Quantum-inspired computing technology in operations and logistics management

Miguel Núñez-Merino
Department of Business Organization, Marketing and Sociology, University of Jaén, Jaén, Spain and
CoE Data Intelligence, Fujitsu, Pozuelo de Alarcón, Spain
Juan Manuel Maqueira-Marín and José Moyano-Fuentes
Department of Business Organization, Marketing and Sociology, University of Jaén, Jaén, Spain, and
Carlos Alberto Castaño-Moraga
CoE Data Intelligence, Fujitsu, Pozuelo de Alarcón, Spain

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Abstract

Purpose – The purpose of this paper is to explore and disseminate knowledge about quantum-inspired computing technology's potential to solve complex challenges faced by the operational agility capability in Industry 4.0 manufacturing and logistics operations.

Design/methodology/approach – A multi-case study approach is used to determine the impact of quantum-inspired computing technology in manufacturing and logistics processes from the supplier perspective. A literature review provides the basis for a framework to identify a set of flexibility and agility operational capabilities enabled by Industry 4.0 Information and Digital Technologies. The use cases are analyzed in depth, first individually and then jointly.

Findings – Study results suggest that quantum-inspired computing technology has the potential to harness and boost companies' operational flexibility to enhance operational agility in manufacturing and logistics operations management, particularly in the Industry 4.0 context. An exploratory model is proposed to explain the relationships between quantum-inspired computing technology and the deployment of operational agility capabilities.

Originality/value – This is study explores the use of quantum-inspired computing technology in Industry 4.0 operations management and contributes to understanding its potential to enable operational agility capability in manufacturing and logistics operations.

Keywords Quantum computing, Logistics, Manufacturing, Flexibility, Agility, Case study, Industry 4.0, Operational capability

Paper type Research paper

1. Introduction

The development of Industry 4.0 (I4.0) has been driven by rapid technological advances (Choi *et al.*, 2022). Some very emerging technologies such as artificial intelligence, blockchain, 5G/6G

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technologies and quantum computing (Hofmann *et al.*, 2019; Xu *et al.*, 2021) are impacting I4.0 base technologies such as the internet of Things (IoT), cloud computing and big data (Frank *et al.*, 2019). Organizations are interested in using these new technologies, as they could improve their operational capabilities at the organizational and supply chain levels (Doetzer and Pflaum, 2021; Núñez-Merino *et al.*, 2022). Although operational flexibility and agility are key I4.0 capabilities, many organizations find their development challenging (Dalenogare *et al.*, 2018; Frank *et al.*, 2019). These operational capabilities are interrelated, with flexibility being a component of, or an antecedent to agility (Abdelilah *et al.*, 2018; Swafford *et al.*, 2008). Potentially, some emerging technologies can significantly improve the operational flexibility and agility levels achieved to date (Núñez-Merino *et al.*, 2020; Oliveira-Dias *et al.*, 2022b).

Fast and flexible decision-making and process optimization are essential to guarantee optimal resource allocation and efficient Operations Management (OM). OM efficiency implies identifying and eliminating wastage, which can increase flexibility and, therefore, boost operational agility (Enrique *et al.*, 2022; Núñez-Merino *et al.*, 2020; Oliveira-Dias *et al.*, 2022a, b and c). Even more rapid and flexible decision-making is needed in manufacturing and logistics, where complexity and uncertainty need to be managed in real time. As these issues can be addressed with mathematical models and suitable technology (Olhager *et al.*, 2015), they can also be tackled through advanced optimization techniques (Gupta *et al.*, 2022). However, many combinatorial optimization problems are complex and solutions are time-consuming. Conventional computers can be used but their solutions are often suboptimal (Gyongyosi and Imre, 2019). Therefore, quantum computing could play a critical role in decision-making and process optimization in OM (Gupta *et al.*, 2022; Sarkis *et al.*, 2021).

Quantum computing offers a vast information processing capacity that eclipses conventional computers (Arute *et al.*, 2019) but its state of development has limited its widespread practical application so far. However, an innovative solution called Quantum-inspired computing technology (QiC), inspired by the key features of quantum computing, is now capable of solving combinatorial optimization problems with the required speed, accuracy and transparency (Aramon *et al.*, 2019; Denkena *et al.*, 2021). It is largely unknown by academics and managers that some large organizations are already working in partnership with a QiC supplier to explore the technology's ability to provide real-time information to support decision-making in OM to optimize complex processes such as manufacturing planning, optimal routing of vehicle fleets, inventory management and large-scale supply chain planning.

Mohseni *et al.* (2017, p. 172) state that imminent advances in quantum technologies must be capitalized on, which requires that "the discipline broadens its focus and that scientists work more closely with entrepreneurs" on real applications. So, given QiC's potential to enable organizations to solve very complex challenges and impact decision-making, process optimization and the identification and elimination of inefficiencies, it is interesting to investigate its possible effects on operational flexibility and agility and the subsequent outcomes. Also, as the literature shows (Maqueira-Marín *et al.*, 2017), success cases and "killer" applications are factors that can decisively influence the adoption of very emerging technologies. Adoption is mainly driven by technology suppliers whose influence on early adopters is fundamental, as they provide knowledge on technologies and their potential (Maqueira-Marín *et al.*, 2017). Therefore, a literature gap exists, as there is a widespread lack of knowledge on QiC's potential for application in the OM field.

This exploratory multi-case research study informs academia and industry about the potential effects of a very emerging technology, QiC, on operational flexibility and its consequent ability to boost operational agility. Our perspective is mainly based on data from the tech supplier, success cases and killer applications of QiC in OM, which are the determinants of very emerging technology adoption (Maqueira-Marín *et al.*, 2017). We intend to respond to the following research question: What effect does QiC have on the development of operational flexibility and agility capabilities in the manufacturing and logistics areas?

The paper is organized as follows: following this introduction, we present the theoretical framework, with emphasis on the most relevant concepts referred to in this research. We then propose a literature review-based framework that identifies a set of I4.0 capabilities enabled by Information and Digital Technology (IDT) that boost organizational flexibility and agility. Next, we describe the methodology and set out the results in detail. This is followed by a section with research implications and suggestions for future research directions. The final section offers the main conclusions.

2. Literature review and theoretical background

2.1 Flexibility and agility as operational capabilities in the OM area

A firm's competitive success depends on its ability to develop operational capabilities that consistently provide high value to the customer (Sansone *et al.*, 2017). Operational capabilities have been defined as the specific set of abilities, processes and routines that a firm executes in its OM system and regularly uses to reconfigure its operating resources for problem-solving (Roscoe *et al.*, 2019; Wu *et al.*, 2010). Operational capabilities can be tangible (physical resources, processes, practices) or intangible (accumulated know-how, skills, expertise) (Roscoe *et al.*, 2019; Saunila *et al.*, 2020). These capabilities have long been studied from the perspective of their outcomes (performance), including cost, quality, delivery, speed, agility and flexibility (Tan *et al.*, 2004; Wu *et al.*, 2012).

The OM literature has defined flexibility and agility as capabilities, with the terms frequently used interchangeably and with similar meanings (Abdelilah *et al.*, 2018; Giachetti *et al.*, 2003). However, there is also a broad consensus that flexibility and agility are two different elements that enable a firm to obtain competitive advantages by responding to environmental changes effectively (flexibility) and rapidly (agility) (Abdelilah *et al.*, 2018). Flexibility has been defined as the capability to modify a system's operations in response to medium-term changes in the environment (Gupta and Goyal, 1989; Upton, 1994), while agility has been used to refer to an organization's capability to rapidly respond to these changes (Sharifi and Zhang, 1999).

The literature shows that both flexibility and agility are the result of synergies generated by different capabilities (Giachetti *et al.*, 2003; Pérez-Pérez *et al.*, 2016) and that the two concepts are interrelated, with flexibility being the engine that drives agility. So, flexibility is the key to agility, and agility is achieved by exploiting synergies between different forms of flexibility in a firm (Abdelilah *et al.*, 2018; Swafford *et al.*, 2008). Some authors state the existence of first- or higher-order capabilities and second- or lower-order capabilities (Schilke, 2014); a firm develops lower-order capabilities from a set of more specific abilities and processes, which are the higher-order capabilities (Rogers *et al.*, 2011; Zhang *et al.*, 2003). The present exploratory research considers flexibility and agility to be interrelated higher-order operational capabilities and that their development and improvement, therefore, depend on other, lower-order capabilities (Rogers *et al.*, 2011).

