 I4.0 Specifics* and *I4.0 Standards and Recommendations*, as depicted in Fig. 3.

In a second step, we identified associations between the existing entries in the *I4.0 Standards and Recommendations* and *ISO 25010 I4.0 Specifics*, and the addition of what we call *I4.0 Engineering and Operational Aspects*, which bridges the *I4.0 Standards and Recommendations* and *ISO 25010 I4.0 Specifics*. The refinements and relations of the elements that compose these categories corresponds to what we call *The Quality 4.0 Model to Architect I4.0 Systems* (cf. Section 5), and was achieved after several iterations with practitioners and research experts.

4.3. Key architecture drivers for I4.0

In our approach, we understand by architectural drivers those quality scenarios that are useful to monitor the quality of I4.0. This section describes step 1.3 of the research methodology and reports key architecture drivers we identified in different research and industrial I4.0 projects. Specifically, we exploit the expertise gained in the BaSys 4 series of projects,[8] and its industrial instantiation to companies with different sizes and from multiple domains.[9]

One key input for the development of the Quality 4.0 model was the need to support some specific drivers we observed in different contexts and the quantification required to support the quality requirements. More specifically, in I4.0 research projects, e.g., the BaSys 4.0 project, and in our industrial collaborations, e.g., with NetApp[10] and ObjectivePartner,[11] we observed apply to a wide range of industries,

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[6] https://www.iso.org/standard/43423.html

[7] http://i40.semantic-interoperability.org/

[8] http://www.basys40.de/

[9] http://www.basys40.de/satellitenprojekte/

[10] https://blog.netapp.com/netapp-data-fabric-hybrid-cloud-powering-industry-4.0/

[11] https://www.objective-partner.de/shopfloor-40-flexibilitaet-in-der-fertigung/

Table 1
Popular quality attributes in I4.0 approaches.

Quality attribute	Freq.	Context of use of the I4.0 approach	s
Reliability, Fault-tolerance, Recoverability	10	Embedded systems [32], Smart Connected Products [20], Manufacturing [2,29,30], IIoT boundary resources [19], IIoT [17], Manufacturing [2], Data processing [22]	5.4
Maintainability, Modularity	7	Cloud-based PLC [33], Embedded systems [32], Smart Connected Products [20], Manufacturing [2,30,39], Smart factory [31]	5.2
Security/Safety, Privacy	7	IoT systems [20,28], Embedded systems [32], Smart Connected Products [20], Manufacturing [29], IIoT [17]	5.4, 5.5
Interoperability	5	Smart factory [31], IoT [20], Manufacturing [2,39], IIoT [17]	5.2
Changeability, Flexibility, Adaptability, Portability	5	Evaluation of an I4.0 architecture [38], Manufacturing [29], Manufacturing [2,22]	5.2, 5.3
Scalability, Elasticity*	5	Cloud-based PLC [33], IoT [20], CPS [37], IIoT [17]	5.1, 5.2, 5.3, *N/A
Availability	4	Data processing [22], IIoT boundary resources [19], Manufacturing [30], IIoT [17]	6
Performance, Responsiveness, Capacity	4	CPS [37], Manufacturing [29], Smart factory [31], Manufacturing [30]	5.1, 5.2
Time behavior	3	Cloud-based PLC [33], Manufacturing [39], IIoT boundary resources [19]	N/A
Usability, Accessibility	3	IoT systems [28], IIoT boundary resources [19], Data processing [22]	N/A
Accuracy	1	Data processing [22]	5.1, 5.2
Cost	1	Manufacturing [29]	N/A
Stability	1	IIoT resources [19]	5.1

