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Assessing the uptake of Industry 4.0 technologies: barriers to their adoption and impact on quality management aspects

Keywords: Industry 4.0; Quality Management practices; Product and Service Performance; Satisfaction Performance.

Paper type Research paper.

Acronyms

I40 - Industry 4.0
IoT - Internet of Things
I40Ts - Industry 4.0 technologies
QMA - Quality management aspects
AM - Additive manufacturing
AI - Artificial Intelligence
AV - Artificial Vision
BDAA - Big Data and Advance Analysis CS - Cybersecurity
RB - Robotics
VAR - Virtual and Augmented Reality
BTA - Barriers to adopt
NB - New Barriers

1. Introduction

Industry 4.0 (I40) has been defined as a new paradigm for improving process/enterprise performance through digitization and integration (vertical, horizontal and end-to-end) of so-called cyber technologies through the Internet of Things (IoT) (Ghobakhloo, 2018). This digital transformation has revolutionized industrial processes and created the need to invest in I40 technologies (I40Ts) to maintain the competitiveness. However, deciding where to focus investments is usually one of the greatest uncertainties business managers face (Bosman *et al.*, 2020).

According to Lichtblau (2015), the objectives of I40 are related to quality management aspects (QMAs). However, there are very few comparative empirical academic analyses about the impact of I40Ts on QMAs. These impacts depend on the barriers to adopt (BTAs) I40Ts. BTAs have been studied by some authors (Kamble *et al.*, 2018b; Ślusarczyk, 2018; Groß *et al.*, 2019; Türkeș *et al.*, 2019; Sony and Naik, 2020; Stentoft *et al.*, 2020; Bravi and Murmura, 2021). However, some authors highlight the need for more in depth studies that explore new barriers emerging (Li *et al.*, 2019; Sony *et al.*, 2019). In addition, there is a demand in the literature for further research on the influences that each BTA has on the implantation of each I40T (Türkeș et al., 2019; Vuksanović et al., 2020). Such research would facilitate the definition of strategies to manage BTAs, and to predict and improve the results obtained in relation to QMAs (Laskurain *et al.*, 2020; Bosman *et al.*, 2020).

Taking these gaps into consideration, this article addresses two under-researched areas that are essential when defining strategies in the industrial business context . First, the paper analyzes the influence of each I40T on each QMA. Secondly, it analyses the BTAs that slow down the rollout of each I40T and limit each impact.

The remainder of the paper is organized as follows. In section two, the literature reviews is presented. In sections three and four, the methodology used in the study and the results are outlined. The fifth section presents discussions. The sixth section provides the conclusions, implications, limitations and future research lines. Finally, the references are cited.

2. Literature Review

2.1. Classification of I40Ts

In the literature, there are many classifications of I40Ts (Tjahjono *et al.*, 2017; Dalenogare *et al.*, 2018; Fettermann *et al.*, 2018; Ghobakhloo, 2018; Bai *et al*, 2020; Laskurain-Iturbe *et al,* 2021) but most of them, include the following eight I40T groups identified by SPRI (2017):

- **Additive manufacturing (AM)** is a computer-controlled industrial process that includes 3D printing. It creates three-dimensional objects by depositing materials, usually in layers (Gibson *et al.*, 2015).
- **Artificial Intelligence (AI)** is a cognitive science to improve decisions with important research activities in many areas such as, image processing, natural language processing, robotics or automatic learning (Lee *et al.*, 2018).

- **Artificial Vision (AV)** is a scientific field that deals with how machines can gain high-level understanding from videos or digital images. It is used to gather information from industrial processes (Chella *et al.*, 1997).
- **Big Data and Advance Analysis (BDAA)** is a collection and evaluation of data from different sources such as, production equipment and systems or company and customer management systems, to support faster decision making based on data analysis (Rubmann *et al.*, 2015).
- **Cybersecurity (CS)** is the cyber protection offered to critical industrial systems and intelligent manufacturing lines connected to the Internet. (Thames and Schaefer, 2017).
- **Internet of Things (IoT)** is the use of intelligent devices, such as sensors that interact with each other, to improve decision-making and allow for multiple, simultaneous responses (Lee and Lee, 2015).
- **Robotics (RB)** is the interaction of robots with each other or with humans. (Siciliano and Khatib, 2016).
- **Virtual and Augmented Reality (VAR)** allows for the simulation of real situations in order to train workers, thereby avoiding dangerous situations, working with procedures and improving decision-making (Telukdarie *et al.*, 2018).

2.2. Quality Management Aspects

There is much research on QMAs in the literature. These studies usually make reference to three main groups of variables and they highlights the following items (Arana, 2004; Heras-Saizarbitoria *et al.* 2006; Modgil and Sharma 2016; Lu, 2017; Dalenogare *et al.*, 2018; Laskurain *et al.*, 2020):

- Quality Management Practices: Decision-making uncertainty, Process control, Training of workers, Manufacturing errors, Productivity and Stock level.
- Product and Service Performance: Product customization, Added-value, Product cost, Product delivery time and Product Innovation.
- Satisfaction Performance: Customer satisfaction and Employee satisfaction.

2.3. Industry 4.0 Technologies and Quality Management Aspects

The impact of the different I40Ts on QMAs is a topic of interest that has been studied from different perspectives (Liao *et al.*, 2017). Some authors analyse the implementation of different I40Ts collectively, while others have focused on a single technology. Table 1 summarizes several papers that study the impact of different I40Ts on Quality Management Practices, Product and Service Performance and Satisfaction Performance. As can be seen, very few papers analyse individual I40Ts empirically. More specifically, there is a lack of empirical studies about the impact of these I40Ts on the various QMAs and I40Ts, such as cybersecurity, have been "left out" of those papers relating I40Ts and QMAs.

This paper aims to shed light on these issues by analysing the eight categories in an empirical manner and with the same evaluation criterion. For that, the first research question and the related research questions have been raised:

Research question 1: How does each I40T impact on the different quality management aspects in industrial companies?

- Research question 1.1: How does each I40T affect the quality management practices?
- Research question 1.2: How does each I40T affect the product and service performance?
- Research question 1.3: How does each I40T affect the satisfaction performance?

Table 1. Summary of the review of the literature on influences of I40Ts on QMA.