2.2 Impact of IDT of I4.0 on flexibility and agility in OM

IDT of I4.0 comprises a wide range of mature and emerging technologies that are jointly and intensively applied to industry to achieve operational efficacy and efficiency (Frank *et al.*, 2019; Núñez-Merino *et al.*, 2020). Advances in IDT of I4.0 have played a key role in information sharing through intra- and inter-organizational cooperation and communication, which improves an organization's ability to respond to uncertainty (Núñez-Merino *et al.*, 2020; Sambamurthy *et al.*, 2003). However, the literature does not offer consistent results; while some studies claim that these technologies act as a mechanism that enables flexibility and agility capabilities (Oliveira-Dias *et al.*, 2022a, b and c; Sambamurthy *et al.*, 2003), others find that they have a negative impact (Lambert and Peppard, 1993). The controversy around the effect that technologies have on operational flexibility and agility can be justified by the fact that not every IDT of I4.0 has the same impact on operational flexibility and/or agility (Dubey *et al.*, 2019; Oliveira-Dias *et al.*, 2022a, b and c; Swafford *et al.*, 2008).

Other authors state that IDT enables process flexibility and that it is the leveraging of lower-order flexibility capabilities that leads to agility (Dubey *et al.*, 2019). Others claim that there is a domino effect in the integration of information technologies, flexibility and agility (Swafford *et al.*, 2008). This suggests that firms should first invest in technology as an information integration tool to achieve flexible processes, and then exploit the latter to achieve agility (Swafford *et al.*, 2008).

2.3 QiC and flexibility and agility in the OM area

Quantum computing is still at a very early stage of development and many more hurdles will have to be overcome for it to become accessible to companies (Mohseni *et al.*, 2017). However, in 2017, Fujitsu, a global corporation in the Information and Communication Technology sector, took a giant leap forward in developing QiC with the creation of an innovative product called Digital Annealer (DA). DA is the first computing architecture in the world inspired by quantum computing and is capable of carrying out parallel optimization calculations with a speed and an accuracy that are impossible with conventional computers (Aramon *et al.*, 2019; Denkena *et al.*, 2021).

Lately, great interest has been shown in the research and development of QiC algorithms to solve optimization problems in the OM area as they could potentially increase organizational agility and flexibility (Du *et al.*, 2022; Fiasché *et al.*, 2018; Guo *et al.*, 2008; Zhang and Li, 2012). Multiple studies have recently been published in the Physics and Computer Science research area on the development of, and/or experimentation with, optimization algorithms inspired by quantum computing. These experiments use algorithms to solve production resource allocation issues (Du *et al.*, 2022), production scheduling tasks (Fiasché *et al.*, 2018), inventory management (Ruidas *et al.*, 2021) and carbon emissions in logistics distribution (Ning *et al.*, 2021), among others. However, the lack of any specific studies in the OM area limits the dissemination of extant knowledge on this technology's potential effect on organizations' operational capabilities.

3. Framework of operational capabilities that enable flexibility and agility in OM

We propose a framework based on the existing literature on operational capabilities and the impact of IDT of I4.0 on flexibility and agility which considers flexibility and agility as first- or higher-order operational capabilities developed from second- or lower-order operational capabilities (Figure 1). Figure 1 is in tabular form with corresponding references given in Table A1 (included in the supplementary material document). Our vision focuses on two key OM processes, manufacturing and logistics and on how lower-order capabilities contribute to increasing operational flexibility and agility in these. The flexibility and agility levels needed to address changing customer requirements cannot be provided by a single department or function but require the involvement of some of the firm's capabilities as a whole (Yusuf *et al.*, 1999). Therefore, as QiC is an emerging technology and companies usually develop an internal focus before involving external partners (Hsu *et al.*, 2009), we determined to approach these capabilities from an internal perspective. We have also addressed capabilities that enable flexibility and agility in transversal activities, including some in the areas of logistics and production processes. Note that although the capabilities or measures in Figure 1 could resemble performance metrics, they differ conceptually; for example, agility represents the speed with which these results can be changed and not the extent to which they are achieved (performance).

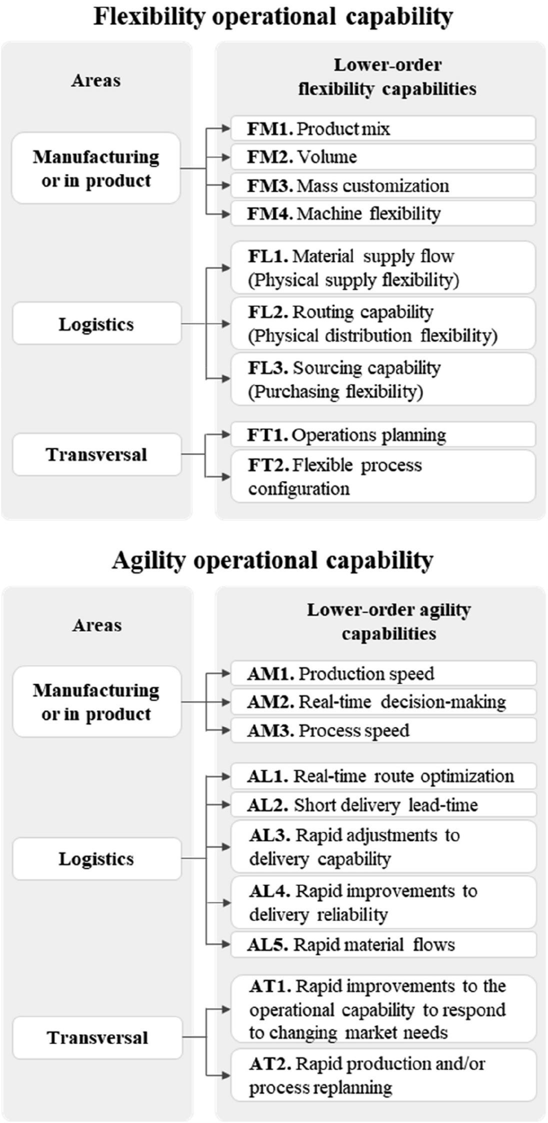

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Figure 1.
Lower-order flexibility and agility capabilities in the manufacturing, logistics, and transversal areas

3.1 Operational flexibility

The lower-order operational capabilities that enable flexibility as a higher-order operational capability include activities in the manufacturing and logistics areas and other activities in the value chain (Abdelilah *et al.*, 2018). In the manufacturing area, these include: (1) product mix flexibility, that is the organization's capability to economically and effectively produce different product combinations given its capacity (Ghobakhloo and Azar, 2018; Sethi and Sethi, 1990); (2) volume flexibility, that is the organization's capability to operate with different lot sizes and/or production levels (Ghobakhloo and Azar, 2018; Sethi and Sethi, 1990);

(3) mass customization, that is a system's capability to manufacture customized products at a low unit cost (Katayama and Bennett, 1999; Zhou *et al.*, 2022) and (4) machine flexibility, that is the equipment's capability to economically and effectively execute a range of operations (Gupta, 1993; Zhang *et al.*, 2003); the greater a machine's flexibility, the higher the levels of volume flexibility and product mix flexibility (Abdelilah *et al.*, 2018; Gupta, 1993).