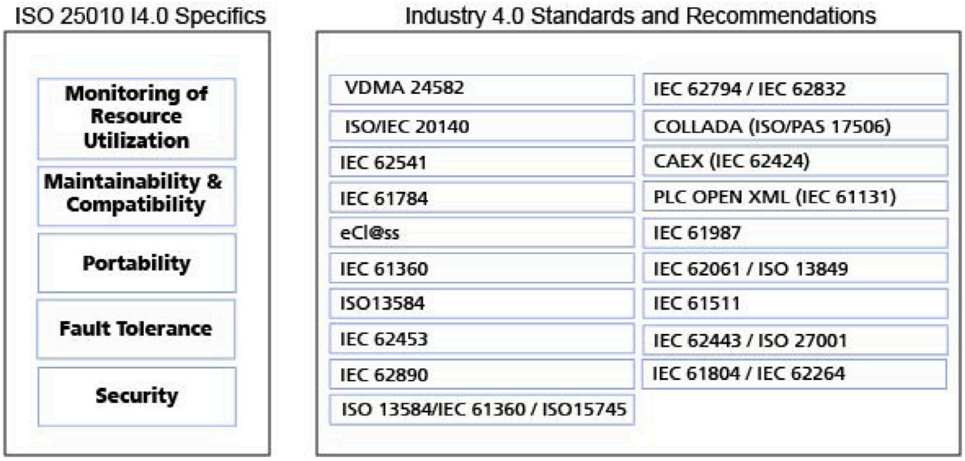
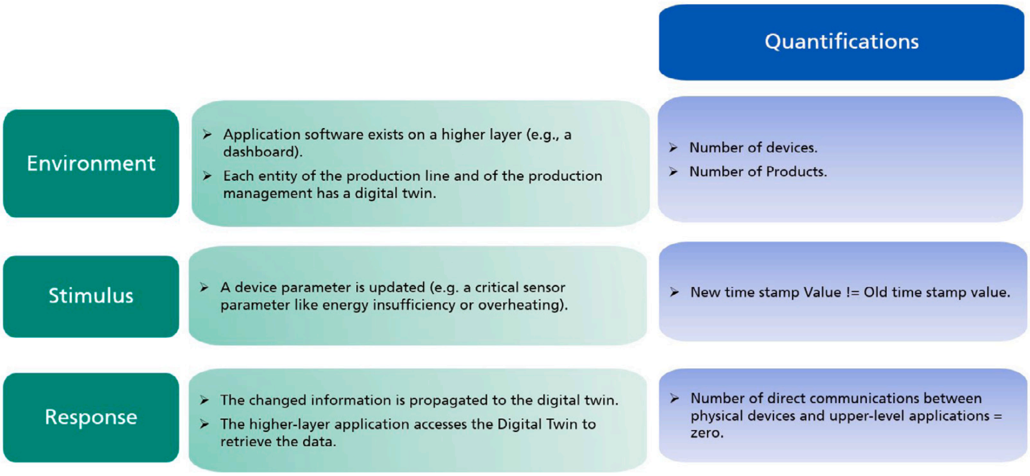


Fig. 3. ISO 25010 I4.0 Specifics and I4.0 Standards and Recommendations.

independent of the domain. The work in [2] discusses a set of architectural drivers forming a blueprint of the key aspects that should be considered for transitioning to I4.0-based production plants. Two of these drivers are depicted in Figs. 4 and 5, and they were chosen because of their adequacy to illustrate the quality aspects listed in Section 4.2; more specifically, the first scenario focuses on data exchange relates to the "Monitoring and Resource Utilization I4.0 Specifics" quality aspect since it can cause an update of a parameter (see the stimulus of the scenario); the "Maintainability and Compatibility" quality aspects are related to the communication for the information exchange; portability (moving a workpiece from one device to another) is related to the second scenario (fault tolerance), even though portability seems to be described mainly as the physical movement of a device. Security is relevant for both scenarios.



Environment:

- Application software exists on a higher layer (e.g., a dashboard).
- Each entity of the production line and of the production management has a digital twin.
- Number of devices.
- Number of Products.

Stimulus:

- A device parameter is updated (e.g. a critical sensor parameter like energy insufficiency or overheating).
- New time stamp Value != Old time stamp value.

Response:

- The changed information is propagated to the digital twin.
- The higher-layer application accesses the Digital Twin to retrieve the data.
- Number of direct communications between physical devices and upper-level applications = zero.

Fig. 4. Architecture driver describing the Information exchange between systems from different layers of the automation pyramid.

These drivers were specified according to the approach proposed by Knodel and Naab [48], who claim that architecture drivers must be specified in terms of: (i) the environment or condition in which this driver occurs; (ii) the event that stimulates the occurrence of the driver; (iii) the expected response of the system to the driver event; and (iv) the quantifications associated with the three previous aspects. Each of these measurable effects indicates whether the driver is addressed by the architecture.

The first architecture driver (cf. Fig. 4) refers to data exchange among devices, products, and systems on different layers of production management, like MESs and ERPs. In this case, as described in the Environment field, we assume that there are Digital Twins for each entity of the production line and of the production management. The stimulus for the occurrence of the driver is a change in any parameter of one of these systems, such as a sensor warning indicating a possible malfunction caused by overheating. To quantify the stimulus, the time stamp of the data is used. An update of this time stamp indicates to the system that new data is available and that the corresponding actions have to be performed. In the case of this stimulus, the response is that the parameter change must be propagated to its Digital Twin, which forwards this information or makes it available for the Digital Twins of the other participants of the production line, even those at a higher hierarchy level, which, in the traditional automation pyramid, would hardly have access to this information. Regarding the quantification of this response, numerical values must indicate that communication only happens based on Digital Twins and not between the physical entities.

The second architecture driver (cf. Fig. 5) refers to shifting the production of a workpiece from one device to another when the primary device fails. In this case, the status of the workpiece at the moment of the failure shall be retrieved from its Digital Twin and sent to the Digital Twin of the redundancy of the device that failed. The Digital Twin of the redundant device calculates its capacity to process the interrupted workpiece production and, if capacity is available, the physical device redundancy should take over the production of the workpiece. The quantification for the environment is the upper limit of the supported devices, if there is any. Additionally, the number of scheduled devices has to be known to ensure that correct rescheduling can be performed. The stimulus is quantified by the error flag of the primary device. In case of failure, this flag will be raised. After the response, the quantifications ensure that no work-piece remains in a stuck state and that it is successfully rescheduled and produced. As an additional quantification, it is ensured that only one rescheduling happens to prevent potential schedule oscillations.