2.4. Barriers to adopt I40Ts

As noted in the previous subsection, I40Ts can bring benefits to companies. However, BTAs can limit the benefits obtained (Dijkman *et al.*, 2015; Tay *et al.*, 2021). For this reason, it is very important to analyse the causes of the BTAs in order to define a strategy that maximizes the benefits. The scant literature available mainly focuses on the I40Ts as a group or on two specific I40Ts; IoT and BDAA (Dijkman *et al.* 2015; Li *et al.*, 2019). Therefore, Table 2 classifies BTAs according to their causes in five groups; economic and legal, workers, organization, lack of training, and information and technology. This article attempts to shed light through interviews and internal documentation on BTAs of the I40Ts. For this purpose, research question 2 and the related research questions are formulated.

Research question 2. Which barriers limit the adoption of I40Ts by industrial companies?

- Research question 2.1. Which "economic and legal" barriers limit the adoption of I40Ts by industrial companies?
- Research question 2.2. Which "workers" barriers limit the adoption of I40Ts by industrial companies?
- Research question 2.3. Which "organization" barriers limit the adoption of I40Ts by industrial companies?
- Research question 2.4. Which barriers related to a "lack of training and information" limit the adoption of I40Ts by industrial companies?
- Research question 2.5. Which "technology" barriers limit the adoption of I40Ts by industrial companies?

Table 2. Summary of the review of the literature on BTAs I40Ts.

3. Methodology

The initial research process consisted of a literature review, which involved analysis of the conceptual context, perspectives and theoretical models. This review revealed some salient features of the phenomenon to be studied (see Figure 1). I40 is heterogeneous, multidimensional and strongly dependent on the real context. A holistic multiple case study with a single complex unit of analysis is recommended for the study, according to Yin (2018). Yin also proposes basing the strategy on the development of theoretical propositions or research questions, the development of case descriptions (from quantitative and qualitative data) and the examination of rival explanations through cross-case analysis to identify common patterns of behaviour across cases.

Accordingly, the authors developed an appropriate approach to both the design of the case study and the central research questions that have guided the entire process (see Fig. 1).

Initially, a preparatory phase of the multi-case study was conducted. Companies that were selected to participate in the first four editions of BIND 4.0 were contacted. This is a public-private acceleration programme for technology-based companies from all over the world, awarded by the European Commission's Business Environment Improvement Award (European Commission, 2020).

A questionnaire was developed for a total of 168 innovative I40T projects from Europe, America, Asia and Africa. The objective was to measure managers' perception of the influence of each I40T on each QMA and the main BTAs. Participants were given nine possible answers according to a *Likert* scale and were also given the opportunity to add information to clarify their answers in the open-ended questions. Pilot testing was carried out to prepare the final version of the questionnaire with the participation of five project managers. This design approach was used to ensure content validity and accuracy (Malhotra and Grover, 1998). In total, 130 responses were obtained from 168 innovative I40T projects presented across the four editions of the BIND 4.0 entrepreneurship programme. Six of the responses obtained were discarded as incomplete. The remaining 124 projects were classified according to the technology implemented: AM (11); AI (28); AV (8); BDAA (24); CS (5); IoT (27); RB (6); VAR (15). The sample was insufficient to provide a minimum level of confidence, but the authors applied statistical techniques that allow us to obtain very useful information to improve the case protocol and the evidence collection plan in the subsequent phase.

The cases were intended to be informative, accessible, and to have a minimum representation of all technologies. Indeed, it is essential to select cases that offer the greatest opportunity for learning and the necessary access to information (Patton, 2015; Yin, 2018). Therefore 26 case studies were analysed and distributed as follows: AM (4); AI (4); AV (2); BDAA (2); CS (2); IoT (6); RB (2); VAR (4), see Table 3. An attempt was made to maintain a balance between the number of cases analysed and the depth and breadth with which the analysis of the cases was intended, striving for a cross-analysis of the cases (comparative analysis) operational according to the amount of information obtained.

Table 3. List of projects classified by type of technology.

Likewise, taking into account the minimum number of cases recommended by Eisenhardt (1989), the authors aimed to study a minimum of two cases whenever possible. A certain multiplicity of cases would allow us to replicate the results obtained, reach theoretical saturation, and thus the generalisation of the results (analytical generalisation as opposed to statistical generalisation). Subsequently, a protocol for evidence collection was established. This research protocol involved the following: In-depth interviews with 31 members of the project development teams according to a semi-structured script; I40 project reports, technical documentation, test reports, internal communications...; Visits to companies to collect data through passive and active observation.

The protocol is the main unifying element of the research. By applying the protocol, cases can be compared to establish common patterns of behaviour and it becomes possible to present the theoretical replication that gives validity to the study (Miles *et al.*, 2020).

Thus, once the characterisation of the cases investigated was completed, individual case analysis and cross-case analysis for each technology was carried out. The process initially consisted of examining, categorising, tabulating and examining the evidence collected.

Subsequently, an attempt was made to identify common patterns of behaviour across cases by technology, and to determine the connection between the data and the research questions performed by technology (Miles *et al.*, 2020). To finalise the fieldwork, in order to reinforce the conclusions drawn from the case study (theoretical triangulation) (Farquhar, Michels, & Robson, 2020), a panel of identified project managers with deep domain expertise was composed from 9 customer companies (Cus 1-9) (feedback on each I40T from a minimum of two clients was obtained). The results of the previous phase were shown to these clients, with the aim of obtaining a reliable group opinion. It reduces the degree of subjectivity in the assessment of the results, which Patton (2015) points out as one of the possible techniques to establish the constructive validity of qualitative research.

Figure 1. Methodological design of the research.

4. Results

The results are shown below for each I40T. The Tables (from 4 to 11) show the preliminary quantitative results for the 124 projects and the qualitative results for the 26 case studies. The specific applications for I40Ts, and the barriers to their implementation are identified for each project.

4.1. *Additive Manufacturing*

In Table 4, the quantitative results show high or very high positive influences on "product innovation" (3.63), "product customization" (3.50), "added-value" (3.50) and "product cost" (3.00). In addition, there is a positive influence on the rest of the aspects. The Qualitative results confirmed these influences except for "manufacturing errors" (1.63) and "decision making uncertainty" (2.00).

Regarding the barriers, the BTA1 has been identified in three companies and a new barrier (NB)- "Lack of technology development" (NB1) - has been observed in the AM1 and AM4 cases, which are related to the limitations of the technology (materials, sizes and manufacturing efficiency). Some customers point to the fear of being over-dependent on their suppliers (NB5).