As a higher-order operational capability, the flexibility of an organization's logistics processes is generated by a variety of lower-order operational capabilities in several key process activities (purchasing, supply, warehouse management and distribution): (1) physical supply flexibility implies operational capabilities in material supply flow. Materials can be handled in a continuous flow with reduced or zero waiting times, thus enabling the production and delivery of high-quality added-value products (Custodio and Machado, 2020; Dolgui *et al.*, 2019); (2) physical distribution flexibility depends on the routing capability, which involves various transportation planning and management activities, and, specifically, the capability to efficiently change distribution processes to adapt to customer requirements (Abdelilah *et al.*, 2018; Sethi and Sethi, 1990) and (3) purchasing flexibility and sourcing capability, which generate the capability to make all the materials and supplies needed to respond to customer demand available through collaborative relationships with suppliers (Custodio and Machado, 2020; Sethi and Sethi, 1990). The operational capabilities that enable flexibility as a higher-order operational capability in other value chain activities are related to lower-order operational capabilities: (1) operations planning, and (2) flexible process configuration (Abdelilah *et al.*, 2018; Lee *et al.*, 2020).

3.2 Operational agility

The various capabilities that enable agility (higher-order operational capability) include activities in manufacturing, logistics and the value chain. Operations planning and production capabilities for rapid adaptation to market requirements have been identified in the manufacturing area, including: (1) production speed, which reduces manufacturing times (lead time) (Jeong *et al.*, 2006; Sharifi and Zhang, 1999); (2) real-time decision-making, which enables real-time resource allocation, among other things (Gu *et al.*, 2015; Jeong *et al.*, 2006) and (3) process speed, which enables continuous workflows and a reduction in downtime (Lee *et al.*, 2020; Lei *et al.*, 2017).

An organization's logistics process agility requires several lower-order operational capabilities such as: (1) real-time route optimization (Cooper, 2021; Martins *et al.*, 2021); (2) short delivery lead-time (Gu *et al.*, 2015; Lee *et al.*, 2020); (3) rapid adjustments to delivery capability (Gu *et al.*, 2015; Katayama and Bennett, 1999); (4) rapid improvements to delivery reliability (Sharifi and Zhang, 1999; Swafford *et al.*, 2008) and (5) rapid material flows, with fewer physical material movements, among others (Chen *et al.*, 2008; Lee *et al.*, 2020). The capabilities that enable agility in transversal activities include: (1) rapid improvements to the operational capability to respond to changing market needs; (2) rapid production and/or process replanning in the operations area (Fiasché *et al.*, 2018; Liu *et al.*, 2017).

4. Methodology

This research explores QiC's effect on operational flexibility, its ability to boost operational agility and its effect on organizations' manufacturing and logistics processes. Due to the novelty of QiC implementation and the fundamental nature of exploratory research, we adopted a multi-case study approach with the analysis of manufacturing and logistics data collected from firms that have experimented with QiC technologies under the guidance of the tech supply corporation. This study is exclusively based on data provided by the tech supplier, which introduces bias as the customer perspective is not included. The methodology was, therefore, designed to minimize the mentioned bias and improve the accuracy of the analyzed data.

The main strength of the case study research technique is that phenomena are studied in their natural environment. This technique is also useful for constructing theories based on deep-field analysis when researchers need to understand how a specific phenomenon occurs (Yin, 1994a). The case study approach is widely recognized in OM and emerging technology research (Helo and Hao, 2021). The Voss *et al.* (2002) guidelines were followed, the main steps of which are discussed further in the text.

4.1 Research design

To respond to the RQ, the research was designed around the framework of capabilities that enable operational flexibility and agility (see Figure 1 and Section 3). The key aspect of the research design was the consideration of the elements involved in optimization: the objective function and the constraints. These are fundamental for defining the problem and guiding the process to find the optimal solution. The problem's constraints are defined by the organization's lower-order flexibility capabilities, whereas the objective function is linked to lower-order agility capabilities. The firm workgroup's deep understanding of the agility issues that required improvement was crucial in every case and enabled the complexities and constraints of the system to be included in the problem's formulation. The tech supplier work team's collaborative focus converted these requirements into a mathematical formulation of the optimization problem (objective function and constraints), thus providing a synergistic vision of the customer's problem.

The objective function is a mathematical expression that describes the main goal of the optimization problem. For example, in the manufacturing context, the aim could be to minimize the total time required to complete all the manufacturing jobs or to maximize the machine utilization rate. In the logistics context, the aim could be to minimize the total time needed to deliver all the shipments to their final destinations or to minimize the total distance covered. These aspects are linked to lower-order agility capabilities, including production speed and reduced delivery lead time, for example.

Constraints are the conditions or restrictions that have to be taken into account in a valid solution to the optimization problem. They could involve the availability of resources, physical constraints or any other type of limitation that is relevant to the problem in question. In general, the constraints limit the set of possible solutions to a set of feasible solutions. They are directly related to an organization's lower-order flexibility capabilities to adapt to environmental changes with available resources, for example, volume flexibility and machine flexibility. Table A2 (included in the supplementary material document) sets out and interrelates the problem constraints and the pre-existing lower-order flexibility capabilities in the analyzed cases along with the objective function lower-order agility capabilities obtained by leveraging the flexibility capabilities generated by QiC use.

4.2 Research sampling

The multi-case approach increased external validity and reduced bias from potential observers (Voss *et al.*, 2002). Due to limited case availability, an opportunity sample of cases of QiC use in OM was selected with the tech supplier indicating the most highly developed and relevant examples (Maqueira-Marín *et al.*, 2017). The analyzed cases were selected for their availability and for their relevance in responding to our specific research question and addressing the key manufacturing and logistics processes. This case study selection strategy is justified by the novelty and emergence of this interdisciplinary research area, where case availability is extremely restricted but highly valuable for generating knowledge at the intersection between quantum computing and OM.

We sought an adequate number of case studies that addressed a wide range of processes and issues in the OM field; as is well-known, the higher the number of cases, the more robust the results and the more solid the basis for theory building (Yin, 1994a) and identifying new focuses in OM. Eight organizations that have implemented QiC were selected. All are large multinational corporations with substantial business volumes that invest considerable resources in research and innovation. Table 1 gives further details of the analyzed organizations.

4.3 Data collection

The tech supplier provided access to data. Data sources were identified from the primary information generated during the sales process and project development. These included documentation and data on all aspects of the project and the development of the optimization model generated by the personnel of both the tech supplier and the organization experimenting with QiC technology. This focus enabled us to implicitly include the customer perspective in this study neutrally and objectively via the formulation of the optimization problem. As argued above, the elements of the optimization model are directly related to the organization's lower-order operational flexibility and agility capabilities. Using the optimization problem as the main information source guarantees a neutral and objective focus for data analysis and helps to minimize any bias that could be caused by exclusively relying on information provided by the tech supplier.

A wide range of tech supplier personnel was selected for unstructured interviews. As the use of multiple data sources provides greater data reliability and further supports the constructs and propositions (Yin, 1994b), after an initial analysis of the information provided by the tech corporation, interviews were held with senior managers, middle managers, quantum engineers and sales engineers throughout the multi-case study's entire lifecycle. This enabled any questions that arose during case analysis to be resolved, while also offering a better understanding of the implications of QiC at both the technical and business levels, and greater knowledge of the needs, challenges and context of the organizations in which this technological solution was implemented. Six workers from the tech supplier were interviewed. Table 2 gives further details about the interviewees.

4.4 Data analysis

We analyzed several success cases where the technology has been applied to solve complex manufacturing and logistics sector issues. First, each of the use cases was analyzed in-depth

Case	Sector	Size	Market	Countries in which operates
#1: Job shop scheduling	Technology and electronics manufacturing	Large company	Multinational	Asia
#2: Operations planning in crude oil blending	Energy and petrochemical	Large company	Multinational	Europe
#3: Robot movement optimization in manufacturing	Automotive	Large company	Multinational	Europe
#4: Picking optimization for factory parts	Technology and electronics manufacturing	Large company	Multinational	Asia
#5: Distribution logistics	Automotive	Large company	Multinational	Europe
#6: Pharmaceutical distribution logistics	Pharmaceutical	Large company	Multinational	Europe
#7: Port logistics	Port	Large company	Multinational	Europe
#8: Last-mile delivery	Courier and Parcel Delivery	Large company	Multinational	Europe

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Table 1.
Complementary information on analyzed organizations

Table 2. Complementary information on interviewees

Profile	Role/useful functions for research	Time in the company/Total experience (in years)
Senior manager, technical director	Supervision and management of technical development	10/15
Project Manager	Definition of business problem requirements in collaboration with customers	7/12
Project Manager	Definition of business problem requirements in collaboration with customers	5/18
Quantum engineer	Development of technical solution to problem	3/4
Quantum engineer	Development of technical solution to problem	1/3
Sales engineer	Helping customers understand how a technological solution can address customers' needs and challenges	6/14

Source(s): Created by authors

(within-case analysis) to understand the phenomenon and then all the cases were analyzed together (cross-case analysis) to meet the general research purpose (Yin, 1994a). Eisenhardt (1989) recommends within-case analysis for preliminary theory generation, and cross-case analysis for researchers to see beyond their initial impressions and examine evidence through multiple lenses. A cross-case analysis is considered appropriate and more robust as it enables a comparison of similarities and differences between cases (Eisenhardt, 1989).

