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From Concept to Industry: Development of a Capability Roadmap Towards Quality 4.0

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Abstract

While Q4.0 does not replace traditional quality methods, it adapts them so that the concept of quality embraces new technology to maximize value. The combination of quality management practices with technological tools can become a critical factor for organizational success. In the face of this transition, the development of implementation and capability roadmaps has gained interest. By providing an assessment of maturity for Q4.0, models show organizations their current state of readiness for the digital transition allowing them to see what they lack to meet the desired level of maturity through an analysis of each dimension or structural field of the model in depth. As a result, organizations can end up with a customized roadmap to help them achieve their strategic goals. This work presents the development of the Capability Roadmap towards Quality 4.0. This capability roadmap looks at 3 dimensions – "value chain and operations", "strategy and organization" and "people and culture" – each with 3 sub-dimensions. The capability levels are divided into readiness, for levels 1 to 3, and maturity, for levels 4 to 6, where traditional quality tools and approaches are integrated with the use of technology.

Keywords
Quality 4.0, Capability roadmap, Maturity model, Transition strategy.

1. Introduction

A connection between the digital and physical domains with the integration of people, devices and processes was brought to the forefront with the Fourth Industrial Revolution (I4.0). With the focus on Digital Transformation the concept of Quality 4.0 (Q4.0) also emerges.

Quality 4.0 can be seen as an approach involving people, systems, and technologies to improve connectedness, intelligence, and automation to achieve quality and performance goals. (Radziwill 2018). Antony et al. (2022) define Quality 4.0 as "the use of advanced technologies – such as IoT, CPS, and cloud computing – to design, operate, and maintain adaptive, predictive, self-corrective, automated quality systems along with improved human interaction through quality planning, assurance, control, and improvement to achieve new optimums in performance and operational excellence". Dias et al. (2022) see Quality 4.0 as the "delivery of superior quality, using modern technology to augment the capabilities of both people and quality tools and methods". Since Quality 4.0 is still a relatively new concept there is not a single universal agreed-upon definition, but all the proposed definitions seem to refer to the synergy between people and emerging technologies – with a focus on its predictive and auto-corrective capacities - to achieve quality and performance goals, and organizational excellence.

While Quality 4.0 does not replace the traditional quality methods, it adapts them so that the concept of quality not only embraces the new technology but also its users and processes to maximize value (Armani et al. 2021). The combination of quality management practices with technological tools can become a critical factor for organizational success, allowing organizations to take advantage of real-time data and Big Data analytics, implement innovative products and processes successfully by incorporating emerging technologies and materials and, efficiently identify how to fulfil the needs and requirements of stakeholders and redefine them as needed (Carvalho et al. 2021), while, due to the resulting products' and services' adaptive capacity, ensuring superior quality and performance and, consequently, increasing customer satisfaction and stakeholder interest along the value network (Dias et al. 2022; Salimova et al. 2020). Quality 4.0, supporting dynamic data-based decisions, can reduce the turnaround time to launch a product or service, leading to similarly reduced costs of redesign and rework, empowering internal and external customers with effective collaboration, connectivity, and co-creation (Dias et al. 2022). Furthermore, the implementation of Quality 4.0 can impact an organization's financial and social performance, environmental sustainability, and external business growth (Antony et al. 2022; 2023a). Quality management also benefits from automated and digital production processes that make quality inspection easier and more reliable, allowing the shift from control by sampling to total control. Furthermore, by using new and emerging technologies it becomes possible to anticipate and eliminate non-conformances and the workers, or even the machines themselves, could have the capacity to perform any corrective or preventive measures that may be needed (Dias et al. 2022).

The new tools and techniques allow the collection and analysis of great amounts of data, enhancing decision-making, minimizing bias, and reinforcing human intelligence while also ensuring transparency and traceability (Antony et al. 2023). Moreover, with the capacity to analyze big amounts of data, these tools associated with new technologies have a great potential for robust predictions, that can be utilized, among other uses, to predict product failure be it on the production line or after delivery to the customer, potentially reducing downtimes and warranty claims (Radziwill 2018; Santos et al. 2021).