Table 4. Influences, applications and barriers of AM technology.

4.2. *Artificial Intelligence*

The quantitative results detect high, or very high, positive influences on "manufacturing errors" (3.56), "productivity" (3.44), "customer satisfaction" (3.33), "process control" (3.33), "decision-making uncertainty" (3.11) and "product innovation" (3.00). The qualitative results confirm these results because there is evidence of these influences for all aspects, except for the two with the lowest values: “stock level” (0.56) and “product customization” (1.56).

As can be observed in Table 5, the barriers BTA4, BTA6, BTA10 and BTA13 were identified in the interviews. An additional new barrier was also observed: “high cost of the information in private hands” (NB2), which is related to limited access to public information due to private control of satellite information. It should be noted that BTA6 was detected in two of the projects. A customer links the adoption of this technology to psychosocial problems (BTA7) that have led to two reported absences from work in the months following implementation.

Table 5. Influences, applications and barriers of AI technology.

4.3. *Artificial Vision*

The quantitative results highlight the influence of I40Ts on “process control” (3.39), “productivity” (3.29) and “decision making uncertainty” (3.14) (see Table 6). In the qualitative phase, influence of I40Ts on reducing “stock level” (1.68), “delivery time” (1.71), improving “product customization” (1.82) and “product added-value” has not been confirmed (1.93).

BTA5, BTA6 and BTA12 have been detected as the main barriers to implementing AV projects. Staff resistance has been stressed in the interviews, and the importance of prior communication and training has been put forward as strategic to combat these barriers in future projects.

Table 6. Influences, applications and barriers of AV technology.

4.4. *Big Data and Advance Analytics*

In the quantitative results, the highest-rated factors of influence are “decision making uncertainty” (3.42), “process control” (3.33) and “productivity” (3.13). Furthermore, the effect on “reducing the delivery time” (2.08) has not been observed in the qualitative phase.

As it can be seen in Table 7, BTA1, BTA5, BTA6 and BTA11 have been identified as the most significant barriers.

Table 7. Influences, applications and barriers of BDAA technology.

4.5. *Cybersecurity*

In the interviews conducted, all the QMAs that had obtained the highest influence in the quantitative phase were confirmed in the qualitative phase: “process control” (3.40), “decision making uncertainty” (3.20), “product innovation” (3.20), “added-value” (3.00) and “customer satisfaction” (3.00) (see Table 8).

Regarding barriers, the factor "lower perception of risk limits investment" (NB3) has been observed. In addition, the BTA9, BTA11 and BTA12 cited in the literature have been identified.

Table 8. Influences, applications and barriers of CS technology.

4.6. *Internet of Things*

The quantitative results that show medium-high influences on implementation are: "productivity" (2.92), "process control" (2.85), "decision making uncertainty" (2.77) and "customer satisfaction" (2.69). In the qualitative results, differences between the applications carried out with this technology were observed. Otherwise, influences were not detected for the cases of "product innovation" (1.96) and "product customization" (1.88) (see Table 9).
Regarding the barriers, BTA1, BTA2, BTA3, BTA6, BTA8, BTA9, BTA11, BTA12 and NB1 were identified in the interviews and in the analysis of the internal documentation.

Table 9. Influences, applications and barriers of IoT technology.

4.7. *Robotics*

The quantitative results show that robotics has a high or very high influence on several QMAs, namely: "customer satisfaction" (3.33), "employee satisfaction" (3.33), "productivity" (3.00) and "manufacturing errors" (3.00). The qualitative results confirm evidence of such influence in all the cases.
In addition, Table 10 shows the NB1, BTA1 and BTA6 barriers were detected in two of the analysed projects. The interviewees reported that certain groups of employees demonstrated an active resistance to project implementation.

Table 10. Influences, applications and barriers of RB technology.

4.8. *Virtual and Augmented Reality*

The quantitative results pointed out that VAR technology positively impacts on "productivity" (3.38) and "training of workers" (3.23) (see Table 11). It should be noted that in the qualitative phase, no influences were detected for several QMAs: "product cost" (2.31), "stock level" (1.62), "delivery time" (1.54), "product customization" (2.38), "added-value" (2.38) and "decision making uncertainty" (2.92).
Besides, in this phase, the main barriers identified were "workers' resistance" (BTA6) and the "dependence of other I40Ts" (NB4).

Table 11. Influences, applications and barriers of VAR technology.

5. Discussion

In this section, the level of influence has been quantified by crossing-checking the data obtained in the quantitative and qualitative phases. It should be noted that the negative influences detected mainly occur in the adaptation processes. In this adaptation-phase, tension between employees, loss of productivity or lack of control of the inventory have been observed. However, it has been remarked that in latter phases these influences are compensated. While not common, in some cases, negative impacts were mainly related to costs, overconfidence and workers' frustrations.

In the literature review, no studies were identified including the eight I40Ts and the Quality Management Practices, Product and Service Performances, Satisfaction Performances and BTAs in the same analysis. In this section, we will focus the discussion on influences with sufficient level of evidence, i.e., on the average, strong or critical exerted on QMAs by each I40T, following Miles *et al.* (2014). Secondly, we will discuss the relevance of the barriers that have been analysed (Table 12).

Starting with the influences exerted by the I40Ts, the authors find that AM exerts an influence on Stock level and Process control confirming the results of Gibson el al. (2015) and Dalenogare *et al.* (2018). In addition, impacts on Productivity were also observed, a finding, which differs from the results obtained by Kamble (2018a). PMPs receive influences confirming the results of Weller *et al.* (2015), and Stock and Seliger (2016) with respect to the following variables: Added Value, Product customization and Product innovation. Finally, we highlight the impact received by the level of customer satisfaction.

Among the influences of AI on Quality Management Practices, its impact on Process control and Manufacturing errors is confirmed (Feterman *et al.*, 2018). The influence of AI on Decision-making uncertainty and Productivity is also evidenced. Regarding the impacts on Product and Service Performances, influences on Added value are detected, confirming the results of Dalenogare *et al.* (2018), as are additional effects on Product cost and Product innovation. Finally, the impact on Customer satisfaction reported by Dalenogare *et al.* (2018) is confirmed and, to a lesser extent, an improvement in Employee satisfaction is detected.