5. Results

5.1 Within-case analysis

This section describes each of the analyzed manufacturing and logistics case studies (within-case analysis) using information provided by the tech supplier. This information was generated throughout the project in interactions between the tech supplier and the firms involved in the case studies. The lower-order agility capabilities identified in each case were based on the optimization problem's objective function. These capabilities are closely linked to the operational issues that the firm was seeking to improve with QiC. The lower-order flexibility capabilities were also identified based on the restrictions included in the formulation of the optimization problem that the firm defined. This analysis supports the hypothesis that QiC facilitates the development of operational agility by driving the efficient exploitation of existing flexibility capabilities. The interrelations in each of the analyzed study cases are presented in Table A2 (included in the supplementary material document). The case studies are described further in the text.

5.1.1 Manufacturing case studies. Some of the main automobile makers in the world and other large manufacturers have developed projects to radically improve agility capabilities to respond more efficiently in areas such as production planning and the optimization of robot positioning in manufacturing scenarios. Three success cases are presented further in the text in which DA has been applied to resolve issues in these areas.

5.1.1.1 Case 1: job shop scheduling. The first success case is a corporation that manufactures a wide range of products from mechatronics to electronics in general, modular end products such as smart phones, devices that incorporate IoT and computer monitors. Manufacturing a large number of products in the same facility requires a flexible Job Shop process that allows the manufacture of different product lots (see Figure 1; FM1, FM2, FM3, FM4). In such an environment, production planning is complex due to the large number of products manufactured. In this case, the corporation has exploited the capabilities of DA to optimize production planning. Manufacturing jobs require multiple sequential operations executed by different machines, with each product type requiring a different duration and order of machine use. Also, some of the parts are used in different products in the manufacture of modular products (group technology). Determining the right job sequence in manufacturing and production replanning can be a very complex task if production volumes are also different for each product and production orders can be changed at any time due to sudden high-priority orders or a lack of materials.

To minimize total manufacturing time in general and to enable fast replanning when there are changes in production priorities, the corporation in this use case exploited the power of DA to optimize machine use in production orders (FT1). This allowed very rapid production replanning (AM2, AT2) and made it possible to respond to changes in demand with higher levels of operational agility (AT1). The DA-optimized planning system also improved production speed (AM1) with a rise in the machine utilization rate. This enabled a greater number of products to be manufactured by maximizing the exploitation of the system's operational flexibility capabilities (FM2) without the need for any investments to be made in expanding the facilities or purchasing new machinery. Production planning optimization and flexible process configuration (FT2) eliminated bottlenecks in production lines (AM3), which reduced manufacturing lead times (AM3) and helped maintain low inventory levels, meet delivery times (AL4) and even speed up the latter and increase the percentage of fast deliveries (AL2, AL3). So, in conjunction with other technologies such as advanced manufacturing technologies, IoT and advanced robotics, DA, an emerging technology, enabled the automatization of different production lines (FL1, FL2) by providing the flexibility that the Job Shop process required and fast programming and reprogramming for a large number of different products.

5.1.1.2 Case 2: operations planning in crude oil blending. Success case 2 is a multinational energy and petrochemical corporation that refines oil and sells a variety of derivatives. This company has developed a Proof of Concept (PoC) to test the power of DA and has specifically applied it to optimize some of the planning processes for mixing crude oil (Crude Oil Blending, COB). The oil's quality properties (density, total acid number and sulfur content) determine its market value and also represent a refinery's greatest operational cost. COB is designed to blend input products to achieve an end product with the required quality. Flexible refineries are not limited to producing a narrow range of oils (FM1), so, optimizing the input product blend to achieve output products of different qualities enables a firm to increase its margins and remain competitive. COB planning aims to maximize the quality of output products. In this case, the petrochemical multinational tested DA's potential to optimize COB planning to identify, in the shortest time possible, the required combinations and proportions of oil inputs and which blending tanks to use, based on properties of the oil and the refinery's physical limitations.

The solution demonstrated DA's ability to maximize product quality, reduce the waste released into the air and bring down unloading times (AL5). DA exploited the system's operational flexibility to improve the firm's operational agility through faster operations planning (AM1, AM2, AM3), which allowed the configuration of the production processes to be adapted in real-time to the characteristics of the crude oil entering the refinery (FT1, FT2, AT2).

5.1.1.3 Case 3: robot movement optimization in manufacturing. The corporation in success case 3 is a global-scale German automotive original equipment manufacturer that has used DA to optimize robot movements in automobile manufacturing, specifically in the application of a waterproof seal. This is a paint shop operation that coats the car's underbody with a PVC sealant to prevent water from entering the vehicle when in motion. The challenge was to find the optimal non-conflicting movement paths of the robots that carry out this operation while minimizing the time taken.

DA synchronized and optimized the robots' movements (FM4) to waterproof 64 seams simultaneously and virtually in real time. This complex job was completed in a shorter time with 40% fewer robot movements. Overcoming this optimization challenge made the production line more efficient and enabled the manufacturer to produce more vehicles with the same resources (FM2), thus reducing manufacturing costs and giving the plant a competitive advantage over the competition. In addition, the manufacturer estimated a capital expenditure saving of over $60.2mn. So, thanks to this emerging technology, the OEM increased both its flexibility, as it was able to absorb greater demand (FM2) by using its robots more efficiently, and its agility, by completing the sealing operation more quickly than before (AM1, AM3).

5.1.2 Logistics case studies. Key operations for business success such as warehouse management, picking optimization for supplying parts to the production lines and distribution logistics management are fields in which DA's qualities have been demonstrated to add value. Five success cases are presented further in the text in which DA has been applied to solve various problems in logistics.

5.1.2.1 Case 4: factory parts picking optimization. Success case 4 is a corporation that designs, develops, manufactures and markets high-capacity smart storage systems, business servers for critical activities in business processes and supercomputers. Due to its great diversification to meet market needs, this corporation produces a wide range of low-volume products. One of the critical activities for assembly process efficiency is the transfer of the required parts from the store to the production lines. In this corporation, the procedure used to consist of operatives being given a list of the required parts with their descriptions and the shelf numbers where they were stored. Although locating the parts was a simple matter, the store's 1,000 square meter surface area and the over 3,000 references stored there used to cause mistakes and excess operative movements that made the collection process inefficient.

To improve process agility, it was decided to implement DA in one of the facilities to support the original pick ticket system. Using a list of required parts and their locations, DA finds the optimal combination of orders (AL4) and pick route to minimize picking times (FL2, AL2) while considering maximum capacity when collecting products (AL3). Store operatives were given a tablet showing the order in which to pick the parts and the optimal route (AL1, AL5). As a result, every month there was a 20% reduction in the distance covered. Parts were also relocated in the store based on their rotation and placed closer to the production line where they were most frequently required. This reduced the pick distance by almost 45% and significantly increased the corporation's efficiency.

5.1.2.2 Case 5: distribution logistics. The corporation in success case 5 supports automobile production with Just-In-Time distribution logistics. It supplies components to multiple vehicle assembly plants by purchasing the parts from hundreds of suppliers (FL3) and channeling operations through several intermediary warehouses, that is it develops Vendor Managed Inventory (VMI) functions. The combination of suppliers, warehouses and factories in conjunction with multimodal transportation (train, plane, ship and truck) generates an optimization problem with millions of potential alternative distribution routes (FL1, FT1).

