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Contributions of Healthcare 4.0 digital applications to the resilience of healthcare organizations during the COVID-19 outbreak

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ABSTRACT

In this paper, we examine the contributions of digital applications to the resilience of healthcare organizations during the COVID-19 outbreak. The studied applications are framed as Healthcare 4.0 (H4.0), comprising bundles of information and communication technologies used to improve operations in the health value chain. Data collection was carried out through semi-structured interviews with 10 senior managers from clinician and non-clinician departments of two large-sized Brazilian hospitals treating patients infected with SARS-CoV-2. Interviews were analyzed through content analysis, using data analysis categories related to the application focus (i.e., supply chain, patient diagnosis, patient treatment, and patient follow-up) and targeted resilience ability (i.e., monitor, anticipate, respond, and learn). Results indicate that applications oriented to supply chain and patient diagnosis contribute to all resilience abilities. Furthermore, depending on the resilience ability to be improved, different applications may be prioritized. Four research propositions for theory-testing in future studies are also presented.

1. Introduction

Inherent to activities conducted in a supply chain (SC), there is the risk of disruptions that may have undesirable operational and financial impacts (Jüttner and Maklan, 2011; Hosseini et al., 2019). Disruptions are unexpected breakdowns that affect the normal flow of goods and materials within an SC (Craighead et al., 2007), exposing organizations to operational and financial losses (Snyder et al., 2016). In the last two decades, some major disruptive events have caused significant damage to SCs worldwide, such as the 9/11 terrorist attack (Bueno-Solano and Cedillo-Campos, 2014), the 2008 Great Recession (Revilla and Saenz, 2017), the 2011 earthquake and the tsunami it unleashed on Japan (Matsuo, 2015), and the health scares around the Ebola virus in 2013–2016 (Sumo, 2019) and SARS in 2002–2003 (McCormack et al., 2008). More recently, the Coronavirus Disease 2019 (COVID-19) pandemic has generated unprecedented disruptions for most SCs, posing uncertainties and risks in supply, demand, logistics, and labor (Ivanov, 2020; Ivanov and Das, 2020; Ivanov and Dolgui, 2020; Golan et al., 2020). In order to cope with the effects of such events, SCs must be resilient.

A resilient SC must adapt and respond to disruptions, returning to its original operations or moving to a new and desirable state after disturbances (Ponomarov and Holcomb, 2009; Jüttner and Maklan, 2011; Scholten et al., 2014; Kamalahmadi and Parast, 2016). Different strategies have been recommended to foster resilience in SCs, such as collaboration among SC partners, development of redundant suppliers, capacity slack, the establishment of pool demand, and balancing in-house production and outsourcing (Tang, 2006; Pettit et al., 2010; Wieland and Wallenburg, 2013; Scholten and Schilder, 2015). Furthermore, some researchers (e.g., Brandon-Jones et al., 2014; Singh and Singh, 2019; Gu et al., 2020; Dubey et al., 2019; 2020) have investigated the role of new information and communication technologies (ICTs)

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from Industry 4.0 (e.g., big data analytics and blockchain) to enhance SC resilience, suggesting an overall positive impact.

The healthcare SC was particularly affected by the COVID-19 outbreak regarding products, services, infrastructure, and labor directly involved with the containment of the pandemic and those supporting other health treatments (Govindan et al., 2020; Gereffi, 2020; Sharma et al., 2020). According to WHO (2020a), difficult decisions are being made to balance the demands of responding directly to the COVID-19 pandemic with the need to maintain the delivery of other essential health services. Many routine and elective services have been suspended, and existing delivery approaches are being adapted to the evolving pandemic context as the risk-benefit analysis for any given activity changes. When the delivery of essential health services comes under threat, effective governance and coordination mechanisms, and protocols for service prioritization and adaptation, can mitigate the risk of outright system failure.