However, despite the focus on technology, this should not be considered the sole or most critical aspect of the Digital Transformation and Q4.0 transition (Kane et al. 2015; Vial 2019; Carvalho et al. 2020). People are one of the foundations of an organization's development and continuous improvement. Even though upskilling people to adapt to emerging technologies is essential, it is also important to make sure the technologies employed adapt to the people, their needs and their practices (Breque et al. 2021). These efforts are essential in generating individual motivation, identifying training needs and managing the transition to new roles. An established culture of Quality is recognized as a facilitator in the transition process (Carvalho 2020). Promoting human-oriented perspectives in pursuing sustainable industrial transitions is essential to engage people in new ways of working.

With the ever-changing customer preferences, volatile markets and high stakeholder expectations, the potential benefits of Quality 4.0 become even more attractive. Besides, associated with these, there are also other possible organizational motivators, like the current society's focus on circular economy and sustainability, and the

expectation's shift from continuous quality improvement and sustainment to dynamic product and service development (Antony et al. 2023).
However, the implementation of Quality 4.0 also has its challenges. Antony et al. (2023) in a survey of managers across several industries, found that the main challenges felt by organizations trying to make the transition included the lack of resources but also a lack of awareness of the potential benefits. The high initial investment required and the mismatch of Quality 4.0 with the existing corporate strategy were also mentioned. Additionally, the already effective continuous improvement strategies implemented by organizations limited the adoption of Quality 4.0. Furthermore, since digital empowerment, digitalization, and dynamic quality enhancement seem to be essential for Quality 4.0 implementation along with the need for cultural transformation, the people involved could become the greatest challenge - either due to the lack of specific skills or due to their resistance to change (Balouei et al. 2022).
In the face of this transition, the development of implementation and capability roadmaps has gained interest. Maturity models are often used as an evaluative and comparative tool, designed to assess the maturity – or competency, capability – of an organization in a selected domain based on a set of criteria.

They can serve as a basis for improvement and in order to derive an informed approach to increase the capability of a specific area within an organization (de Bruin et al. 2005). In addition, these models can also provide a roadmap and detailed guidelines to assist organizations, with increased relevance to management practices (Santos and Martinho 2020). Since these models help define the capabilities that should be developed to meet future needs and how those capabilities should be developed, capability roadmaps are more often being used with technology roadmaps, or even substituting them, in a market environment where organizations need to be even more flexible and adaptable to fast changes and disruptions (Schumacher et al. 2019; Eagar et al. 2013). These kinds of models can also allow organizations to assess antecedents and precedents in the digital transformation phase thus contributing to organizational transformation and enabling the decisions of when and how to intervene and how can the success of the implementation of the selected domain be measured (Hizam-Hanafiah et al. 2020). By providing an assessment of maturity for I4.0 or Q4.0, models show organizations their current state of readiness for the digital transition allowing them to see what they lack to meet the desired level of readiness or maturity through an analysis of each dimension or structural field of the model in depth. As a result, organizations can end up with a customized roadmap to help them achieve their strategic goals.

1.1 Objectives
Since most of the literature is focused on Industry 4.0, the availability of dedicated tools to guide a Quality 4.0 transformation is still very limited. In order to mitigate this gap, this paper presents a Quality 4.0 roadmap. The proposed model is intended to work as a descriptive tool, assisting organizations to reach a greater understanding of Quality 4.0 and in identifying the necessary steps to pursue its sustained implementation, while also functioning as a diagnostic and roadmap tool that allows organizations to position themselves in a readiness/maturity scale and understand what they lack to make a successful transition to Quality 4.0.

2. Methods
The model development was done as a design exercise (Maier et al. 2012) and followed the development process for Capability maturity models and roadmaps (Kumar et al. 2011; Maier et al. 2012; Schumacher et al. 2016). The methodology consists of three distinct stages - the first stage entails obtaining a broad understanding of the subject; the second stage comprises the framework design; and the third and concluding stage corresponds to the model validation.

A narrative literature review was developed to allow a broad understanding of the Q4.0 subject through the research and review of the published body of knowledge (Green et al. 2006; Paré et al. 2015). For that purpose, the databases used for information collection included Scopus and Web of Science, complemented by Google Scholar. The references of the selected documents were also used to expand the selection process. Only documents in English or Portuguese were considered.

The literature review also included documents on maturity models and readiness assessment tools, focusing on those highlighting organizational capabilities. According to Maier et al. (2012), organizational capabilities entail an organization's skills, abilities, and expertise. Therefore, studies predominantly focused on the technical performance of new technologies and systems were excluded. The identified models were analyzed, categorized, and compared which helped define the relevant concepts to build the model structure, such as methodology, dimensions, stages,

roadmap decision points, and assessment tools. The dimensions analysis was also considered a starting point for the model design.