DA was applied to optimize the corporation's business processes by calculating the optimal routes (AL1) to minimize distribution cost considering the quantity and available types of transportation (FL2), the total distance and in-warehouse package classification tasks to improve load efficiency (AL3), and a 2–5% cost reduction.

5.1.2.3 Case 6: Pharmaceutical distribution logistics. In pharmaceutical distribution logistics, having the means of transportation and the delivery capability to meet delivery times and frequencies is not sufficient on its own (FL2). The quantity and quality of purchased products also have to be guaranteed (FL3) and supplied (FL1), and the products must be kept in optimum condition. A minimum stock level that considers expiry dates must also be maintained to prevent any shortages (FL3). The corporation in success case 6 plays a fundamental role in pharmaceutical distribution logistics in a European country where it supplies medicines to some 10,000 pharmacies. It manages over half a million orders per day and has a network of some 30 warehouses.

Efficient and profitable pharmaceutical logistics are underpinned by the optimization of distribution processes (FT1). In this success case, DA was implemented with two objectives: (1) warehouse management with the optimization of required stock levels and reorder points

(AT1), and (2) optimization of deliveries from warehouses to pharmacies (AL1). DA implementation minimized the corporation's warehousing costs and guaranteed on-time delivery and frequency (AL2, AL3, AL4) while optimizing the delivery routes (AL1) reduced the required transportation fleet by 25% and delivery cost by 17%.

5.1.2.4 Case 7: port logistics. Success case 7 is one of the world's largest ports, which handles one of the greatest volumes of containers, covers an area of some 40 km^2, and has almost 75 km of loading bays receiving up to 20,000 trucks per day. In this case, DA technology and service capabilities have been demonstrated to reduce traffic jams, which optimizes logistics and reduces greenhouse gas emissions.

DA optimizes traffic throughput in the port area by using traffic light-based control infrastructure to manage circulation at intersections. Sensors placed on all the roads connecting with the intersections give an overview of the state of the traffic and the corresponding data are inputted into a digital twin that provides a real-time overview of the traffic flow. DA uses these data to simulate the current traffic flow and instantaneously calculates a vast number of possible traffic-light settings and their effects on the traffic flow. The goal is to achieve a constant traffic flow and to prevent trucks from having to frequently stop and start. Based on the optimal global solution, DA selects the best traffic light timings at each intersection at any given time but also considers multiple other factors that could change priorities. Thus, if a ship is being unloaded, the truck convoy that is forming can be quickly identified, prioritized and given a green light wherever it is in the port area (AL3, AL4).

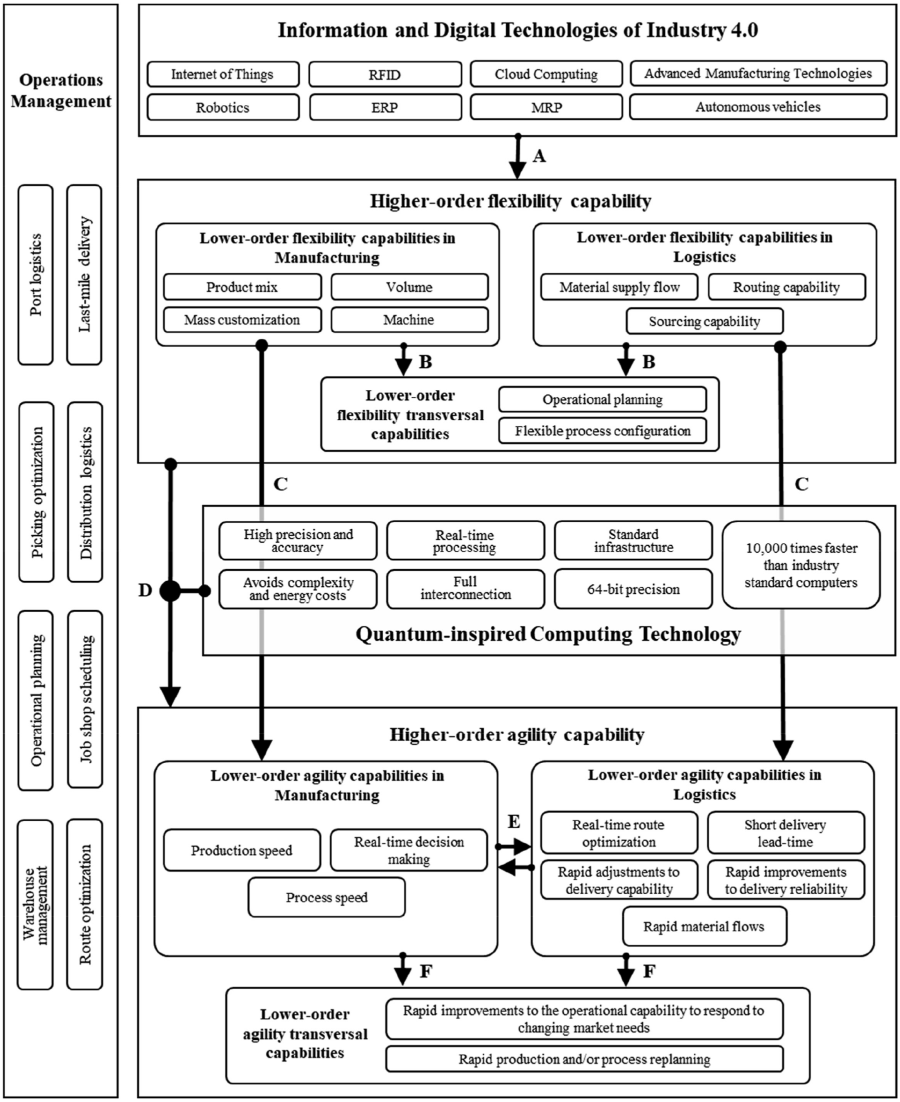
Cars also have to be factored in at peak times, when there is an increase in the stress level on port roads. So, if the volume of traffic at any given intersection is too high, the traffic lights switch from their normal weekly schedule to local control. This gives the direction of flow maximum priority and green lights a longer duration. Although this optimization could cause the traffic flow to revert to a lower speed at some localized points, road users reach their destinations more quickly on average. The nonstop search for optimization solutions also allows an immediate reaction to temporary incidents such as accidents.

In this case, DA implementation has sped up logistics flows by reducing traffic congestion in the port area. This has significantly minimized the time vessels and trucks remain in the area and reduced distribution logistics journey times (AL2) by as much as 15% in the case of trucks. DA has contributed to achieving a greater and faster flow of goods (AL5) and to making transportation more sustainable by reducing carbon emissions by up to 9%.

5.1.2.5 Case 8: last-mile delivery. Success case 8 is a European nationwide courier, parcel delivery and urgent mail last-mile delivery service. DA's PoC was limited to a specific area with some 40 offices to cover delivery destinations. The technology was implemented to optimize transportation scheduling for parcel delivery (FT1) and identified the optimal delivery routes (AL1) in terms of time and distance while considering constraints such as arrival times, vehicle loads (weight, volume) (AL3) and carrier uptime. As a result, the firm increased its process configuration flexibility (FT2). The number of vehicles required (AL3) was reduced by approximately 10%, vehicle load capacity (AL3) was improved by 12% and transportation costs were reduced by approximately 8%. Delivery times (AL2) and delivery reliability (AL4) were also improved. DA also reduced the amount of fuel required, which, in turn, reduced carbon emissions and vehicle maintenance costs.

5.2 Cross-case analysis

Cross-case analysis results are based on the within-case analysis results. In this section, we aim to generalize the value proposition and impact of QiC generated by its more efficient exploitation of existing flexibility and consequent boost to operational agility. To synthesize the most important findings of this exploratory research, we propose an explanatory model (Figure 2) that reflects, *inter alia*, the direct impact and implications of some specific IDT of



Source(s): Created by authors

Figure 2.
Explanatory model

I4.0 for operational flexibility capabilities, and QiC's effect on the exploitation of these operational flexibility capabilities, the elimination of inefficiencies and, ultimately, the improvement in operational agility.