Aiming at supporting and facilitating health treatments and administrative processes, healthcare SC actors have increasingly adopted new ICTs from Industry 4.0, e.g., big data, cloud computing, and Internet-of-Things (Yi and Cai, 2018; Elhoseny et al., 2018). Such ICTs promote digitization and interconnectivity of processes, products, services, and people (Lasi et al., 2014; Koh et al., 2019). Their application in healthcare has originated the term Healthcare 4.0 (H4.0) (Thuemmler and Bai, 2017), a technology-driven approach that enables real-time customization of healthcare, facilitating the transition to a patient-centered environment (Wang et al., 2018a). The use of Industry 4.0 ICTs to support existing healthcare processes/treatments or develop new ones gives rise to the term 'H4.0 digital application' (Tortorella et al., 2021a). There are some taxonomies of H4.0 applications in the literature. Considering the application focus, Tortorella et al. (2021a) propose four groups: supply chain, patient diagnosis, patient treatment, and patient follow-up. Frank et al. (2019) and Meindl et al. (2021) propose other taxonomies, that while being originated in the Industry 4.0 movement, are useful for health services. These authors propose four ICTs (i.e., IoT, cloud computing, big data, and artificial intelligence) that give rise to four front-end technologies that vary according to their focus of application: (*i*) smart working, (*ii*) smart manufacturing, (*iii*) smart supply chain, and (*iv*) smart product-services. Thus, H4.0 digital applications can be considered an analogous version of the smart functionalities proposed to Industry 4.0 implementation in the manufacturing context.

Some works (e.g., Sharma et al., 2016; Aceto et al., 2018; Oueida et al., 2018; Sannino et al., 2018; Munzer et al., 2019; Tortorella et al., 2020a) have examined the impact of H4.0 on the management of healthcare operations, indicating a positive association between H4.0 digital applications' adoption and healthcare performance. Some recent surveys based on expert-opinion (Rosa et al., 2021; Tortorella et al., 2021b) suggested that those technologies are potentially beneficial to resilient performance in hospitals. However, primary data from real-world applications, interpreted in the light of resilience implications, are still scarce, which is understandable given the novelty of those applications. This research gap grows in importance when considering the highly disruptive scenario imposed by the COVID-19 pandemic, whose implications are unprecedented and might impair the applicability of learning from previous disruptive events (Remko, 2020; Queiroz et al., 2020). That gave rise to the following research question:

> "How has the integration of H4.0 digital applications contributed to the resilience of healthcare organizations during the COVID-19 outbreak?"

To answer that, we conducted an empirical study based on semi-structured interviews with senior managers from clinician and non-clinician departments of Brazilian healthcare organizations. According to WHO (2020b), Brazil is one of the most affected countries in both confirmed cases and deaths from COVID-19. Its healthcare system, however, ranks in the 125th position globally in terms of performance (Tandon et al., 2019). We focused our investigation on the integration of H4.0 digital applications into two Brazilian hospitals and its effects on resilience capability in the scope of disruptions resulting from the COVID-19 pandemic.

Our research followed a qualitative approach, useful in investigating emerging, contemporary phenomena or issues in their real-world settings (Barratt et al., 2011). We grounded our study on concepts from Resilience Engineering (RE), a systems-oriented discipline concerned with finding, assessing, and influencing resilience in socio-technical systems through design (Nemeth and Herrera, 2015). When applied to healthcare, RE is known as resilient healthcare, which is the "ability of the healthcare system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required performance under both expected and unexpected conditions" (Hollnagel et al., 2013, p. xxv). Data collected from the interviews was consolidated and analyzed with respect to the abilities of a resilient system, i.e., monitor, anticipate, respond, and learn (Hollnagel, 2017a, b). Our analysis led to propositions on the contributions of H4.0 digital applications to the resilience of healthcare organizations during the COVID-19 pandemic.

The contribution of our research is two-fold. First, studies on H4.0 implementation are relatively new and still lack empirical evidence of its implications (Wang et al., 2018b; Tortorella et al., 2019a). That is particularly true when considering H4.0's effects on the resilience of healthcare organizations in the face of severe disruptive events, such as the COVID-19 pandemic. Our research contributed to the state-of-the-art on H4.0 by exploring that relationship, providing initial evidence for further empirical validation. Second, we offer insights that may support the establishment of health policies and encourage more assertive investments in digital applications to enhance resilience in healthcare organizations. We thus contribute to the state-of-the-practice on H4.0, exploring its potential as a mitigator of severe disruptive events in communities, organizations, and society. Although our findings emerged from an in-depth investigation in the context of two Brazilian hospitals, we believe they may be useful to other healthcare organizational contexts up to a certain extent.