3. Quality 4.0 Capability Roadmap

3.1 Design and Development

The broad literature review on Q4.o allowed for the definition of the model's content and architecture. A table format was selected to simplify reading and highlight the intersection between the stages. To achieve the detail required for the model to act as an effective roadmap, each of the dimensions was divided into sub-dimensions.

Effective transitions occur in stages (Gökalp et al. 2017) and this paradigm leads to a roadmap based on a series of capability stages, each built on the preceding one. As a result, it was decided to assign the first three stages to a readiness state and the final three to a more advanced state – maturity. The readiness and maturity stages were created based on the literature review and the models analyzed resulting in a conceptual model (Table 1) that can be used to better understand capability stages when traditional Quality tools and approaches are integrated with technology. The levels go from the physical to the digital and cyber-physical domains, integrated with the human-oriented approach. From readiness level one to the advanced maturity stages like level 6 there is a shift from a reactive approach to an increasingly predictive and prescriptive approach. The outcome is a six-stage model that guides users from their initial interaction with Q4.0 through developing company-specific fields of action utilizing state-of-the-art technologies.

Table 1. Capability levels conceptual model

	Level	Designation	Domain
Readiness	1	Stakeholder Interaction	Physical
	2	Process Integration	Physical
	3	Digitization	Digital
Maturity	4	Automation	Digital
	5	Connectivity	Cyber-physical
	6	Intelligence	Cyber-physical

3.2 Conceptual Validation

The selection of experts considered a balance between academia and industry to validate scientific rigor, coverage/representativeness, usefulness, and usability. Experts were chosen based on their expertise and/or research contributions in the areas of Quality and digital transformation. Since merging these areas is a recent concept, finding experts in this domain was no easy task. However, a validation session was able to be carried out with four invited experts. Further discussion towards the validation was obtained at a university public session, with about 20 workers and students enrolled in a quality-related master course.

Before the validation session with experts, the model and a brief explanation of the objectives were made available for a first contact and an individual and impartial evaluation. Then, they were invited to participate in a workshop to discuss the model architecture, content, and applicability; and to provide general comments and suggestions. While discussing architecture and content, the following topics were addressed: dimensions and subdimensions, readiness and maturity stages adequacy; model features fit between dimensions and stages; content and representativeness; interpretation; and innovation. The applicability, usefulness, and usability were also debated.

Tree primary suggestions were given concerning the model's dimensions: (1) stronger emphasis on the value chain due to its central role in the management of organizational processes; (2) adding education and training in the Pole part; and (3) to designate the model as a human-oriented approach instead of describing it as a human-centered approach. The model's applicability also triggered a debate on potential pitfalls. After gathering experts' opinions and comments, a public session was held, but no significant contributions were registered.

3.3 The Quality 4.0 Capability Roadmap

The validated version of the Quality 4.0 Capability Roadmap is composed of three dimensions – "Value Chain and Operations", "Strategy and Organization" and "People and Culture". Each dimension is broken down into three

subdimensions – “Customers”, “Products and Services”, “Processes”; “Strategy”, “Integration”, “Innovation and Improvement”; “Role Transition”, “Organizational Culture”, and “Leadership”. Each subdimension is then characterized into six stages.
Although it still emphasizes the use of technology, the “Value Chain and Operations” dimension represents the operational part of the model. The intention is to support the idea that Quality is an integral part of the digital transformation process and that while we face a technology-driven transformation, Quality is the basis of the process. As a result, the subdimensions are focused on trying to integrate technology with "Customers," an integral part of any Quality system, "Products and Services," as the development of new products and services changes, and "Processes," which require an adaptation and update in the face of the new technologies and ways of working.

The “Strategy and Organization” dimension is concerned with overall organizational growth. The “Strategy” sub-dimension focuses on creating, developing, and monitoring a strategy for the Q4.0 transition. Given the technology and systems-driven transition that is I4.0, one very relevant sub-dimension of the entire model is “Integration” - integration of technology, new ways of work, learning, and communication are all important aspects of organizational growth. Furthermore, there can be no progress without "Innovation and Improvement." This sub-dimension was designed to give organizations a fundamental premise of what they would face on their journey to creating new development approaches.