AV also contributes to improving Quality Management Practices in a significant way. It affects the variables Decision-making uncertainty, corroborating the results of Alonso *et al.* (2019), and Process control, Training workers, Manufacturing error and Productivity. With respect to Product and Service Performances, AV improves Product cost and Product innovation. It also contributes to Customer and Employee satisfaction.

The results confirm the findings of other authors about the influences of BDAA on Decision-making uncertainty (Preuveneers and Ilie-Zudor, 2017), Process control and Productivity (Smidt *et al.*, 2015). On Product and Service Performances, it confirms the positive incidence on Added-value, Product cost and Product innovation variables pointed out by Sivathau and Pillai (2018), but differs from the results highlighted by Dalenogare *et al.* (2018) regarding the negative incidence on Added value. It also contributes to highlight a medium positive influence on Customer satisfaction.

CS positively affects Decision-making uncertainty and Process control, confirming the results obtained by Yu *et al.* (2017). Moreover, new positive impacts on Added-value, Product innovation and Customer satisfaction have been detected.

IoT is the I40T that has been most analysed in the literature. Impacts on Decision making uncertainty, Process control and Manufacturing errors are confirmed (Christoulakin

2016; Jeschke *et al.*, 2017; Li *et al.*, 2017). However, the level of evidence is not sufficient to confirm influences on Productivity and Stock level (Ramadan *et al.*, 2017). Product and Service Performances are impacted to a lesser extent. Only a sufficient level of influence is detected to confirm the impact of IoT on Product cost (Sivathau and Pillai, 2018) but the influences reported by other authors such as Strange and Zuccchela (2017) and Witkowski (2017) on the contributions on Product customization, Added value or Product innovation cannot be corroborated. However, the impact of IoT on Customer satisfaction is confirmed (Lu, 2017). Conversely, its impact on Employee satisfaction is not (Oestereich and Teuteberg, 2016; Vereycken *et al.* 2021).

RB exerts a strong influence on QMAs. However, it is one of the least analysed I40Ts. Regarding Quality Management Practices, this study confirms the influences of RB on Manufacturing errors and Productivity (Fengque *et al.*, 2017) and adds new evidence on Process control and Training workers. Regarding Product and Service Performance, previous influences evidenced in the literature in relation to Added-value (Strange and Zuchella, 2017) and Product cost (Fengque *et al.*, 2017)have been confirmed. In addition, Product customization, Product delivery time and Product innovation have been documented. Finally, RB contributions on Customer and Employee satisfaction are noted.

In relation to VAR, the authors have found evidence of its impact on Training of workers, Process control and Productivity pointed out by Moreno *et al.* (2017). However, insufficient evidence has been detected to confirm its impact on Product and Service Performances and, therefore, the benefits related to operational performance reported by Dalenogare *et al.* (2018) cannot be confirmed. However, VAR´s contribution on Customer and Employee satisfaction is confirmed, an aspect pointed out globally by Vereycken *et al.* (2021).

Regarding the barriers, the literature has analysed them from different perspectives. These barriers affect the adoption of different I40Ts depending on the context. In general, five major categories of barriers can be identified: "economic and legal" (Kamigaki, 2017; Christians and Liepin 2017), "workers" (Santana *et al.*, 2017; Türkeș *et al.*, 2019; Dalmarco *et al.*, 2019; Vuksanović *et al.* 2020), "organization" (Hussain, 2017; Rauch *et al.*, 2020) "lack of training and information" (Türkeș *et al.*, 2019; Li *et al.*, 2019) and "technological" (Mueller *et al.*, 2017; Türkeș *et al.*, 2019). Despite combining several barriers into groups, no particular group is shown to hinder the full implementation and rollout of all I40Ts. The groups identified as "economic and legal" and "workers" exert a greater influence than the rest, confirming previous results of Christians and Liepin (2017) and Vuksanović *et al.* (2020). In general, evidence has been found showing that these groups have a negative influence on the decision and implementation process of I40Ts application. Exceptions are the lack of influence of the "economic and legal" group on AV technology, and the "workers" group on AM and CS technologies. If we consider the barriers individually, BTA6 (corroborating Dalmarco *et al.*, 2019; Vuksanović *et al.*, 2020), BTA1 (stated by Kamigaki, 2017) and NB1 are the most evidenced barriers. In the confirmatory analysis, the results of the group of customers obtained is remarkable. In addition, they highlight how over-dependent on its technology suppliers a company becomes after the adoption of I40Ts. This barrier is considered very important by the customers in the case of BDAA and RB, although the project managers surveyed had ignored it.

Table 12. Impact of I40Ts on QMAs and barriers that limit their development.

6. Conclusions, implications, limitations and future research lines

I40Ts have potential to improve the quality management performance of industrial companies. Their applications and their integration with other technologies are critical elements that determine the capacity to influence on each QMA. The technology baseline situation and the company's objectives are determining factors when predicting the impact that the implementation of I40Ts will have on an industrial company's results and required investment.

The investment requirements to integrate I40Ts can vary greatly and this variance depends not only on the type of technology but also on the characteristics of the company. For these reasons, when defining its strategies, a company should take into account these variables to optimize the investment returns and the risks assumed. In addition, it should be noted that there has been a decrease in implementation times and costs. Conversely, the relative competitiveness of industrial companies declines if they delay the adoption of I40Ts. For this reason, public incentives and programs appear to be crucial to promote I40Ts.

In the adoption of the I40Ts, some barriers that limit their application should be considered. These barriers have been classified into five main categories: "economic and legal", "workers", "organization", "lack of training and information" and "technology". The barriers vary rapidly over time. Some of these barriers are being overcome, such as those related to the internet coverage, but new barriers are being revealed. Managers interested in adopting I40Ts should plan the implementation process to minimize the impact of these barriers and to optimize the results for each stakeholder. In this sense, the barriers that concern the workers should be managed. It is the responsibility of managers to inform and explain how data will be handled, and how privacy concerns will be addressed. It is also essential to explain and convince workers about the need for a renewal of tasks. New types of jobs (i.e. the use of robots) will involve training for workers to enable their integration alongside the new technologies.

Perhaps the main limitation is the generalisability of the findings of qualitative studies (ergo the case study). In this sense, statistical generalisability, characteristic of a random sample, is not intended in this paper, as the set of cases studied does not represent or attempt to constitute a meaningful sample from the point of view of statistical inference. The generalisation lies in the development of findings that can be transferred to other cases (Yin, 2018). Therefore, the use of multiple case studies has been chosen to reinforce analytical generalisations with corroborated evidence (literal replication), which is essential to provide internal validity to the research (Patton, 2015; Yin, 2018).