2. Background

2.1. Healthcare 4.0

The Fourth Industrial Revolution, also denoted as Industry 4.0 (I4.0), derives from digitization and automation trends in the manufacturing environment (Lasi et al., 2014; Koh et al., 2019). I4.0 promotes the use of new ICTs in organizations, supporting more effective and adaptable processes, services, and products (Liao et al., 2017; Tortorella et al., 2019b; Gong and Ribiere, 2020). One of the contexts in which I4.0 ICTs have been used is healthcare (Chen et al., 2014), which led to H4.0. The H4.0 trend encompasses the use of innovative ICTs to customize in real-time the type of healthcare provided to patients (Thuemmeler and Bai, 2017; Chen et al., 2018).

H4.0 systems are characterized by interconnected ICTs, electronics, and microstructure technology that are used to create more effective therapeutic models and auxiliary processes (Yang et al., 2016; Wang et al., 2018a). According to Aceto et al. (2018), four types of interrelated subsets of ICTs are found in healthcare organizations; they are: (*i*) communication, which congregates ICTs that promote diverse ways of interacting and disseminating health-related information; (*ii*) sensing, comprising ICTs to collect data on patients, equipment, materials or processes; (*iii*) processing, concerning ICTs able to transform the collected data into information; and (*iv*) actuation, which encompasses ICTs able to move and control a system, mechanism or software based on the received information.

The application of these ICTs in healthcare is prolific, and its focus varies according to the desired functionality. Table 1 displays some of

Table 1
H4.0 digital applications in healthcare.

	Applications	References
Supply chain	Remote monitoring of vendor managed inventory	12, 16, 17, 20, 22
	Real-time accuracy of inventory status and policies	11, 12, 16, 18, 24
	Radio frequency identification device (RFID) for materials' and products' traceability	2, 11, 12, 16, 17, 22, 24
	Upstream/downstream integration through a common Enterprise Resource Planning (ERP)	2, 12, 16, 19, 22
	Digital platforms to facilitate supplier relationship management	1, 12, 16, 19
	Automated scheduling and control of patients/materials	2, 10, 12, 18, 22
	Modular and customized on-demand medical devices and non-consumables	10, 12, 22
	Real-time demand forecast based on cloud	11, 12, 18, 19, 22
	Interconnected internal material distribution	10, 11, 12, 17, 22
Patient diagnosis	Interconnected and real-time electronic medical record of patients	4, 8, 9, 10, 11, 12, 16, 18, 22, 23
	Augmented reality as clinical decision support	9, 12, 15, 20, 22, 23, 25
	IoT-based health prescription assistant	1, 2, 3, 8, 10, 12, 15, 17, 19, 22, 25
	Virtual doctor-patient interaction and examination	8, 9, 12, 15, 19, 23
	Remote diagnosis through mobile applications	2, 6, 8, 9, 11, 13, 15, 16, 17, 18, 25
	Digital screening of patients' symptoms	8, 9, 11, 12, 15, 19, 23
	Real-time medical encyclopedia cloud	6, 9, 15, 19, 22, 25
	Digital platforms for collaborative sharing of information	2, 19, 20, 22, 23, 24
Patient treatment	Patient real-time information recorded in electronic database	4, 5, 7, 9, 10, 11, 12, 23, 25
	Medical devices traceability system	4, 5, 7, 10, 11, 12, 16, 20, 22, 24
	Wireless body area network	1, 4, 6, 7, 9, 10, 11, 12, 13, 14, 16, 17, 20, 23
	Collaborative robots for complex medical procedures	12, 23
	Virtually aided clinical procedures	12, 13, 15, 20, 23
	Interconnected medical staff, equipment and devices	9, 10, 11, 12, 13, 14, 16, 17, 19, 22, 24
	Digital non-invasive medical techniques	11, 13, 15, 20
	Electronic standardization of medical procedures	9, 12, 13, 14, 17, 20
Patient follow-up	Real-time vital parameters measurement	1, 2, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 16, 17, 21, 23
	Remote monitoring through mobile cloud computing applications	2, 4, 6, 7, 8, 9, 12, 13, 14, 16, 17, 21, 23, 25
	Virtual customization of drug management	8, 11, 12, 15, 20, 21
	Cloud-based real-time prediction of patient status	6, 8, 9, 11, 12, 13, 16, 17, 18, 21, 23, 24
	Secure patient data sharing systems	6, 7, 8, 9, 10, 12, 18, 25
	Digital nutrition management and data record	8, 11, 12, 15, 20, 21
	Synthetic medical data generation	6, 8, 10, 11, 18, 19, 21
	Interconnected medical emergency support	2, 7, 8, 11, 12.17, 21, 23, 24