5. A Quality 4.0 Model to Architect I4.0 Systems

This section describes the *Quality 4.0 Model to Architect I4.0 Systems*, which answers RQ3. According to the second step in Section 4.2, we identified associations between the existing entries in the I4.0 Standards and Recommendations and ISO 25010 I4.0 Specifics and what we called new I4.0 Engineering and Operational Aspects. This resulted in the inclusion of new entries in the I4.0 Standards and ISO 25010 I4.0 Specifics. The quality model has been defined taking into account the quality attributes, architecture drivers, and standards for I4.0. An overview of the Quality 4.0 model to architect I4.0 systems is depicted in Fig. 6, and each quality aspect is detailed in the remainder subsections of this section.

5.1. Monitoring and Resource Utilization I4.0 Specifics

The *ISO 25010 I4.0 Specifics* regarding ***Monitoring of Resource Utilization*** quality aspects are depicted in Fig. 6 , and detailed in the remainder of this subsection.

The ***M01 Condition Monitoring and Machine Diagnostic*** corresponds to capabilities for monitoring whether a plant is adequately operating according to different pre-determined parameters, as well as to diagnose electro-mechanical situations related to machine oil quality, bearing and vibration, and pattern deviation of actuators. The status values defined by the associated *I4.0 Standards and Recommendations* VDMA 24582 [49] are *Good, Warning, Critical Condition, Defect/Error*, and *No Status Statement*. This condition monitoring is a key building block to enable proper predictive maintenance [50,51].

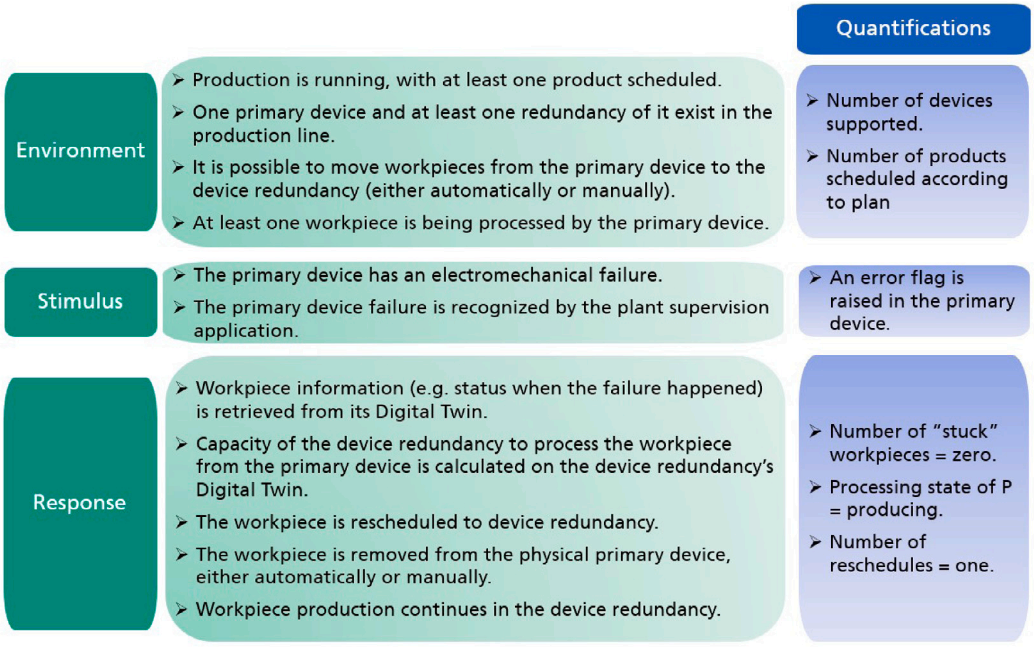
The ***M02 Environmental Influences*** corresponds to monitoring of manufacturing aspects that influence the environment like energy efficiency, the amount of emissions and discharges and of polluting incidents [52].

5.2. Maintainability and Compatibility

The *ISO 25010 I4.0 Specifics* regarding the ***Maintainability and Compatibility*** quality aspects are depicted in Fig. 6 and detailed in the remainder of this subsection.