Finally, the “People and Culture” dimension is presented in connection to the human side of the transition. People are the foundation of any organization, and progress does not imply that this foundation is altered. One of the most important purposes of Q4.0 is to enhance rather than disregard people's capabilities. For this, it is essential to create new "Role Transition" methods to skill and reskill people in the organization, to adapt to new working methods and address individual motivation. In every organization, and especially in a more advanced phase of transformation, the awareness of the "Organizational Culture" is critical, as it contributes as a facilitator in many aspects. Finally, “Leadership” is mainly responsible for all this transformation and is prominent in this model.
As for the stages, readiness and maturity stages were designed to provide the Q4.0 transition with a sense of progression. The main goal of these stages is to convey to organizations that without the basic foundations of Quality, innovation will not be sustainable - that is, placing itself at higher stages of the model without having the previous ones will not result in sustainable progress in the long term. Thus, the order of stages was designed to be followed and get a sense of what is missing.

The first stage, "Stakeholders Interaction," is a fundamental stage that all organizations must comply with since the model was designed for organizations already embedded in the quality culture. The next stage, “Process Integration”, is intended to promote the integration of Q4.0 approaches into the organization's various processes. Finally, the "Digitization" stage, which is still within readiness status, is set aside to bridge the gap between the fundamentals and what begins to be an advanced stage in the transition to Q4.0. This stage aims to transfer organizational data to a digital format and, as a result, establish effective communication channels to assist in day-to-day management.

At a higher maturity stage, the "Automation" stage aims to employ technology to automate touchpoints in different organizational processes, facilitating data collection and analysis and augmenting human capabilities and decision-making. As we progress to the intermediate stage of maturity, we find the “Connectivity” stage. "Connectivity" supports effective communication between people, machines, and systems, resulting in the simplification of information and knowledge exchange along the active value network, which comprises the various intra- and extra-organizational systems involved. Finally, the use of state-of-the-art technology allows organizations to reach the stage of “Intelligence”. At this stage, organizations should be able to predict various process parameters and market changes, and progress toward a more resilient, sustainable, and human-centered organization in alignment with the principles of Industry 5.0 (Breque et al. 2021).

Considering the model is designed to be used as a Roadmap, a second layer was developed in which the concepts mentioned in the first layer of the model were further detailed. As a result, it is expected that the model will become even less complex and that organizations can turn it into an easy-to-use assessment tool for self-assessing their Q4.0 readiness and positioning themselves to define a strategy for moving up the model's stages.

3.5 Industrial validation

The Quality 4.0 Capability Roadmap proposed allows an exploration of the dimensions of Q4.0 while providing well-founded, human-centered, and comprehensive guidance in the transition towards Quality 4.0. However, it has only been validated theoretically through a survey of a panel of experts, leaving some opportunities for future work, including the empirical validation of the developed model. This empirical validation will be done through a case study approach since it is suitable not only for answering how and why questions but also for theory development, testing and refinement (Voss et al. 2002). Two organizations were selected – a manufacturing plant and a consulting service – through intentional sampling, to get data from two different ways of working and due to constraints of time and access. The main source of data will be semi-structured interviews, where despite having a set of questions prepared and reviewed, follow-up questions can come up organically during the interview both for clarification and to cover possible gaps in the data needed. Two people, within the selected organizations that have the necessary knowledge and experience to answer the questions, will be selected for the interviews.

In order to adhere to the underlying principle of triangulation, and in an effort to increase the validity and reliability of the data collected, the interviews will be backed up by direct observation and participation in meetings or events related to the quality management practices at the selected organizations and by the review of archived documents that illustrate those practices. The application of the roadmap will consist of the attribution of a score from 1 to 6 in each dimension of the capability roadmap, based on the information collected during the interviews, direct observation, and archival review.

Using a gap analysis approach a strategy for the implementation of Quality 4.0 projects will be developed. Taking into account the levels of readiness or maturity achieved by each organization where the roadmap will be tested, we can evaluate the current state, the strengths – where the scores are higher – and weaknesses – where the scores are lower – of each organization. A priority list for action can then be created based on those strengths and weaknesses, and a strategy developed to increase the scores and achieve the readiness or maturity level desired by the organizations.