References: 1-Oueida et al. (2018); 2-Catarinucci et al. (2015); 3- Hossain et al. (2018); 4-Elhoseny et al. (2018); 5-Sannino et al. (2018); 6-Hassan et al. (2019); 7-Almulhim et al. (2019); 8-Manogaran et al. (2018); 9-Wu et al. (2018); 10-Azzawi et al. (2016); 11-Rizwan et al. (2018); 12-Demirkan (2013); 13-Yi and Cai (2018); 14-Uddin (2019); 15-Munzer et al. (2019); 16-Wang et al. (2019); 17-Hamidi (2019); 18-Pace et al. (2018); 19-Wang et al. (2018a); 20-Rajan and Rajan (2018); 21-Yang et al. (2016); 22-Wang et al. (2018b); 23-Sakr and Elgammal (2016); 24-Rghioui and Oumnad (2018); 25-Chen et al. (2018).

the most common H4.0 digital applications, grouped according to four categories of applications (Tortorella et al., 2021a): (*i*) supply chain, (*ii*) patient diagnosis, (*iii*) patient treatment, and (*iv*) patient follow-up. *Supply chain* applications involve the integration of ICTs into the management of materials, products, and equipment used to support health treatments (Catarinucci et al., 2015; Azzawi et al., 2016); they also facilitate communication with suppliers and internal customers (Demirkan, 2013; Rizwan et al., 2018). Applications for *patient diagnosis* aim at fostering more accurate identification of pathologies and patient issues (Yang and Hsiao, 2009; Manogaran et al., 2018), as well as promoting more effective ways to manage patient information, corroborating to the assertiveness of diagnostics (Elhoseny et al., 2018; Munzer et al., 2019). Applications for *patient treatment* aim at facilitating clinical procedures leading to safer, faster, and cheaper methods (Sakr and Elgammal, 2016; Rghioui and Oumnad, 2018). Finally, *patient follow-up* comprises digital applications that remotely allow real-time information and monitoring of patients' conditions (Rajan and Rajan, 2018; Almulhim et al., 2019), favoring continued care after clinical procedures.

The integration of ICTs into healthcare may benefit not only patients but also caregivers as these may have at their disposal accurate and real-time information for decision-making (Wu et al., 2018; Wang et al., 2019; Pan et al., 2019; Tortorella et al., 2020b). According to Tortorella et al. (2020a), the effects of H4.0 on hospitals' performance can be observed both in terms of process measures, e.g., cost and productivity, and patient care measures, e.g., patient satisfaction and safety. Hence, H4.0 implementation may represent a socio-technical change in which not only the technical aspects of healthcare organizations will shift, but also the way caregivers and patients interact (Grover et al., 2018; Wong et al., 2018). The socio-technical nature of H4.0 makes its implementation relevant to healthcare operations management (Pianykh et al., 2020).

Particularly in emergencies such as the COVID-19 pandemic, research on the digital transformation of healthcare has explored different perspectives. For instance, Hassounah et al. (2020) investigated how Saudi Arabia has used digital applications during the pandemic in the domains of public health, health care services, education, telecommunication, commerce, and risk communication. Ohannessian et al. (2020) and Ye (2020) argued that integrated intelligent healthcare systems based on novel health digital applications (e.g., artificial intelligence, big data, 5G, Internet-of-Things, cloud computing technology, sensor technology, telehealth service, and mobile health applications) play an important role in blocking the spread of the pandemic. Badawy and Radovic (2020) discussed a similar role of ICTs but focused on pediatric health care delivery during the pandemic. Overall, most studies have indicated the digitization of healthcare as a facilitator to cope with the COVID-19 pandemic. Nevertheless, the emphasis on enhancing the resilient abilities of healthcare organizations has been tangential, thus reinforcing the relevance of the present study.

2.2. Resilience engineering (RE) and the COVID-19 outbreak

RE models interactions in socio-technical systems, with characteristics that may vary according to the system's complexity. Interactions (*i*) mostly occur between neighboring components (Hollnagel, 2014), with neighboring referring to physical or intangible (e.g., shared professional or cultural background) proximity (Perrow, 1999), (*ii*) are non-linear, meaning an asymmetry between input and output, and the occurrence of small events producing large effects in the system (Bergström et al., 2011), (*iii*) may also occur with the environment, which represents a permanent source of variability (Wears and Vincent, 2013), (*iv*) are path-dependent, i.e., past performance influences current behaviors, (*v*) are dynamic, with intensity varying over time (Wachs et al., 2012), and (*vi*) may happen between a large number of diverse actors (Braithwaite et al., 2019). In RE, failure is understood as a maladaptation, i.e., the system was unable to perform necessary adaptations to handle real problems. Thus, failure is not seen as a system's breakdown or malfunction; they indicate a need to adjust individuals' or organization's performance to the prevalent conditions (Madni and Jackson, 2009; Son et al., 2020).