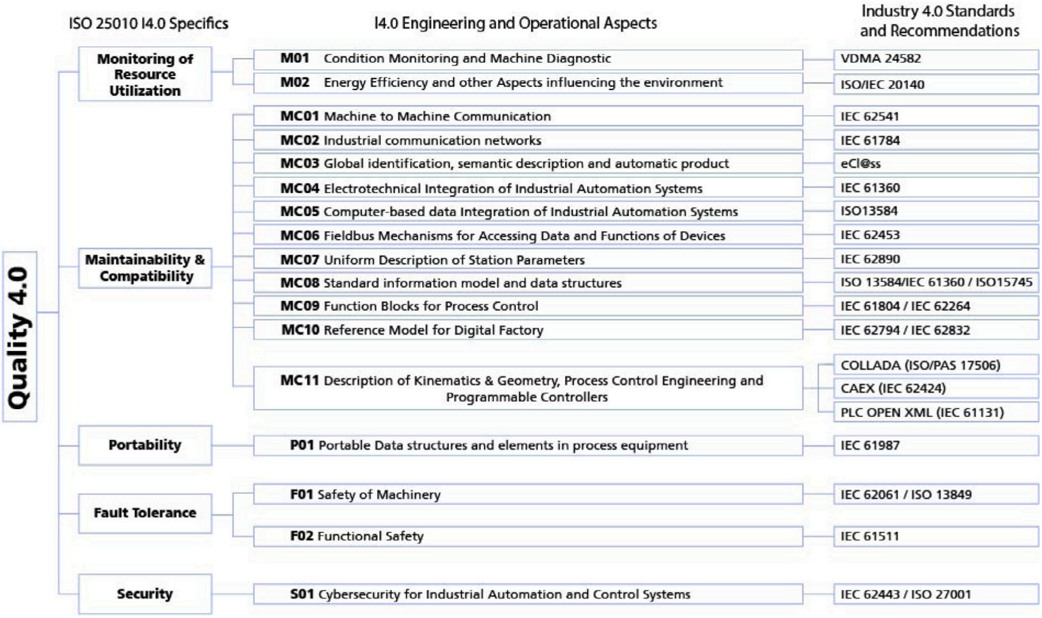
The ***MC01 Machine to Machine Communication*** is about the usage of the wide-spread OPC Unified Architecture (OP CUA), which is a machine-to-machine communication protocol that aims to enable interoperability for service-based process control platforms. It is governed by the IEC 62541 standard [53].

The ***MC02 Industrial communication networks*** corresponds to diverse Communication profile families that aim at guiding the design of equipment communicating in production plants. It additionally describes fieldbus profiles for real-time networks [54].



		Quantifications
Environment	➢ Production is running, with at least one product scheduled. ➢ One primary device and at least one redundancy of it exist in the production line. ➢ It is possible to move workpieces from the primary device to the device redundancy (either automatically or manually). ➢ At least one workpiece is being processed by the primary device.	➢ Number of devices supported. ➢ Number of products scheduled according to plan
Stimulus	➢ The primary device has an electromechanical failure. ➢ The primary device failure is recognized by the plant supervision application.	➢ An error flag is raised in the primary device.
Response	➢ Workpiece information (e.g. status when the failure happened) is retrieved from its Digital Twin. ➢ Capacity of the device redundancy to process the workpiece from the primary device is calculated on the device redundancy's Digital Twin. ➢ The workpiece is rescheduled to device redundancy. ➢ The workpiece is removed from the physical primary device, either automatically or manually. ➢ Workpiece production continues in the device redundancy.	➢ Number of "stuck" workpieces = zero. ➢ Processing state of P = producing. ➢ Number of reschedules = one.

Fig. 5. Architecture driver describing Recovery from electromechanical failure.



ISO 25010 I4.0 Specifics	I4.0 Engineering and Operational Aspects	Industry 4.0 Standards and Recommendations
Monitoring of Resource Utilization	**M01** Condition Monitoring and Machine Diagnostic	VDMA 24582
	M02 Energy Efficiency and other Aspects influencing the environment	ISO/IEC 20140
Maintainability & Compatibility	**MC01** Machine to Machine Communication	IEC 62541
	MC02 Industrial communication networks	IEC 61784
	MC03 Global identification, semantic description and automatic product	eCl@ss
	MC04 Electrotechnical Integration of Industrial Automation Systems	IEC 61360
	MC05 Computer-based data Integration of Industrial Automation Systems	ISO13584
	MC06 Fieldbus Mechanisms for Accessing Data and Functions of Devices	IEC 62453
	MC07 Uniform Description of Station Parameters	IEC 62890
	MC08 Standard information model and data structures	ISO 13584/IEC 61360 / ISO15745
	MC09 Function Blocks for Process Control	IEC 61804 / IEC 62264
	MC10 Reference Model for Digital Factory	IEC 62794 / IEC 62832
	MC11 Description of Kinematics & Geometry, Process Control Engineering and Programmable Controllers	COLLADA (ISO/PAS 17506) CAEX (IEC 62424) PLC OPEN XML (IEC 61131)
Portability	**P01** Portable Data structures and elements in process equipment	IEC 61987
Fault Tolerance	**F01** Safety of Machinery	IEC 62061 / ISO 13849
	F02 Functional Safety	IEC 61511
Security	**S01** Cybersecurity for Industrial Automation and Control Systems	IEC 62443 / ISO 27001

Fig. 6. Overview of the Quality 4.0 Model to Architect I4.0 Systems.

The ***MC03 Global identification, semantic description and automatic product classification*** corresponds to standardized descriptions of plant services and products in a way that it enables exchange of data related to them. It is ruled by the ECLASS or eCl@ss standard.[12] [55]

The ***MC04 Electrotechnical Integration of Industrial Automation Systems*** is about the uniformity advocated by the ECLASS [55] to electrotechnical constituents of production plants. This is ruled by the IEC 61360 [56].