Some lower-order operational flexibility capabilities must already be in place for QiC adoption to improve processes' operational agility capabilities. In the analyzed use cases, these capabilities were enabled by other I4.0 technologies such as robotics, advanced manufacturing technologies, RFID, IoT and business information systems (ERP, MRP, cloud, etc.) (Figure 2, relationship A). This conclusion is in line with extant knowledge in the literature, which states that an organization must first be flexible for it to become agile (Gligor *et al.*, 2013). However, our set of analyzed cases and the impact of DA on these processes indicate that flexibility does not translate into agility automatically, but that the flexibility capabilities must be exploited. QiC (relationship D) can do this.

Relationship C in Figure 2 indicates that lower-order agility capabilities can be improved by QiC's efficient exploitation of lower-order flexibility capabilities. This can be observed in some manufacturing cases: 1 Job Shop Scheduling and 3 Robot positioning optimization in manufacturing. In these cases, machine constraints (linked to machine flexibility) limit the system's operational agility. So, optimizing QiC to exploit this lower-order flexibility operational capability reduces inefficiencies and maximizes the machine utilization rate, thus generating higher production speed (lower-order agility capability). The case of agility in logistics processes is similar. For example, the resources required for transportation (purchasing flexibility and routing capability) are essential for improving an organization's lead time, delivery capability and delivery reliability (operational agility capabilities). In other words, the organization needs to have the required quantity and variety of available means of transportation (terrestrial, air and/or maritime) and specialized human resources (see: 4 Factory parts picking optimization; 5 Distribution logistics; 6 Pharmaceutical distribution logistics; 8 Last-mile delivery). It also needs to have the products or materials which it is to supply, which is linked to purchasing flexibility (see: 1 Job Shop scheduling; 4 Factory parts picking optimization; 5 Distribution logistics; 6 Pharmaceutical distribution logistics). In these cases, QiC identifies the best combination of all the available options for fast and efficient decision-making and the elimination of inefficiencies. This, in turn, allows the exploitation of the operational flexibility capabilities in the system and decisions to be made on how to use these limited resources to optimize the processes and find the best option, whether in terms of cost, time or distance covered, etc., which is directly linked to a greater operational agility capability.

All the constraints (manufacturing priorities, limited raw materials and specialized resources, among others) modeled in the optimization problem developed to solve challenges with QiC are associated with operational flexibility capabilities. These constraints, therefore, determine any potential improvement in operational agility as they restrict transversal lower-order flexibility capabilities such as operations planning and flexible process configuration (relationship B).

Another example is material flows. Some of the organizations in the manufacturing cases used IoT devices and platforms (see: 1 Job Shop scheduling) to automatize the handling of semi-finished products between the machines in the manufacturing sequence. QiC was used to optimize this process by providing logistics processes in particular, and the manufacturing organization in general, with greater operational agility. This implies that, in the analyzed case studies, the lower-order flexibility capabilities in manufacturing and logistics are independent and do not influence each other, which is not the case with agility, as the lower-order agility capabilities in manufacturing are interrelated and feed each other (relationship E). This indicates that lower-order agility capabilities in manufacturing such as process or production speed, for example, require some specific lower-order agility capabilities in logistics, such as rapid material flows. The opposite is also true; for an organization to be agile in logistics, that is, to have the capability to reduce delivery lead time or the speed to improve delivery reliability, it should have some specific lower-order agility capabilities in manufacturing, such as production speed, process speed and real-time decision-making. So, more agility in logistics processes can provide more agility in manufacturing, and vice versa. This is what ultimately gives organizations the transversal lower-order agility capabilities that provide greater speed to respond to changing market needs and the ability to carry out rapid process and/or production rescheduling (relationship F).

Lastly, in specific cases such as: 5: Distribution logistics and 6: Pharmaceutical distribution logistics, the optimization problem was modeled in terms of costs. The costs associated with these QiC use cases were measured by the total time required or the total distance covered to fulfill the deliveries. These cases highlight that greater operational agility (the consequence of an improvement in lower-order agility capabilities such as a reduction in delivery times, among others) implies a reduction in the operating costs that come from fuel consumption, wear and tear, vehicle maintenance, etc. This has implications for sustainability due to the reduction in carbon emissions. Another specific problem can be found in: 2: Operations Planning in Crude Oil Blending. In this case, the need to maximize the quality index of the generated products was used, as this has implications for company profits. This could mean that QiC has the potential to exploit a system's flexibility to improve production quality agilely.

6. Implications and future research

6.1 Implications for theory and practice

QiC adoption is an emerging topic with deep implications for industry and society, in general, and OM, in particular. As far as the authors know, this is the first exploratory study to investigate QiC's potential for solving problems in the OM area and enabling organizations to develop capabilities that improve operational agility in manufacturing and logistics processes. The results of this study shed light on practical applications of QiC and provide empirical evidence of the benefits that it brings. It clearly shows that if an organization determines to improve the agility of its operations through QiC, it should first guarantee that its systems possess the required flexibility capabilities as, without them, it will be impossible to improve agility. Our exploratory research demonstrates the potential that QiC has to efficiently leverage a system's flexibility to improve operational agility. Thanks to its computing power and advanced quantum algorithms, a large number of variables and scenarios can be analyzed in real time, and this translates into faster and more precise decision-making that eliminates inefficiencies and better exploits the flexibility in the process, giving rise to greater agility. This greater agility allows better adaptation to market needs, which could result in an improvement in operating costs by reducing manufacturing or delivery times.

Whatever their size and the resources that they have at their disposal, organizations that wish to embark on the digital transformation route or have already done so require cooperation from other agents (Maqueira-Marín *et al.*, 2017). The need is even greater in the adoption of very emerging technologies, including QiC. Along with tech suppliers, studies that analyze success cases are determinants of emerging and disruptive technology adoption (Maqueira-Marín *et al.*, 2017). Our study demonstrates that quantum computing is a technology with great promise. Indeed, some pioneering large companies, motivated by new trends in operations designed to provide rapid customer response and the necessary flexibility to address customer requirements, are already making great strides in experiments thanks to the enormous potential of this technology. In interviews, some quantum engineers stated that organizations that had already implemented optimization algorithms had a solid basis for pushing on with QiC. In addition, experimentation with DA can enable organizations to obtain an advantage over their competitors and gain experience and know-how before quantum computers reach the market.

The fact that this study is exclusively based on information provided by the tech supplier introduces bias into the investigation and limits the implications. The lack of any direct information from the firms that have used the technology limits knowledge of the challenges, limitations and outcomes of the implementation process and prevents a full and objective view of its implementation. Further, the information given by the supplier does not include the firms' operational contexts or their specific organizational cultures, which makes it difficult to understand the factors that contribute to the success or failure of the implementation. It must also be acknowledged that the supplier is more focused on presenting the technology's virtues than its weak points. So, the tech supplier's perspective introduces a positive bias into our appraisal of the technology's implementation and ignores any issues or limitations that might come from its use. In short, the lack of any direct information from the firms that utilize the technology prevents objective verification of the supplier data.

6.2 Future research

As QiC is a nascent technology and knowledge in the area is only just emerging, many challenges still need to be addressed. The academic and business worlds must collaborate for the future development and application of this technology. Some of the research goals and issues that researchers will have to address in the future can be synthesized in the following research topics (RT).

RT1. Research into convergence between QiC and management strategies designed to reduce sources of variability such as Lean Management, Just-in-Time, Six Sigma, etc. and how it might influence flexibility, agility, cost reduction and quality.

RT2. Analysis of areas of QiC application in OM and the associated challenges that can be solved with existing quantum-based optimization algorithms. Investigation of potential future application cases can help to identify new algorithms that must be formulated. The potential of quantum-inspired computing technologies is enormous and their use is in its infancy. Expert reflection exercises in the technology-OM area would identify new areas where this technology can be deployed for organizations to develop agility capabilities.