RE takes an organizational perspective of resilience, postulating that resilient systems rely on four abilities, namely (Hollnagel, 2017a,b): (*i*) *monitor*, which implies knowing what to look for, focusing on what is critical or may become a threat in the short term; (*ii*) *anticipate*, which implies knowing what to expect, foreseeing threats and opportunities, potential changes, disruptions, pressures, and their consequences; (*iii*) *respond*, which implies knowing what to do, addressing regular and irregular disruptions and disturbances either by implementing a prepared set of responses or by adjusting normal functioning; and (*iv*) *learn*, which implies knowing what has happened from successes as well as failures, addressing the factual to learn the right lessons from the right experience. The four abilities are interrelated and should not necessarily be deployed with the same intensity, i.e., depending on the context, an organization may need to be more or less effective in one of those abilities (Hollnagel, 2011). The four abilities also convey that resilient performance has a proactive (e.g., anticipating) and a reactive (e.g., responding) dimension.

It is also worth mentioning that the concept of resilience (as proposed by RE) implies managing the trade-off between efficiency and thoroughness (or safety). Given the scarcity of resources and uncertainty that characterize complex situations, such as the pandemic, systems are constantly adjusting their performance and negotiating goals in order to survive and comply with societal and customers' requirements. This means that a resilient system may prioritize either efficiency or thoroughness depending on the circumstances (Hollnagel, 2017a,b). This concept differs from efficiency and effectiveness. While efficiency may be denoted by the ability to avoid wasting resources (in general) in doing something or in producing a desired result, effectiveness might refer to the degree to which something is successful in producing a desired result (Jeong and Phillips, 2001; Mouzas, 2006). Although the development of resilience might be interrelated with the achievement of efficiency and effectiveness in organizations, their concepts are not equal. A key aspect that is used to verify resilience is how the focal organization copes with a severe disruptive event, either by monitoring and anticipating its occurrence or by promptly responding and learning from this disruption (Tortorella et al., 2021b). In other words, the capacity of absorbing, adapting, and restoring after the occurrence of severe disruptive events is attributed to the resilience of the organization (Hosseini et al., 2019). An organization may be efficient and effective; but if it is not resilient, such efficiency and effectiveness are unlikely to be verified during (and even after) the occurrence of a disruptive event, such as the pandemic.

In healthcare, RE has shed light on the gap between what is prescribed in standardized operational procedures and what really occurs in practice, as well as on new approaches for patient safety, which rely on learning from everyday work, instead of only from adverse events (Clay-Williams et al., 2015). One of the most common applications of RE involves the retrospective analysis of undesired events, such as industrial accidents and natural disasters (Righi et al., 2015). Studies usually stress that these events do not have any single root cause, rather emerging from unintended interactions between a large number of social and technical elements (Patriarca et al., 2018). These characteristics are clearly present in the COVID-19 outbreak, which indicates the applicability of RE in that context.

The COVID-19 outbreak has challenged the resilience of healthcare systems. As the virus rapidly propagates, delays or failures in coping with its prevalence increase the number of infected people (Emanuel et al., 2020). In such a critical scenario, a shortage of healthcare resources (e.g., material, products, equipment, and personnel) tends to emerge, directly affecting the ability of healthcare systems to mitigate the epidemic effects (Govindan et al., 2020). That also has side effects in treating other diseases, as the few existing resources are usually redirected to contain and treat COVID-19 patients (Ji et al., 2020). As a result, a shortage of healthcare resources leads to an increase in the number of infected people, implying an even larger disaster (Geng et al., 2020).

As such, healthcare organizations have been forced to build adaptive capacity on the fly to keep their systems running in the face of adversity. Although digital applications might support resilient performance both in everyday work and during emergencies, little is known on how that support plays out, especially in a crisis. Digital applications are often approached in RE and in the human factors' literature in general as an additional source of complexity that brings their own risks (Rosa et al., 2021). Digital applications' contribution to successful performance has been much less explored. That is paradoxical with the RE concern in understanding why successful outcomes occur, in addition to why unwanted outcomes occur (Hollnagel, 2011, 2017). In this context, it becomes relevant to understand how to improve the system's resilience so that a rapid reaction is developed, mitigating the implications of the pandemic.