The ***MC05 Computer-based data Integration of Industrial Automation Systems*** is about the ECLASS uniformity to logical computer-based data (e.g., like library data) to enable data exchange independent of the nature of the computer system. This is ruled by the ISO 13584 [57].

The ***MC06 Fieldbus Mechanisms for Accessing Data and Functions of Devices*** is about the definition of an interface that exposes object behavior and interactions by means of commands and static functions, among others, forming the so called FDT (Field Device Tool). This is ruled by the ISO 62453 [58].

The ***MC07 Uniform Description of Station Parameters*** advocates that stations in production plants should describe their operational state and performance parameters so they can be read by different equipment and systems composing the I4.0 ecosystem. This is ruled by the IEC 62890 [59].

The ***MC08 Standard information model and data structures*** is about the description of products of the production in a way that

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[12] https://www.eclass.eu/

it can shared among different business partners, exchanging messages, for example, according to specific business protocols or shared databases [60]. To this end, the ISO 13584 [57] describes a metamodel to support the creation of products ontologies, the IEC 61360 [56] provides a common data dictionary and concept repository, and the ISO 15745 [61] describes the interfaces necessary to integrate the resources to be shared [62]. These are key aspects to enable interoperability of business-related information.

The ***MC09 Function Blocks for Process Control*** is ruled by the IEC 61804 [63] and the IEC 62264 [64], and corresponds to the functional specification of the plant entities, focusing on the services delivered by each entity, and how the functional blocks are grouped and related to each other to support specific operations [62]. The ISO 61804 also recommends to describe how equipments and business processes should be grouped to address each function group. This is an explicit demand of functional traceability to business level and the technical realization. The aspects addressed by the IC09 described here are about a higher-level specification of the functions executed by the electronic and computation entities and data aspects described in the *IC04* and *IC05* previously described.

The ***MC10 Reference Model for Digital Factory*** corresponds to the description of the automation entities that compose the production plant in terms of structural and operational relationships. This can be seen as the highest-level description of production, followed by the items addressed by the *IC01*, which are then refined by the *IC04* and *IC05*, previously described. This is ruled by the IEC 62832 [65].

The ***MC11 Description of Kinematics & Geometry, Topology and Programmable Controllers*** corresponds to representation and schemas ruled respectively by the COLLADA (ISO/PAS 17506) [66], CAEX (IEC 62424) [67], and the PLC OPEN XML (IEC 61131) [68]. COLLADA is a short for COLLAborative Design Activity, comprises an XML-based schema to guide the development of 3D proprietary applications dealing with kinematics and geometry, and enables accurate information among applications compliant with the COLLADA scheme.[13] CAEX is a data transfer language that is used to enable accurate data exchange between process control engineering and Piping and Instrumentation Diagram (P&ID) tools, which are used to support designing the production plant and its operational execution. Finally, PLC Open XML aims at standardizing programming languages for Programmable Logical Controllers (PLCs) from industrial automation. It comprises equipment requirements and related tests for PLCs and their associated peripherals, programming languages for fuzzy control, etc.

5.3. Portability

The quality aspect ***Portability*** is refined by the I4.0 specific ***P01 Portable Data structures and Elements in Process Equipment*** depicted in Fig. 6 This is about structuring product features of industrial-process measurement and control equipment in a way that the product descriptions are facilitated when porting the equipment from one location to another, or when integrating new equipment or systems into an existing infrastructure. This aspect is ruled by the IEC 61987 [69].

5.4. Fault Tolerance

The quality aspect ***Fault Tolerance*** is refined by the I4.0 specifics ***F01*** *Safety of Machinery* and ***F02*** *Functional Safety* as depicted in Fig. 6 and described in the remainder of this subsection.

The ***F01 Safety of Machinery*** is about Safety of E/E-programmable electronics and control systems on machines that are not manually portable after being deployed. This aspect of the Safety of Machinery is governed by ISO 62061 [70]. Another aspect to be considered is the safety related to (SRP/CS) electrical, electro-mechanical and mechanical (hydraulics) parts. This aspect is governed by the ISO 13849 [71].

The ***F02 Functional Safety*** is about the IEC 61508 [72] requirements being tailored to the process industry sector. This is governed by IEC 61511 [73], which recommends safety measures for avoiding, identifying, and mitigating failures that might lead to injury or death of humans in the production line.

5.5. Security

The quality aspect ***Security*** is refined by the I4.0 specific ***S01 Cybersecurity for Industrial Automation and Control Systems***, which is ruled by the IEC 62443 [74] and the ISO/IEC 27001 [75] (cf. Fig. 6) IEC 62443 recommends the existence of measures for dealing with security threats that industrial networks and systems are subject to according to the different logical components of production plants, referred to in the standard as *Plant Logical Framework*.