However, in the future, when the dissemination of I40Ts is more widespread, it would be interesting to conduct further research with more cases in order to deepen and enhance the level of knowledge. On the other hand, the quantitative study would allow us to complete and improve the results of the case study. Finally, it would be advisable to analyse the deployment of these I40Ts according to different variables such as size, sector or results obtained.

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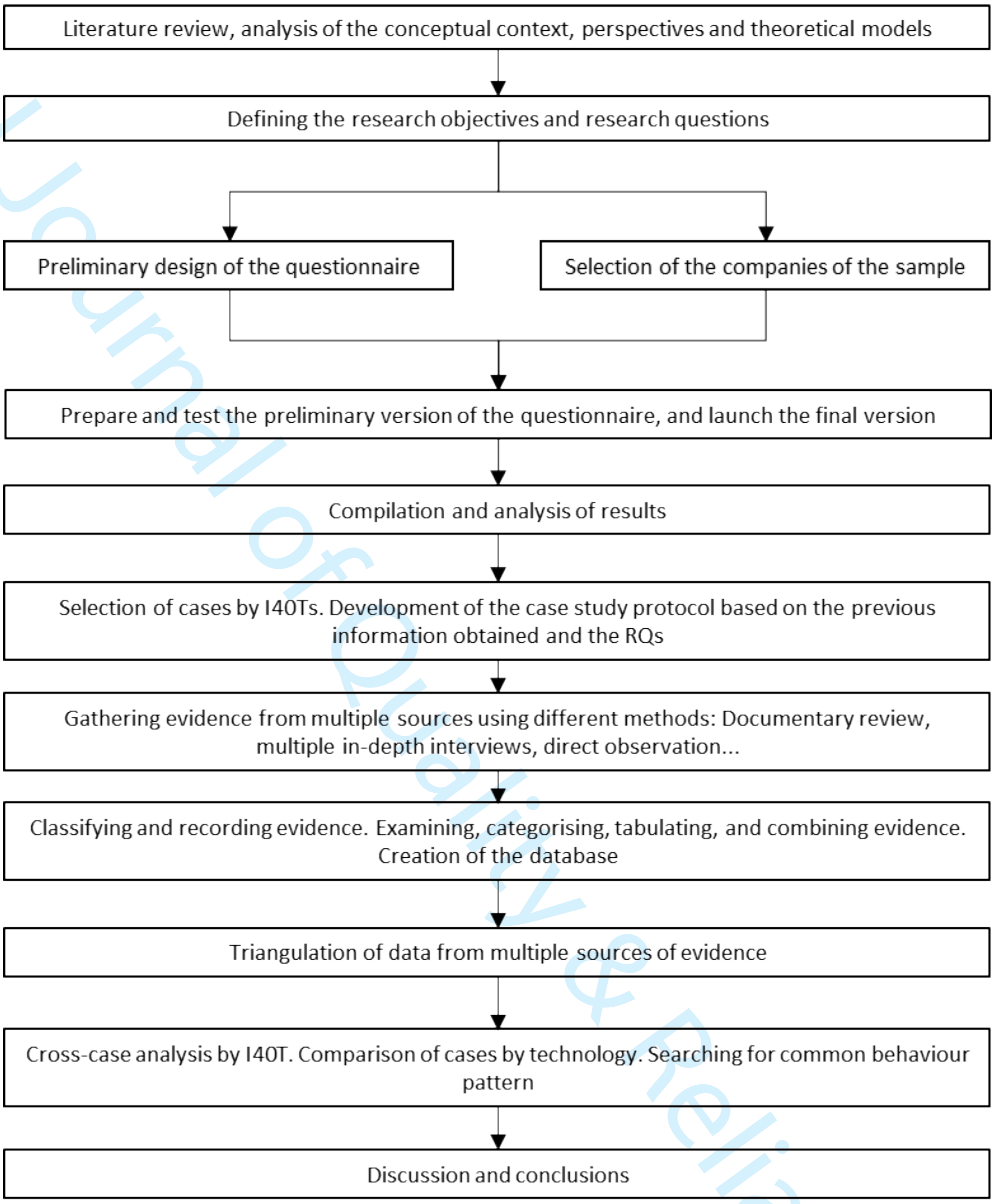
Figure 1. Methodological design of the research.



Source: compiled by the authors, adapted from Eisenhardt (1989) and Yin (2018).

Table 1. Summary of the review of the literature on influences of I40Ts on QMA.

Quality Management Practices			
Study	**Methodology**	**I40T**	**Main results**
Gibson *et al.* (2015)	Theoretical work	AM	The number of processes can be significantly reduced. Workshops can be much cleaner, more streamlined, and more versatile.
Kamble *et al.*(20181a)	Literature Review (85 papers)	AM	3D printers face technical challenges such as limited types of usable materials, low accuracy and low productivity
Dalenogare *et al.* (2018)	Survey (2,225 answers)	AM	Reduction of processing times, resources and tools needed
Fettermann *et al.* (2018)	38 Case studies	AI	Main impact in operation management and just-in-time manufacturing
Alonso *et al.* (2019)	3 case studies	AV	Facilitate decision making
Wamba *et al.* (2015)	Literature review (62 works) and case study	BDAA	Leveraging innovation, competition and productivity in business processes
Schmidt *et al.* (2015)	Survey (592 answers)	BDAA	Facilitates mass customization, use of inactive data and improved lead times
Preuveneers and Ilie-Zudor (2017)	Theoretical work	BDAA	Predictive decision support to increase productivity and efficiency
Tao *et al.* (2018)	Theoretical work	BDAA	Increase the manufacturing process efficiency
Yu *et al.* (2017)	Theoretical work	CS	Necessary to control the information of the companies in order to guarantee acceptable and reliable systems
Thramboulidis and Christoulakin (2016)	Case study	IoT	Improve productivity, efficiency and reliability of the processes
Jeschke *et al.* (2017)	Theoretical work	IoT	Enhancing the visibility of manufacturing processes still in the design phase
Li *et al.* (2017)	Case study	IoT	Achieve process agility and flexibility. Load imbalance and inefficiencies can arise.
Mueller *et al.*, 2017)	Theoretical work	IoT	Increasing employee, equipment and products safety and more effective quality control Better control of intelligent machines, synchronized production and easier maintenance scheduling.