3. Research design

Our research deals with two recent phenomena: (*i*) H4.0 implementation and (*ii*) the COVID-19 pandemic. As impacts of both phenomena on healthcare are still incipient, we followed a qualitative approach, which is aligned with the exploratory and descriptive nature of our study (Voss et al., 2002; Barratt et al., 2011). Following McCutcheon and Meredith (1993) and Ketokivi and Choi (2014), the study used *a priori* theorization to frame the research design; findings are therefore not statistically generalizable. More specifically, the conduction of case studies allows the formulation of hypotheses rather than quantitatively stating statistical facts (Yin, 2012). In other words, the claims made when generalizing from case studies cannot be considered as "proof" in a statistical sense (Wikfeldt, 2016). Rather, they build theoretical premises which function as a tool to make assertions about situations akin to the one studied (Yin, 2013). That allowed an in-depth understanding of the contribution of H4.0 digital applications to the resilience of healthcare systems during the COVID-19 outbreak, producing novel insights to the field.

The proposed method consists of three main steps: (*i*) determination of selection criteria for organizations and interviewees; (*ii*) interviews with leaders of healthcare organizations; and (*iii*) content analysis and propositions. These steps are detailed next. The analysis of the information collected allowed the investigation of the conceptual model illustrated in Fig. 1. H4.0 digital applications were categorized according to their application focus, as suggested by Tortorella et al. (2021a). Then, we examined their impact on healthcare organizations' resilience abilities (Hollnagel, 2017a,b) during the disruptions caused by the COVID-19 pandemic. The understanding of the relationships proposed in the conceptual model, from the RE perspective and derived from a case-based research, grounds our theoretical propositions that add to the body of knowledge on the digitalization of healthcare.

3.1. *Determination of selection criteria for organizations and interviewees*

Multiple case studies can strengthen external validity and help prevent observer bias, creating more robust and testable theories than a single case study (Barratt et al., 2011). Selection criteria were established to ensure that the investigated cases were relevant for the research purpose. First, since we wanted to control the socioeconomic context, organizations should be located in the same region of Brazil. According to Bhaskaran and Sukumaran (2007) and Schneckenberg and Milosevic (2012), significant differences in management practices may

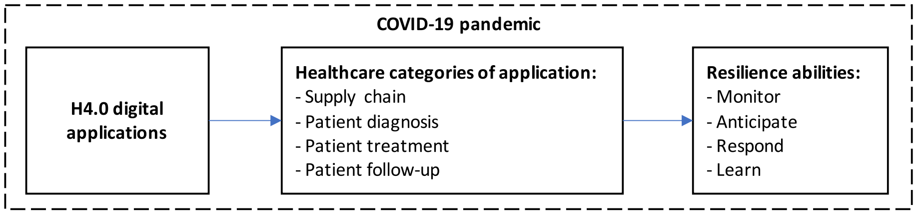

Fig. 1. Investigated conceptual model.

be found across organizations owned and managed by individuals of different nationalities, especially in healthcare organizations (Kaplan et al., 2010). Second, organizations should have reasonable experience with H4.0 implementation integrating ICTs into their administrative processes and health treatments. Third, considering our scope, organizations should be treating patients infected with SARS-CoV-2. Finally, since an extensive H4.0 implementation entails investments in expensive ICTs (Tortorella et al., 2020b), we included healthcare organizations of public and private ownership. That would allow us to identify the pervasiveness of the effects of H4.0 on the resilience of healthcare organizations with different capital expenditure capacities.

The following criteria were established to select interviewees. First, they should have been working for at least five years in the organization. Second, they should play a key leadership role, which would supposedly allow them to have a broader view of the organization and its processes, legitimizing their perceptions. That is a common selection criterion found in studies that also aimed at assessing the whole organization based on the empirical evidence collected from few respondents (e.g., Mandal, 2020; Tortorella et al., 2020a). Further, leaders are crucial in supporting and implementing radical changes (Huy, 2001), such as shifting towards H4.0. Third, as healthcare organizations encompass a variety of administrative processes and health treatments, we aimed at leaders from both clinician and non-clinician departments. The combination of different perspectives would enable a holistic understanding of our research problem.