Other qualities: It is important to highlight that other quality attributes listed in the ISO 25010 like *Modifiability* and *Testability* are also of importance, and are implicitly addressed by the sophisticated combinations of the Quality 4.0 Aspects discussed in this section. For example, aspects like data uniformity, reference models at various levels, and portable data structure are fundamental for properly modifying and testing these complex systems. However, we decided not to discuss them in the scope of this paper because we aim, first and foremost, at providing a foundation model that is directly mapped to both ISO 25010 and the I4.0 Standards and Recommendations that have been widely discussed by certification authorities and industry practitioners. Moreover, aspects like modifiability and testability demand not only sophisticated combinations of the I4.0 Engineering and Operational Aspects presented in this paper, but also a broad discussion of related techniques like simulations, which are key to addressing these aspects in I4.0 systems. As a follow-up research, we aim at properly analyzing what orchestrations among the components of our current Quality 4.0 Model for architecting I4.0 Systems are necessary to address these and other quality aspects.

6. Evaluation of the I4.0 quality model

The questions we aim to answer for evaluating the I4.0 quality model are:

EQ1: To what extent do existing I4.0 reference architecture and solutions address the qualities as defined in the *Quality 4.0 Model to architect I4.0 Systems* presented in this paper?

EQ2: To what extent does the *Quality 4.0 Model to architect I4.0 Systems* presented in this paper address the demands of industry practitioners?

To provide an answer to questions EQ1 and EQ2 we have analyzed existing I4.0 reference architectures against the model. We have selected the Eclipse BaSyx platform[14] and the Stuttgart IT Architecture for Manufacturing (SITAM) [76]. These platforms were selected because of their visibility in industry and their repeated use in I4.0 solutions engineered in German SMEs [77][15] and large enterprises in Europe and in the USA like BOSCH, ZF, PSI, among others,[16] and also because of the availability of material that enabled analyzing the architecture with reasonable level. Another key reason was that these platforms are developed according to the I4.0 reference architecture RAMI [1], which has been widely used as a reference model by industry and academia.

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[13] https://www.iso.org/standard/59902.html

[14] https://www.eclipse.org/basyx/

[15] https://www.basys40.de/satellitenprojekte/

[16] https://www.basys40.de/basys-demonstratoren/

Table 2
Mapping of the Quality 4.0 model to I4.0 platforms (1/3).

Quality I4.0	BaSys		SITAM	
	Rat.	Rating reasoning	Rat.	Rating reasoning
M01 Condition Monitoring and Machine Diagnostic	PSA	Provides foundations (Submodels, VAB) but does not implement the application itself	PSA	Provides foundation (Analytics Middleware & Integration Middleware) but does not implement application itself
M02 Energy Efficiency and other Aspects influencing the environment	PSA	Provides foundations (Submodels, VAB) but does not implement the application itself	PSA	Provides foundation (Analytics Middleware & Integration Middleware) but does not implement application itself

The evaluation of the proposed Quality 4.0 model demands knowledge in reference architectures of the I4.0 platforms and on the systems that they have been instantiated on. Thus, the evaluation of the platforms against the *Quality 4.0 Model to architect I4.0 Systems* was performed by two engineers with more than 3 years of experiences in the design and implementation of I4.0 solutions. The evaluation itself consisted of analyzing the architectures of the platforms in order to understand to what degree the platforms address the aspects of the quality model presented in Section 5. The engineers involved in the platform evaluations did not participate in the definition of the quality model, and had access to it only in the evaluation phase, to reduce possible bias. Also, additional Fraunhofer experienced engineers in designing and implementing I4.0 solutions, and that had no interaction with the paper at all, have analyzed the evaluation performed, and confirmed the evaluation accuracy.

The analysis of the architecture of the platforms was performed according to the Fraunhofer RATE architecture evaluation methodology [78], more specifically the *Solution Adequacy Check*, which aims at evaluating the adequacy of architecture solutions to specific architecture drivers. The Fraunhofer RATE architecture evaluation methodology was used because of the familiarity of the authors with the methodology. However, other approaches like SEI ATAM [79], for instance, could have been used as well. In the scope of this paper, the architecture drivers correspond to the quality aspects of the *Quality 4.0 Model to Architect I4.0 Systems* and the architecture solutions correspond to the I4.0 solutions selected.

The engineers that evaluated the platforms against the quality model proposed in Section 5 were not at all involved in the definition of the proposed quality model. Regarding the evaluation of BaSyx and SITAM against the Quality model proposed in this paper, the engineers rated the adequacy of architecture solutions to specific architecture drivers according to the following rate scheme, slightly adapted from the original RATE [78] rating scheme:

- **No Solution Adequacy (NSA hereafter):** means that the Quality 4.0 aspect is not addressed by the platform.
- **Partial Solution Adequacy (PSA hereafter):** means that the platform partially implements the Quality 4.0 aspect, providing foundations for the quality concept but not addressing it to the full extent.
- **Full Solution Adequacy (FSA hereafter):** means that the platform implements the Quality 4.0 aspect to its full extent, offering capabilities for addressing the quality recommendations to the full extent.

The ratings and reasoning behind them are summarized in Tables 2, 3, and 4, and the details in Sections 6.1 and 6.2.

6.1. *Eclipse BaSyx 4.0 evaluation*

We describe in this section the different levels of adequacy of the proposed solution for BaSys.