Ramadan *et al.* (2017)	Case study	IoT	Better capacity of monitoring and control the cost
Yang *et al.* (2017)	Theoretical work	IoT	Real-time detection/action capability and rapid transmission of data/information, facilitating stakeholder collaboration
Fengque *et al.* (2017)	Case study	RB	Robots can perform most intelligent factory processes with a very high cost benefit ratio
Moreno *et al.* (2017)	Case study	VAR	Reduction of machine setup times. Facilitate the understanding of the behaviour of the machines
Product and Service Performances			
Study	**Methodology**	**I40Ts**	**Main results**
Weller *et al.* (2015)	Theoretical work	AM	Highly customized products, increasing their perceived value
Stock and Seliger (2016)	Case study	AM	Cheaper prototypes, small batches of custom products or complex and lightweight designs
Yin *et al.* (2017)	Theoretical work	AM	Acceleration of product innovation More customized products
Ghobakhloo and Fathi (2020)	Case study	IoT	Improved process and machine control, increased efficiency to reduce defects and help continuous improvement
Siciliano and Khatib (2016)	Theoretical work	RB	More intelligent factory processes with a very high costenefit ratio
Telukdarie *et al.* (2018)	Theoretical work	VAR	Simulation models virtually support customer service Reduce product costs
Sivathau and Pillai (2018)	Case study	BDAA, IoT & AI	More effective and efficient work teams.
Strange and Zucchella (2017)	Theoretical work	BDAA ,AM, IoT & RBs	Value-added within different chains
Dalenogare *et al.* (2018)	Survey (2,225 answers)	BDAA & VAR	Negative association to the benefits expected for product performance Positively associated to operational expected benefits
Witkowski (2017)	Theoretical work	IoT & BDAA	Creation of opportunities to meet customer needs and contribute to the development of logistics and supply chain management
Satisfaction Performances			

Study	**Methodology**	**I40Ts**	**Main results**
Dalenogare *et al.* (2018)	Survey (2,225 answers)	AI	Increased customer satisfaction with the perceived value
Lu (2017)	Literature review	IoT	Achieve customer satisfaction
Oesterreich and Teuteberg (2016)	Literature review	IoT	Identification of safety hazards to improve employee satisfaction
Vereycken *et al.* (2021)	Survey (5,609)	General	Improve employee satisfaction

Source: data collected by authors.

Table 2. Summary of the review of the literature on BTAs I40Ts.

Study	Methodology	I40T	Type of BTAs
Economic and Legal			
Lee and Lee (2015)	5 case studies	IoT	High cost (BTA1)
Kamigaki (2017)	Theoretical work	IoT	
Lin (2016)	Theoretical work	General	Regulatory compliance factors (BTA2)
Christian *et al.* (2017)	Theoretical work	General	
Christians and Liepin (2017)	Theoretical work	General	Legal, privacy and contractual factors(BTA3)
Workers			
Study	**Methodology**	**I40T**	**Type of BTA**
Ganshar *et al.*(2013)	Survey (662 answers)	General	Employment disruptions (BTA4)
Hung (2016)	Practitioner work	General	Need for enhanced skills (BTA5)
Benešová and Tupa (2017)	Theoretical work	General	
Ryan and Watson (2017)	Literature review (144 works)	General	
Christian *et al.* (2017)	Theoretical work	General	
Li *et al.* (2017)	Theoretical work	General	
Ślusarczyk (2018).	Literature review (+2000 works)	General	
Türkeş *et al.*, (2019)	Survey (176 ans.)	General	
Dalmarco *et al.* (2019)	10 case studies	BDAA	Workers resistance (BTA6)
Vuksanović *et al.* (2020)	Survey (122 answers)	General	
Santana *et al.*, (2017)	Theoretical work	General	Psychosocial factors (BTA7)
Organization			
Study	**Methodology**	**I40T**	**Type of BTA**
Kletti (2015)	Practitioner work	General	Organizational and process changes (BTA8)
Hussain (2017)	Theoretical work	IoT	
Li *et al.* (2017)	Theoretical work	General	
Babiceanu and Seker (2016)	Literature Review	General	Security and privacy factors(BTA9)
Yu *et al.* (2017)	Theoretical work	General	
Alaba *et al.* (2017)	Literature Review	IoT	
Rauch *et al.* (2020)	Literature Review(58 works)	General	
Da Xu *et al.* (2014)	Theoretical work	IoT	Integration and compatibility factors (BTA10)
Hussain (2017)	Theoretical work	IoT	
Lack of training and information			
Study	**Methodology**	**I40T**	**Type of BTA**
Da Xu *et al.* (2014)	Theoretical work	IoT	Lack of knowledge management systems(BTA11)
Dijkman *et al.* (2015)	Qualit. study (11 companies) and survey (103 ans)	IoT	
Rymaszewska *et al.* (2017)	Case study	IoT	
Li *et al.* (2017)	Theoretical work	BDAA	Lack of clear comprehension about I40T (BTA12)
Ryan and Watson (2017)	Literature review	IoT	
Türkeş *et al.* (2019)	Survey (176 ans.)	General	
Li *et al.* (2019)	Qualit. study (10 experts)	BDAA	
Technology			
Study	**Methodology**	**I40T**	**Type of BTA**
Haddud *et al.* (2017)	Survey (87 ans.)	IoT	Lack of standards and reference architecture (BTA13)
Mueller *et al.* (2017)	Theoretical work	General	
Türkeş *et al.* (2019)	Survey (176 ans.)	General	
Fang *et al.* (2016)	Theoretical work	IoT	Lack of internet coverage and IT facilities (BTA14)

Source: data collected by authors.

Table 3. List of projects classified by type of technology.