RT3. Drivers and barriers to organizations implementing QiC. As is the case with any new technology that comes to market, identifying and disseminating knowledge of the factors that enable or hamper its adoption will allow senior managers to address these and enable a safer and more controlled adoption of the technology.

RT4. Analysis of potential and possible applications of QiC adoption in conjunction with 5G technology for the creation of digital twins to support smart operations, smart manufacturing and collaborative manufacturing. In conjunction with digital twins, 5G technology enables end-to-end real-time connectivity and provides visibility in the OM area. Along with quantum computing, these technologies have the potential to generate new technological concepts of collaborative organization using the principles of open dynamic systems, self-organization, self-learning and self-adaptation. Implications for operations and performance could include greater flexibility, improvements to adaptability, agility and resilience, and greater exploitation of productivity, efficiency and/or sustainability, among others.

RT5. Needs and challenges to integrating QiC and its rollout as part of today's technological infrastructure in firms and their processes. The new emerging technologies that are coming to market have to be integrated with more mature technologies that firms already utilize in production. So, identifying the requirements and techniques for integrating QiC with other technologies will facilitate its adoption.

RT6. Management challenges in QiC adoption, and the human–machine relationship in the Quantum Computing-Industry 5.0 context. The advent of new emerging technologies will trigger great changes in industry. The role of people may be redefined, with some work positions disappearing and new positions associated with the development of these technologies emerging. Analyzing the changes in management and the way that individuals interact with these technologies will be an extremely interesting topic for future research.

7. Conclusions

Our findings contribute to the existing literature by shedding light on and complementing existing knowledge of the relationship between operational flexibility and agility, and specifically focus on how QiC enhances this connection. The analyzed success cases demonstrate that QiC adoption has enabled decision-making to be automatized and optimized in some of the main automobile manufacturers, other large manufacturing firms and the logistics sector. It does this by improving radically different capabilities that generate operational agility to respond to issues such as workshop scheduling, production planning and the optimization of robot movements in manufacturing. Other key business operation optimization success cases have been analyzed, such as warehouse management, the optimization of parts picking for production lines and distribution logistics management. Therefore, this study explores and supports QiC's ability to overcome very complex real-world challenges in the OM area by optimizing key processes and generating or boosting agility capabilities in organizations. In addition, this research proposes a literature-based theoretical-explanatory model and a case study analysis that shed light on the way that organizations improve agility in their operations via flexibility.

This research is not without its limitations. The implications of this work are based on case studies. However, this is exploratory research that contributes to and disseminates knowledge of how QiC impacts OM by leveraging flexibility to develop the agility capability. So, as QiC is a very emerging technology, the study's exploratory nature can be regarded as a minor limitation. However, there is a major limitation to this research: the bias caused by it being based solely on information provided by the tech supplier. This prevents a full understanding of the limitations and outcomes of implementing the technology. Another relevant limitation of this research is that it only presents the positive side of the technology. Notwithstanding, it is important to state that this research is exploratory and that its purpose is to demonstrate the potential of a very emerging technology, QiC, for OM, which would enable its dissemination and adoption by other companies. Lastly, the studied use cases may represent only a fraction of the range of issues that QiC has been able to solve, as our study only analyzes the impact of DA and other suppliers of this type of technology also exist in the market.

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Supplementary materials

Flexibility operational capability		
Areas	Lower-order flexibility capabilities	References
Manufacturing or in product	FM1. Product mix	Abdelilah *et al.* (2018), Ghobakhloo and Azar (2018), Sethi and Sethi (1990), Swafford *et al.* (2008)
	FM2. Volume	Abdelilah *et al.* (2018), Devaraj *et al.* (2012), Katayama and Bennett (1999), Sethi and Sethi (1990), Zhang *et al.* (2003)
	FM3. Mass customization	Katayama and Bennett (1999), Zhou *et al.* (2022)
	FM4. Machine flexibility	Abdelilah *et al.* (2018), Gupta (1993), Sethi and Sethi (1990)
Logistics	FL1. Material supply flow (Physical supply flexibility)	Custodio and Machado (2020), Dolgui *et al.* (2019), Gu *et al.* (2015), Lee *et al.* (2020), Zhang *et al.* (2003)
	FL2. Routing capability (Physical distribution flexibility)	Abdelilah *et al.* (2018), Sethi and Sethi (1990), Swafford *et al.* (2008), Zhang *et al.* (2003)
	FL3. Sourcing capability (Purchasing flexibility)	Custodio and Machado (2020), Devaraj *et al.* (2012), Forslund *et al.* (2020), Sethi and Sethi (1990)
Transversal	FT1. Operations planning FT2. Flexible process configuration	Abdelilah *et al.* (2018), Chen *et al.* (2008), Fiasché *et al.* (2018), Gu *et al.* (2015), Jeong *et al.* (2006), Lee *et al.* (2020), Sethi and Sethi (1990)

Agility operational capability		
Areas	Lower-order agility capabilities	References
Manufacturing	AM1. Production speed	Chen *et al.* (2008), Gu *et al.* (2015), Jeong *et al.* (2006), Lei *et al.* (2017), Liu *et al.* (2017), Sharifi and Zhang (1999)
	AM2. Real-time decision-making	Gu *et al.* (2015), Jeong *et al.* (2006), Lee *et al.* (2020), Zhou *et al.* (2022)
	AM3. Process speed	Gu *et al.* (2015), Jeong *et al.* (2006), Lee *et al.* (2020), Lei *et al.* (2017), Liu *et al.* (2017), Zhang and Li (2012)
Logistics	AL1. Real-time route optimization	Cooper (2021), Liu (2019), Martins *et al.* (2021), Wang *et al.* (2012)
	AL2. Short delivery lead-time	Gu *et al.* (2015), Lee *et al.* (2020), Liu (2019), Martins *et al.* (2021), Swafford *et al.* (2008), Wang *et al.* (2012)
	AL3. Rapid adjustments to delivery capability	Gu *et al.* (2015), Katayama and Bennett (1999), Martins *et al.* (2021), Wang *et al.* (2012)
	AL4. Rapid improvements to delivery reliability	Martins *et al.* (2021), Sharifi and Zhang (1999), Swafford *et al.* (2008), Wang *et al.* (2012)
	AL5. Rapid material flows	Chen *et al.* (2008), Martins *et al.* (2021), Zhou *et al.* (2022)
Transversal	AT1. Rapid improvements to the operational capability to respond to changing market needs AT2. Rapid production and/or process replanning	Chen *et al.* (2008), Fiasché *et al.* (2018), Katayama and Bennett (1999), Liu *et al.* (2017), Swafford *et al.* (2008)

Table A1. Flexibility and agility capabilities in the manufacturing, logistics and transversal areas

Table A2.
Operational flexibility and agility capabilities linked to the optimization problem in the analyzed case studies

Case	Lower-level order flexibility capabilities	Constraints	Lower-level order agility capabilities	Objective function
#1: Job shop scheduling	*FM1*. Product mix *FM2*. Volume *FM3*. Mass customization *FM4*. Machine flexibility *FL1*. Material supply flow *FL2*. Routing capability *FL3*. Sourcing capability *FT1*. Operations planning *FT2*. Flexible process configuration	*Machine constraints:* each machine has a limited capacity and availability. Each machine has specific capabilities and can only carry out certain tasks *Physical limitations of manufacturing installations:* expanding or purchasing new machines is not an option *Precedence constraints:* some jobs must be completed before others can begin *Resource constraints:* limited availability of resources required by jobs, including machines, tools and personnel *No overtime:* scheduling must comply with normal work schedule and not involve overtime for personnel or machines *Delivery constraints:* delivery times must be met	*AM1*. Production speed *AM2*. Real-time decision-making *AM3*. Process speed *AT1*. Rapid improvements to the operational capability to respond to changing market needs *AT2*. Rapid production and/or process replanning	Minimize total manufacturing time
#2: Operations planning in crude oil blending	*FM1*. Product mix *FT1*. Operations planning *FT2*. Flexible process configuration	*Quality Standards:* blended crude oil products meet the required quality standards *Input Product Blend:* the blend of input products to achieve the desired qualities of the output products *Physical Limitations:* limitaciones en la capacidad de los tanques *Input Product Proportion:* the proportion of each input product and the tanks in which blending should be done to obtain an output product with the desired quality *Incoming Crude Oil Characteristics:* characteristics of the crude oil entering the refinery, including variations in properties and availability	*AM1*. Production speed *AM2*. Real-time decision-making *AM3*. Process speed *AL5*. Rapid material flows *AT2*. Rapid production and/or process replanning	Maximize quality index of generated products

(*continued*)

Table A2.