Full adequacy: The Eclipse BaSyx 4.0 platform has full adequacy regarding ***IC01*** *Machine to Machine Communication* by means of (i) the so-called Virtual Automation Bus, which enables connecting the digital twins of the different entities from the production process, and (ii) OPCU UA integration. The BaSyx's Asset Administration Shell and sub-models exhibits also full adequacy regarding the ***IC03*** *Global identification, semantic description and automatic product classification*, the ***IC04*** *Electrotechnical Integration of Industrial Automation Systems*, the ***IC05*** *Computer-based data Integration of Industrial Automation Systems*, the ***IC08*** *Standard information model and data structures*, and the ***P01*** *Portable Data structures and elements in process equipment*. As similar thing happens with ***IC09*** *Function Blocks for Process Control*, where it is fully enabled by means of the topology and capability description sub-models. Finally, the ***IC10*** *Reference Model for Digital Factory*, BaSyx has full adequacy to it because the topology sub-model reflects the structural relationships between individual assets, thus, it also enables creating a sub-model that reflects operational relationships.

Partial adequacy: The BaSyx's ***M01*** *Condition Monitoring and Machine Diagnostic* and the ***M02*** *Energy Efficiency and other Aspects influencing the environment* are partially adequate for BaSyx because the platform itself does not contain dedicated submodels for these two quality aspects. In the case of the former, the BaSyx SDK offers means for external applications to realize this monitoring with specialized condition monitoring and with the environment submodels. For the latter, the challenges are due to some environmental information for devices, such as energy efficiency, being static and equal for all instances of machines, whereas some would be dynamic, e.g., in condition monitoring (example: current emission). Thus, the machine information can be split into two Asset Administration Shells: one that describes the asset type (static and equal for all instances) and one that describes the asset instance (current environmental impact). In addition, the ***IC06*** *Fieldbus Mechanisms for Accessing Data and Functions of Devices* exhibits the same property because it offers the basics, to address it, there is no submodel available, while for ***IC07*** *Uniform Description of Station Parameters*, BaSyx provides control components that enable accessing this data but not fully according to IEC 62890 recommendations. Moreover, the adequacy of ***IC11*** *Description of Kinematics and Geometry, Process Control Engineering and Programmable Controllers* is due to the fact that the BaSyx submodel does not incorporate each characteristic described in this quality aspect. To realize this, it would be necessary to create one submodel type for each characteristic described in this quality aspect. Finally, ***S01*** *Cybersecurity for Industrial Automation and Control Systems* fits in this category as, despite the fact that the platform enables encrypted communication and AAS allows specification of access permissions (ABAC), not all the standard recommendations are addressed. The platform is, however, flexible enough to implement different security demands for specific instantiations.

Table 3
Mapping of the Quality 4.0 model to I4.0 platforms (2/3).

Quality I4.0	BaSys		SITAM	
	Rat.	Rating reasoning	Rat.	Rating reasoning
IC01 Machine to Machine Communication	FSA	VAB, OPC UA Integration	FSA	Manufacturing Service Bus in Integration Middleware
IC02 Industrial communication networks	NSA	–	NSA	Model/Integration layer too abstract
IC03 Global identification, semantic description and automatic product classification	FSA	AAS, Submodels	NSA	ECLASS not addressed
IC04 Electrotechnical Integration of Industrial Automation Systems	FSA	AAS, Submodels	NSA	ECLASS not addressed
IC05 Computer-based data Integration of Industrial Automation Systems	FSA	AAS, Submodels	NSA	ECLASS not addressed
IC06 Fieldbus Mechanisms for Accessing Data and Functions of Devices	PSA	Provides foundations (Submodels, VAB). Does not implement the application itself	PSA	Provides foundation (Integration Middleware). Does not implement application itself
IC07 Uniform Description of Station Parameters	PSA	Control Components support accessing this data but not according to IEC 62890	PSA	Operational could be accessed via a specialized ESB. No uniform description
IC08 Standard information model and data structures	FSA	AAS, Submodels	NSA	No standard information models
IC09 Function Blocks for Process Control	FSA	Topology Submodel, Capability Description Submodel	NSA	ESB organized in lifecycle phases, not functional units
IC10 Reference Model for Digital Factory	FSA	Topology Submodel covers structural but not operational relationships	NSA	No factory reference model addressed
IC11 Descr. of Kinematics & Geometry, Process Control Eng. and Prog. Controllers	PSA	Mappable by Submodel, but no submodel specified until now	NSA	Even more detailed than IC08

Table 4
Mapping of the Quality 4.0 model to I4.0 platforms (3/3).

Quality I4.0	BaSys		SITAM	
	Rat.	Rating reasoning	Rat.	Rating reasoning
P01 Portable Data structures and elements in process equipment	FSA	AAS, Submodels	FSA	Integration layer facilitates changeability
F01 Safety of Machinery	NSA	Not directly addressed	NSA	Not directly addressed
F02 Functional Safety	NSA	Not directly addressed	NSA	Not directly addressed
S01 Cybersecurity for Industrial Automation and Control Systems	PSA	Encrypted Communication, AAS allow specification of access permissions (ABAC)	PSA	Supports common security features

No adequacy: BaSyx has no adequacy yet for the ***IC02** Industrial communication networks, **F01** Safety of Machinery*, and ***F02** Functional Safety*. The capabilities for addressing these three aspects are being developed in the context of projects currently being carried out.