Two large-sized (i.e., with more than 100 inpatient beds) Brazilian hospitals were selected, one public (Hospital A) and one private (Hospital B). Both hospitals treat patients infected with SARS-CoV-2, having developed specific routines to avoid widespread contagion of the virus (further detailed in section 4). Six and four leaders were interviewed in the private and public hospitals, respectively, being recommended by their senior management in compliance with our selection criteria. The main characteristics of hospitals and interviewees are given in Table 2. The experience of the interviewees ranged between 7 and 28 years. Five of them worked in clinician departments (e.g., nursing and clinical analysis laboratory), while the other five were from non-clinician departments (e.g., supply chain and ICT). One of them had a coordinator position, four were managers, four were directors, and one played a chief role.

3.2. *Interviews with leaders of healthcare organizations*

We conducted online interviews between mid-July and mid-August 2020 when the pandemic in Brazil was at its peak (at least up to the moment of writing this article). Interview coding, cross-interview analysis, and fact-checking were completed during the second half of August 2020. Given the multidisciplinary background of interviewees, they were initially presented to the H4.0 concepts and main digital applications considered in our research (as seen in Table 1) to establish common understanding; their anonymity was guaranteed to assure candid responses. Our research was approved by the ethics committee of both hospitals, and the interviewees received a consent form.

Individual interviews followed a semi-structured script of questions (see Appendix) that allowed open answers and the introduction of new ideas during the interview based on interviewees' statements, giving them more opportunities to fully express themselves and helping us add questions to the interview script. Questions were grouped into three parts. The first part comprised the professional background of interviewees. The second part sought information on the adoption level of H4.0 in both regular health treatments and administrative processes within hospitals during the past few years. The last part encompassed questions on H4.0 implementation, specifically during the past few months, during the COVID-19 pandemic.

Although we established a framework of themes to be explored during the interview (i.e., the three parts of the interview protocol), none of the questions was explicitly related to the impact of H4.0 digital applications on the *resilience abilities* of the healthcare organizations. That was intentionally designed since the explicit formulation of the leading question can subtly orient interviewers toward a certain way (Westby et al., 2003), potentially adding bias to responses. In pre-tests of the interview protocol, it became evident that several H4.0 digital applications descriptions would directly associate them with certain resilience abilities, inducing responses, e.g., *remote monitoring of vendor managed inventory* and *remote monitoring through mobile cloud computing applications* which are directly associated with the *monitor* ability, although their main application is in *anticipating* events and creating reference databases to be used in *learning*. To overcome that, we prepared questions that would allow interviewees to loosely indicate the contributions of H4.0 digital applications during the COVID-19, such as

Table 2
Hospitals' characteristics and interviewees' profile.

Hospital	Ownership	Nº of inpatient beds dedicated to COVID-19	Nº of ICU beds dedicated to COVID-19	Interviewee	Role (Type)	Experience
A	Public	75 (out of 257)	10 (out of 45)	1	Supply Chain Manager (NC)	28 years
				2	Administrative Manager (NC)	21 years
				3	ICT Manager (NC)	10 years
				4	Clinical Analysis Laboratory Chief (C)	15 years
				5	Medical Director (C)	25 years
				6	Nursing Director (C)	23 years
B	Private	25 (out of 119)	5 (out of 29)	7	Medical Director (C)	8 years
				8	Nursing Director (C)	18 years
				9	Supply Chain Manager (NC)	11 years
				10	ICT Coordinator (NC)	7 years

Notes: ICU = Intensive Care Units; ICT = Information and Communication Technologies; NC = non-clinician; C = clinician.

Table 3
Consolidated information on H4.0 implementation in Hospital A.