Code	Brief description
AM1 - Printing metal and plastic material for aircraft manufacturer suppliers	
AM2 - Minimization of biological waste in the food industry through atomic level applications	
AM3 - Special coating using nanotechnology in the manufacture of brake discs	
AM4 - Consultancy to implement AM in industrial processes	
AI1 - Monitoring the construction of a wind farm using satellite-free images	
AI2 - Voice recognition technology for operators to search for or write down procedures	
AI3 - Analysis of the data (heating, air conditioning) of the buildings/factories	
AI4 - Analysis of camera data to optimize procedures	
AV1 - Quality inspection system for plastic film production	
AV2 - Automation of parts inspection in industrial processes (mainly automotive parts)	
BDAA1 - Data processing to optimize the use of industrial machines	
BDAA2 - Use of information systems to manage and optimize the factory	
BDAA3 - Massive data analysis to optimize production machine indicators	
CS1 - Shielding the entire computer system of an automotive company	
CS2 - Protection of the IT system of a machine tool company including Blockchain technology.	
IoT1 - Devices for monitoring the supply chain	
IoT2 - Monitoring through sensors in the lube oil of the wind turbines	
IoT3 - Data capture from industrial machines using sensors	
IoT4 - Sensorization of industrial machines to optimize mainly energy consumption	
IoT5 - Use of wireless sensors to control the entire value chain (from the supplier to the customer)	
IoT6 - Movement control of workers by sensors to optimize routes and movements	
RB1 - Robotic solutions with sensing technologies and flexible application software	
RB2 - Implementation of intelligent robots in production processes	
VAR1 - Training people who can use fire extinguishers	
VAR2 - Integral support for the digitalization of water treatment plant maintenance processes	
VAR3 - Training to optimize procedures in industry	
VAR4 - Virtual training to train jobs with some risk element	

Source: compiled by the authors.

Table 4. Influences, applications and barriers of AM technology.

Quality Management Aspects	**Quantitative results (N=11)**	**Qualitative results**	**Project application: Barriers [type of barrier]**
Quality Management Practices			**AM1**
Decision-making uncertainty	2.00	-	*High cost of implementation and raw materials [BTA1]*
Process control	2.25	1,3,4	*Lack of technology development [NB1]*
Training of workers	2.38	1,4	**AM2**
Manufacturing errors	1.63	-	*Very expensive technology (only for high value-added*
Productivity	2.88	1,3,4	*products) [BTA1]*
Stock level	2.75	All	*Limitation of materials [BTA10]*
Product and Service Performances			**AM3**
Product customization	3.50	1,3,4	*More expensive than conventional and designed for the*
Added-value	3.50	All	*creation of prototypes or short series [BTA1]*
Product cost	3.00	1,3,4	**AM4**
Product delivery time	2.75	1,3,4	*Size of pieces and need for further manual processing*
Product Innovation	3.63	1,3,4	*[BTA10]*
Satisfaction Performances			**Cus1&3**
Customer satisfaction	2.88	All	*Too dependent on technology suppliers [NB5]*
Employee satisfaction	2.50	2,4	

Source: compiled by the authors.

Table 5. Influences, applications and barriers of AI technology.

Quality Management Aspects	Quantitative results (N=28)	Qualitative results	Project application: Barriers [type of barrier]
Quality Management Practices			**AI1** *Limited and poor quality free access to European constellation images (in private hands) [NB2]* **AI2** *Integration of the product into the companies' systems [BTA10,13]* *Workers' resistance to change (technology) [BTA6]* **AI3** *Fear of losing work (medium to low level employees) [BTA4]* **AI4** *Workers uncomfortable and distrustful of using a camera [BTA6]* **Cus4** *Psychosocial factors [BTA7]*
Decision-making uncertainty	3.11	All	
Process control	3.33	All	
Training of workers	2.11	1,4	
Manufacturing errors	3.56	1,2,4	
Productivity	3.44	2,3,4	
Stock level	0.56	-	
Product and Service Performances			
Product customization	1.56	-	
Added-value	2.22	1,2,4	
Product cost	2.67	All	
Product delivery time	1.33	4	
Product Innovation	3.00	All	
Satisfaction Performance			
Customer satisfaction	3.33	1,4	
Employee satisfaction	2.33	1,2,3	

Source: compiled by authors.

Table 6. Influences, applications and barriers of AV technology.

Quality Management Aspects	*Quantitative results (N=8)*	*Qualitative results*	*Project application:* ***Barriers [type of barrier]***
Quality Management Practices			**AV1**
Decision-making uncertainty	3.14	All	*Customer doubt (cost/performance) [BTA12]*
Process control	3.39	All	**AV2**
Training of workers	2.75	All	*Worker resistance to change (learning to interpret data) [BTA4 + BTA6]*
Manufacturing errors	2.71	All	
Productivity	3.29	All	
Stock level	1.68	-	
Product and Service Performances			
Product customization	1.82	-	
Added-value	1.93	-	
Product cost	2.71	All	
Product delivery time	1.71	-	
Product Innovation	2.25	All	
Satisfaction Performances			
Customer satisfaction	2.11	All	
Employee satisfaction	2.68	All	

Source: compiled by authors

Table 7. Influences, applications and barriers of BDAA technology.

Quality Management Aspects	*Quantitative results (N=24)*	*Qualitative results*	*Project application:* ***Barriers [type of barrier]***
Quality Management Practices			**BDAA1** *Distrust of employees for controlling the whole process in detail [BTA6]* **BDAA2** *Lack of technical knowledge in companies [BTA5+11]* *High investment, slow payback [BTA1]* *Workers' resistance to new procedures [BTA6]* **Cus1,4,6** *Too dependent on technology suppliers [NB5]*
Decision-making uncertainty	3.42	All	
Process control	3.33	All	
Training of workers	2.38	2	
Manufacturing errors	2.46	1	
Productivity	3.13	All	
Stock level	1.75	2	
Product and Service Performances			
Product customization	2.42	All	
Added-value	2.58	All	
Product cost	2.71	All	
Product delivery time	2.08	-	
Product Innovation	2.42	All	
Satisfaction Performances			
Customer satisfaction	2.92	All	
Employee satisfaction	2.54	All	

Source: compiled by authors

Table 8. Influences, applications and barriers of CS technology.

Quality Management Aspects	Quantitative results (N=5)	Qualitative results	Project application: Barriers [type of barrier]
Quality Management Practices			**CS1**
Decision-making uncertainty	3.20	All	*Reduced interest in ongoing investments in safety due to a lack of perceived risk [NB3]*
Process control	3.40	All	
Training of workers	2.20	-	**CS2**
Manufacturing errors	2.80	2	*Fear of exposing their information on the cloud [BTA2+3+9]*
Productivity	2.80	1	
Stock level	0.80	-	
Product and Service Performances			
Product customization	2.20	-	
Added-value	3.00	All	
Product cost	1.40	-	
Product delivery time	1.80	-	
Product Innovation	3.20	All	
Satisfaction Performances			
Customer satisfaction	3.00	All	
Employee satisfaction	2.20	1	

Source: compiled by authors.