4. Conclusion

Quality 4.0 has gained momentum in recent years. However, research on the topic is most often looked at from a technological point of view, with Quality Engineering and Management being overlooked in favor of the implementation of new and more complex technology (Carvalho et al., 2020). This article defines a roadmap for organizations to integrate these aspects in a clear and practical way. This model allows the definition of different priorities for organizations according to their state of maturity (or readiness) in the Quality 4.0 Transition. It provides clear stages along the Quality 4.0 transformation journey, defining transition requirements and marking the boundaries and touchpoints between Technology and Quality management. In each stage, the Quality 4.0 Roadmap highlights the necessary capabilities that organizations need to develop and sustain.

The Quality 4.0 Capability Roadmap works as a descriptive tool to assist organizations in better understanding Quality 4.0, and in identifying the necessary steps to pursue its sustained implementation. The model, being a diagnostic and roadmap tool, allows organizations to position themselves and understand what they lack to make a smooth and sustainable transition to Q4.0. It shows how there can be no full achievement of Quality 4,0 without technology but, more importantly, it demonstrates that there will be no Quality 4.0 without sustained quality practices that are later incorporated with different levels of technology.

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Biography

Ana Rita Dias is an MSc. student in Engineering and Quality Management in the Department of Production and Systems of the University of Minho and is also affiliated with the ALGORITMI Research Centre.
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André holds a PhD (University of Minho, 2020) in Engineering Design and Advanced Manufacturing, resulting from a joint program between Portuguese Engineering Schools and the Massachusetts Institute of Technology. He has been a Visiting Student and Research Affiliate at the Sociotechnical Systems Research Center at MIT (2018-2020), a Visiting Scholar at Northeastern University (2019), and a Postdoctoral Researcher at the Technical University of Denmark (Engineering Systems Design group, 2020).
His research focuses on engineering management, exploring how technology, people and processes intermingle in the ongoing business transitions. Looking at subjects such as quality and performance management, organizational cultures, technology use, and organizational agility, he has sought to identify how organizations can best adapt to respond to the challenges of the world around us. His research has been recognized by organizations such as the Industrial Engineering and Operations Management (IEOM) Society, the International Academy for Quality (IAQ) and American Society for Quality (ASQ).

Pedro Domingues holds a Bachelor's degree in Chemistry (1996), an MSc. in Textile Environmental Chemistry (2001) and a PhD. in Industrial Engineering and Systems (2013) all of them from University of Minho. His doctorate thesis addressed the topic of integrated management systems and the development of a maturity model. Currently, he is a Principal Researcher at ALGORITMI Research Centre (University of Minho, Portugal) engaged in several projects addressing topics such as integrated management systems, digital transformation of management systems, Quality 4.0, and successful sustainable development of companies. Additionally, he lectures at University of Minho. The research work is being carried out at IEM research line (ALGORITMI research centre). He is a co-author in circa 90 papers (journals, conference proceedings, book chapters) some of them recognized and awarded both in Portugal and abroad. His research interests encompass digital transition of management systems, Quality 4.0/5.0 and successful sustainable development of companies.

Paulo Sampaio graduated in Industrial Engineering and Management in 2002 and completed his PhD in Industrial Engineering in 2008 at the University of Minho. He has been lecturing courses in the fields of Quality and Organizational Excellence, whereas his research activities are developed under the Industrial Engineering and Management Research Line of the ALGORITMI Research Centre.
Always privileging research and development for industrial applications, he has been involved in several R&D projects supported by Portuguese Institutions and under European funding programs. He has co-authored or authored

more than 200 publications, 160 of them ISI/Scopus indexed papers and is the Coordinator of the Research Group on Quality and Organizational Excellence at the University of Minho.
Paulo participates as a Keynote Speaker in Quality and Organizational Excellence international conferences, and he is the author of several publications in the Quality field. He coordinates several research projects on Quality and also supervises several researchers.
In 2006, 2008 and 2009, he was distinguished with the award of the Best Paper Presented in the Student Technical Paper Competition during the ASQ World Conference on Quality and Improvement. In 2008, his PhD Thesis was distinguished by the Portuguese Association for Quality as the best thesis developed in Quality. In 2011, he was distinguished with the award of the best presentation at the European Organization of Quality Congress. In 2011 and 2016, Paulo was nominated as one of the Quality Progress "New Voices of Quality" (ASQ) and in 2012 he was awarded the Feigenbaum Medal (ASQ). He has been an Academician of the International Academy for Quality since 2014.

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