6.2. SITAM evaluation

Full adequacy: SITAM has full adequacy for ***IC01** Machine to Machine Communication* due to its Integration Middleware, which is composed of hierarchic Enterprise Service Buses (ESB) for integrating different applications.

Partial adequacy: Apart from that, the architecture has partial adequacy for ***M01** Condition Monitoring and Machine Diagnostic* and the ***M02** Energy Efficiency and other Aspects influencing the environment*, since the Integration Layer and the Analysis layer could support these quality aspects by integrating suitable tools. However, SITAM itself does not directly address these points. Similarly, there exists a foundation and therefore a partial adequacy for ***IC02** Industrial communication networks* by means of the integration layer. It also exhibits the same adequacy for ***IC06*** *Fieldbus Mechanisms for Accessing Data and Functions of Devices*, where specialized ESB could be connected in the Integration Layer to provide access to functions and data. The layer also supports changeable data sources and devices in various lifecycle phases, thus ***P01*** *Portable Data structures and elements in process equipment* is partially adequate. A similar level of adequacy exists as for BaSyx with regard to the ***S01*** *Cybersecurity for Industrial Automation and Control Systems*, because although security is present across all layers, no explicit security requirements are addressed by SITAM.

No adequacy: SITAM poses no adequacy for the ***F01*** *Safety of Machinery*, and ***F02*** *Functional Safety*. Additionally, since eclass is not directly addressed in the SITAM, there is also no adequacy in ***IC03*** *Global identification, semantic description and automatic product classification*, ***IC04*** *Electrotechnical Integration of Industrial Automation Systems* and ***IC05*** *Computer-based data Integration of Industrial Automation Systems*. Regarding ***IC07*** *Uniform Description of Station Parameters*, SITAM also has no adequacy, since a device's operational state and parameters could be accessed through a specialized ESB, but there is no uniform description. The same holds true for ***IC08*** *Standard information model and data structures* and for ***IC11*** *Description of Kinematics and Geometry, Process Control Engineering and Programmable Controllers*, which is even more detailed than IC08. Other I4.0 quality with no adequacy is ***IC09*** *Function Blocks for Process Control*, since the ESB in the Integration Layer is organized by lifecycle phases, not functional units. Also, as the structural relationships in a digital factory are not directly addressed in SITAM, there is no adequacy regarding ***IC10*** *Reference Model for Digital Factory*.

The manual analysis of the platforms could be performed with high confidence because of the large experience of the engineers with the I4.0 platforms analyzed.

In the scope of this paper the evaluation aimed mainly at assessing the reasonability of the Quality 4.0 model, considering that the BaSyx and SITAM solutions are widely used and recognized by bodies of knowledge. However, this evaluation also provided value for the platforms themselves because it could identify non-compliance with some of the quality aspects described in the *Quality 4.0 Model to architect I4.0 Systems*.

7. Conclusions and future work

Although quality attribute models and quality attribute evaluation techniques have been studied in depth for years, to the best of our knowledge this is the first attempt to provide a quality model specifically for I4.0 systems. In this paper, we aimed creating such a model as a way of supporting software architects in the context of I4.0.

Our model development used the design research method [24] in three iterations. The first iteration relied on literature review to identify and validate relevant quality attributes. In a second iteration this was augmented by taking into account existing, relevant quality standards. This led to a comprehensive taxonomy of quality attributes that are highly relevant to I4.0 systems. In a third iteration we looked at a number of existing industrial projects as a basis for deriving our final quality model, which is the main contribution of our paper.

Afterwards, we did a separate evaluation, involving both industrial projects in the I4.0 domain that have not contributed to the initial model construction as well as relying on interviews with colleagues who were not involved initially. While the systematic linkage of the derived quality attributes in our models already provided evidence for the adequacy of the model, this further ensures the usefulness of the model.

As future work, we plan to refine our Quality 4.0 Model for Architecting I4.0 Systems using scenarios from other domains, such as pharmaceutical production, to evaluate the current quality needs and discover new ones. This will be performed in the context of projects dealing with Advanced Therapy Medicinal Products (ATMP), carried on by the Fraunhofer society and its research partners.[17] We also plan to apply and refine our model further in the context of the IIP-Ecosphere project.[18] Moreover, we plan to exploit our quality model for evaluating I4.0 systems of various German companies[19]; more specifically, concrete instantiations are already being made in a joint project with a multinational company. Additionally information in this regard will be disclosed in the future when critical phases of the project are concluded. This will permit, on the one hand, to further validate the usefulness and effectiveness of our quality model with a and on the other hand, to understand additional demands on the model based on the quality needs of these companies, thus giving an opportunity to further refine our model.

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.

Data availability

No data was used for the research described in the article.

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