Table 9. Influences, applications and barriers of IoT technology.

Quality Management Aspects	Quantitative results (N=27)	Qualitative results	Project application: Barriers [type of barrier]
Quality Management Practices			**IoT1** *Change of operation to recover reusable devices [BTA8]*
Decision-making uncertainty	2.77	All	
Process control	2.85	1,2,3,5	
Training of workers	2.12	6	**IoT2** *Limitation of use in some applications (e.g. diesel engine oil is not measurable due to soot contamination) [NB1]* *High cost [BTA1]*
Manufacturing errors	2.35	1,3,5,6	
Productivity	2.92	3,5,6	
Stock level	1.27	1,3,5,6	
Product and Service Performances			
Product customization	1.88	-	**IoT3** *Mistrust of the "gateways" that are installed [BTA2+3+9]* *The cost of implementation [BTA1]*
Added-value	2.00	2,5	
Product cost	2.31	All	
Product delivery time	1.77	3,5,6	
Product Innovation	1.96	-	**IoT4** *Too much time to reach valid conclusions [NB1+BTA1]*
Satisfaction Performances			
Customer satisfaction	2.69	1,3,5,6	**IoT5** *Lack of maturity or knowledge about new I40Ts [BTA11+12]*
Employee satisfaction	2.42	2,5,6	
			IoT6 *Employees are reluctant to have their movements controlled [BTA6]* *Lack of resources (financial, manual...) [BTA1]*
			Cus4 *Too dependent on technology suppliers [NB5]*

Source: compiled by authors.

Table 10. Influences, applications and barriers of RB technology.

Quality Management Aspects	Quantitative results (N=6)	Qualitative results	Project application: Barriers [type of barrier]
Quality Management Practices			**RB1** *Manual work remains the most flexible solution [NB1]* *Too expensive for industrial companies in developing country (cheaper with workers) [BTA1]* *Resistance from employees who are afraid of losing their jobs [BTA6]* **RB2** *Resistance from employees who are afraid of losing their jobs [BTA6]* **Cus3&8** *Too dependent on technology suppliers [NB5]*
Decision-making uncertainty	1.83	-	
Process control	2.67	All	
Training of workers	3.00	All	
Manufacturing errors	3.00	All	
Productivity	3.00	All	
Stock level	1.83	-	
Product and Service Performances			
Product customization	2.33	All	
Added-value	2.33	All	
Product cost	2.83	All	
Product delivery time	2.67	All	
Product Innovation	2.50	All	
Satisfaction Performances			
Customer satisfaction	3.33	All	
Employee satisfaction	3.33	All	

Source: compiled by authors.

Table 11. Influences, applications and barriers of VAR technology.

Quality Management Aspects	Quantitative results (N=15)	Qualitative results	Project application: Barriers [type of barrier]
Quality Management Practices			**VAR1**
Decision-making uncertainty	1.92	-	*The software development depends on the hardware developers (e.g. to simulate gloves, they lose the movement of their fingers) [NB4]*
Process control	2.23	1,2,4	
Training of workers	3.23	All	
Manufacturing errors	2.77	3,4	**VAR2**
Productivity	3.38	3,4	*Difficulties in integrating the product into the customer's IT [BTA10]*
Stock level	0.62	-	
Product and Service Performances			*Acceptance of the new tools and work modes by the workers [BTA6]*
Product customization	1.38	-	
Added-value	1.38	-	**VAR3**
Product cost	2.31	-	*The implementation of Virtual Reality hardware is complicated [NB1]*
Product delivery time	1.54	-	
Product Innovation	2.15	3	*Clients reluctant to change (new procedures) [BTA6+BTA8]*
Satisfaction Performances			
Customer satisfaction	2.46	2	**VAR4**
Employee satisfaction	2.54	All	*Very expensive if you want to customize your results [BTA1]*

Source: compiled by authors.

Table 12. Impact of I40Ts on QMAs and barriers that limit their development.

		QMAs							
		AM	***AI***	***AV***	***BDAA***	***CS***	***IoT***	***RB***	***VAR***
Quality Management Practices	Decision-making uncertainty	0	3	3	3	3	3	0	1
	Process control	2	3	3	3	3	2	3	2
	Training of workers	1	1	3	1	0	0	3	3
	Manufacturing errors	0	3	3	1	1	2	3	1
	Productivity	2	3	3	2	1	1	3	2
	Stock level	3	0	0	1	0	1	0	0
Product and Service Performances	Product customization	3	0	0	2	0	0	2	1
	Added-value	4	2	0	3	3	1	2	1
	Product cost	2	3	3	3	0	2	3	0
	Product delivery time	2	0	0	0	0	1	3	0
	Product Innovation	3	3	2	2	3	0	2	1
Satisfaction Performances	Customer satisfaction	3	2	2	3	3	2	3	2
	Employee satisfaction	1	2	3	1	1	1	1	3
		Barriers							
Economic and Legal	BTA1	3	0	0	1	0	3	1	1
	BTA2	0	0	0	0	1	1	0	0
	BTA3	0	0	0	0	1	1	0	0
	NB2	0	1	0	0	0	0	0	0
Workers	BTA4	0	1	0	0	0	0	0	0
	BTA5	1	0	1	1	0	0	0	0
	BTA6	0	4	1	2	0	2	3	3
	BTA7	0	1	0	0	0	0	1	0
Organization	BTA8	0	0	0	0	0	1	0	1
	BTA9	0	0	0	0	1	1	0	0
	BTA10	0	1	0	0	0	0	0	1
	NB5	1	0	0	2	0	1	2	0
Lack of training and information	BTA11	0	0	0	1	0	1	0	0
	BTA12	0	0	1	0	0	1	0	0
	NB3	0	0	0	0	1	0	0	0
Technology	BTA13	0	1	0	0	0	0	0	0
	BTA14	0	0	0	0	0	0	0	0
	NB1	3	0	0	0	0	3	2	1
	NB4	0	0	0	0	0	0	0	1

Source: compiled by authors.

Note: For the QMAs, 9-point Likert scale (-4: very high negative influence to 4: very high positive influence). For the barriers, 5-point Likert scale (0: No evidence of the barrier to 4: evidence of being a critical barrier).