Case	Lower-level order flexibility capabilities	Constraints	Lower-level order agility capabilities	Objective function
#3: Robot movement optimization in manufacturing	*FM2*. Volume *FM4*. Machine flexibility	*Machine constraints:* each machine has a limited capacity and availability *Seam Coverage:* Each seam must be sealed exactly once, with no overlaps or omissions *Robot Movement Constraints:* Each robot has specific movement capabilities, including speed and range of motion. These constraints should be considered in the optimization algorithm to ensure that robots move efficiently without exceeding their limits *Material Constraints:* constraints related to the availability of PVC sealant material, its application rate and the need for refills or replacements during the operation *Safety Constraints:* Constraints related to maintaining a safe distance from other robots, human workers and fixed machinery *Quality Control:* ensure that the sealant is applied correctly and meets quality standards *Synchronization:* Coordination of the movements of multiple robots to avoid overlaps and collisions, optimize workflow and prevent bottlenecks in the paint shop operation	*AM1*. Production speed *AM3*. Process speed	Minimize total processing time Minimize total travel distance
#4: Factory parts picking optimizations	*FL1*. Material supply flow *FL2*. Routing capability *FT1*. Operations planning *FT2*. Flexible process configuration	*Capacity Constraint:* maximum capacity for the number of products that can be picked simultaneously *Resource Availability:* the availability of store operatives, picking equipment, and other resources to scheduling picking operations *Travel Time:* distance between different shelves and the time it takes for operatives to move between them *Batch Picking:* Consider whether it is more efficient to pick parts individually or in batches	*AL1*. Real-time route optimization *AL2*. Short delivery lead-time *AL3*. Rapid adjustments to delivery capability *AL4*. Rapid improvements to delivery reliability *AL5*. Rapid material flows	Minimization of travel time Minimize total picking distance

(*continued*)

Table A2.

Case	Lower-level order flexibility capabilities	Constraints	Lower-level order agility capabilities	Objective function
#5: Distribution logistics	*FL1*. Material supply flow *FL2*. Routing capability *FL3*. Sourcing capability *FT1*. Operations planning *FT2*. Flexible process configuration	*Supply-Demand Constraints:* the components supplied by suppliers meet the demand at each vehicle assembly plant *Capacity Constraints*: the transportation fleets (trains, planes, ships and trucks) have limited capacity, and the total quantity of components transported by each mode of transportation does not exceed its capacity *Distance Constraints:* Distancia máxima que se pueden transportar los componentes utilizando cada modo de transporte. Esto asegura que las rutas de transporte Sean factibles y no excedan las distancias prácticas *Intermediary Warehouse:* possibility that components are routed through intermediary warehouses efficiently to minimize handling and storage costs *Time Constraints:* components should arrive within the specified time frame *Supplier Constraints:* suppliers can meet production schedules and deliver components on time (supplier reliability and lead times) *Transportation Costs:* costs associated with each mode of transportation *Resource Allocation Constraints:* Allocate resources (trucks, planes, etc.) efficiently to minimize costs and ensure that all plants are supplied without resource shortages	*AL1*. Real-time route optimization *AL3*. Rapid adjustments to delivery capability	Distribution cost

(*continued*)

Table A2.

Case	Lower-level order flexibility capabilities	Constraints	Lower-level order agility capabilities	Objective function
#6: Pharmaceutical distribution logistics	*FL1*. Material supply flow *FL2*. Routing capability *FL3*. Sourcing capability *FT1*. Operations planning *FT2*. Flexible process configuration	*Time window:* each delivery has a specific time window during which it must be delivered to comply with the customer's expectations *Vehicle capacity:* number of items that can be transported (volume, weight . . .) *Number of worker hours* *Traffic constraints* *Availability of vehicles* *Delivery priority* *Warehouse Capacity Constraints:* Ensure that the 30 warehouses have sufficient capacity to store pharmaceutical products and keep them under the right conditions, including temperature and humidity control	*AL1*. Real-time route optimization *AL2*. Short delivery lead-time *AL3*. Rapid adjustments to delivery capability *AL4*. Rapid improvements to delivery reliability *AT1*. Rapid improvements to the operational capability to respond to changing market needs	Delivery cost
#7: Port logistics	*FL2*. Routing capability *FT1*. Operations planning *FT2*. Flexible process configuration	*Real-time Traffic Monitoring:* real-time monitor and record traffic within the port area and creation of a detailed traffic model that represents the road network *Traffic Forecasting:* Use the current traffic volume data to forecast traffic conditions at signalized intersections	*AL2*. Short delivery lead-time *AL3*. Rapid adjustments to delivery capability *AL4*. Rapid improvements to delivery reliability *AL5*. Rapid material flows	*Journey time:* time it takes for trucks, and other vehicles to complete their journeys within the port area
#8: Last-mile delivery	*FL2*. Routing capability *FT1*. Operations planning *FT2*. Flexible process configuration	*Vehicle Load Capacity:* adhering to weight and volume constraints. Ensure that vehicles are neither overloaded nor underutilized *Carrier Uptime:* minimize carrier downtime by optimizing routes and schedules, ensuring that carriers are used efficiently throughout the day *Delivery time windows:* comply with delivery time windows *Fleet Size Optimization:* Strive to optimize the fleet size to ensure that the company maintains a balance between delivery efficiency and cost reduction *Parcel Priority:* prioritization of deliveries based on urgency and customer preferences	*AL1*. Real-time route optimization *AL2*. Short delivery lead-time *AL3*. Rapid adjustments to delivery capability *AL4*. Rapid improvements to delivery reliability	Total delivery time Total distance covered

About the authors

Miguel Núñez-Merino received his master’s degree in Data Science and Computer Engineering from the University of Granada in 2020 and is a graduate in Statistics and Business Administration (University of Jaén). He is currently working toward an Industrial PhD degree with Fujitsu and the Department of Business Organization at the University of Jaén. His research interest is focused on Industry 4.0, logistics, and the supply chain. He has presented works at some prestigious international conferences such as POMs. He has published in the *International Journal of Production Research* (top-cited paper in IJPR, 2020–2021) and in *Technological Forecasting and Social Change.* Miguel Núñez-Merino is the corresponding author and can be contacted at: mnunez@ujaen.es

Juan Manuel Maqueira-Marín is a Full Professor of Business Administration and Management of Technology at the University of Jaén (Spain). He is currently conducting research on factors leading to Cloud Computing technology adoption and Cloud Computing adoption in Supply Chain. He has a wide experience as a Practitioner in some technological firms such us Fujitsu Technology Solutions Inc.

José Moyano-Fuentes is a Full Professor of Operations Management at the Department of Business Organization, Marketing and Sociology in University of Jaén (Spain). He currently conducts research on lean management, supply chain management and firm performance in different industries.

Carlos Alberto Castaño-Moraga studied Telecommunications Engineering at the University of Valladolid and obtained his doctorate degree on Signal Processing from the University of Las Palmas de Gran Canaria. During this time, he became involved with the Harvard Medical School and INRIA Sophia-Antipolis to conduct part of his research activity on medical imaging and advanced signal processing frameworks. Lastly, he complements his training with the business area and holds an Executive MBA by IESE Business School (University of Navarra). After being responsible for research and innovation in a range of companies, he joined Fujitsu in 2014 to develop projects focused on data-driven digital transformation in organizations and to lead projects based on data exploitation to obtain added business value.