Applications		Frequency[a, b]	Motivation	Benefits	Barriers	Stakeholders	Facilitators[c]
Supply chain	Remote monitoring of vendor managed inventory	100.0%	Need to comply with government guidelines and policies, as this is a public hospital. Need to be up-to-date with technologies used in some critical medical procedures to properly teach students. That forced the integration of new digital technologies into specific patient treatments.	Lower costs and ease of treatment of patients in remote locations, through Telemedicine The integration of an ERP system allowed a better management of materials, with accurate information on their availability. Although not fully implemented yet, the use of digital technologies helped to store patient data in a more efficient and secure way. The goal is to go fully digital.	Lack of human and financial resources to fully adopt H4.0 digital applications. As most patients are from low-income families, the use of digital technologies that foster remote diagnosis, treatment or follow-up is not entirely feasible. There is a huge cultural challenge to be overcome. Staff still perceives the integration of digital technologies as a means to reduce personnel.	- Senior management - Federal Government - Large-sized suppliers - Students - Local communities	- ICTs -Maintenance - Finance - Purchasing
	Real-time accuracy of inventory status and policies	0.0%					
	RFID for materials' and products' traceability	0.0%					
	Upstream/downstream integration through a common ERP	100.0%					
	Digital platforms to facilitate supplier relationship management	100.0%					
	Automated scheduling and control of patients/materials	33.3%					
	Modular and customized on-demand medical devices and non-consumables	0.0%					
	Real-time demand forecast based on cloud	16.6%					
	Interconnected internal material distribution	16.6%					
Patient diagnosis	Interconnected and real-time electronic medical record of patients	33.3%					
	Augmented reality as clinical decision support	16.6%					
	IoT-based health prescription assistant	0.0%					
	Virtual doctor-patient interaction and examination	100.0%					
	Remote diagnosis through mobile applications	50.0%					
	Digital screening of patients' symptoms	50.0%					
	Real-time medical encyclopedia cloud	16.6%					
	Digital platforms for collaborative sharing of information	33.3%					
Patient treatment	Patient real-time information recorded in electronic database	33.3%					
	Medical devices traceability system	16.6%					
	Wireless body area network	16.6%					
		33.3%					

(*continued on next page*)

Table 3 (*continued*)

Applications		Frequency[a,b]	Motivation	Benefits	Barriers	Stakeholders	Facilitators[c]
	Collaborative robots for complex medical procedures						
	Virtually aided clinical procedures	0.0%					
	Interconnected medical staff, equipment and devices	0.0%					
	Digital non-invasive medical techniques	50.0%					
	Electronic standardization of medical procedures	0.0%					
Patient follow-up	Real-time vital parameters measurement	16.6%					
	Remote monitoring through mobile cloud computing applications	0.0%					
	Virtual customization of drug management	0.0%					
	Cloud-based real-time prediction of patient status	0.0%					
	Secure patient data sharing systems	66.7%					
	Digital nutrition management and data record	66.7%					
	Synthetic medical data generation	16.6%					
	Interconnected medical emergency support	0.0%					

[a] Represents the percentage of interviewees who indicated the H4.0 digital application as being used in the hospital.
[b] Partial consensus items are mentioned by 50%–99% of respondents; full consensus items are mentioned by 100% of respondents.
[c] Hospital departments involved in H4.0 implementation.

Table 4
Contributions of H4.0 digital applications during the COVID-19 pandemic in Hospital A.

H4.0 applications listed by respondents as useful in the treatment of COVID-19 patients		Direct contributions to fight the pandemic	Indirect contributions to other patients and staff
Supply chain	Remote monitoring of vendor managed inventory Upstream/downstream integration through a common ERP Digital platforms to facilitate supplier relationship management	Specifically for consumables related to the treatment of the COVID-19 (e.g. PPE, hand sanitizer), the use of digital platforms to communicate with suppliers facilitated quicker replenishment and more accurate review of inventory policies. The integration of those digital applications allowed to remotely diagnose patients with respiratory problems, avoiding an overexposure of patients that did not present COVID-19 symptoms, minimizing the risk of contagion. The pandemic is new, and hospitals are still learning how to curb its implications. Digital applications that fostered secure patient data and information sharing were extremely useful.	The use of a corporative ERP enabled to identify unbalance in the distribution of resources across the hospital. That helped to promptly address those issues, minimizing shortages in areas isolated to treat the pandemic as well as other hospital areas. Although more staff was hired, many professionals were relocated from regular departments to the isolated COVID-19 area. In this sense, the possibility of virtually interacting with patients from the original departments facilitated the daily routine. This is a teaching hospital; however, there has always been complaints about the way information was shared. One positive aspect of the pandemic is that it forced to rapidly expand digital applications that support information and knowledge sharing between areas and departments beyond those dedicated to treat COVID-19 patients."
Patient diagnosis	Virtual doctor-patient interaction and examination Remote diagnosis through mobile applications Digital platforms for collaborative sharing of information		
Patient treatment	Patient real-time information recorded in electronic database		
Patient follow-up	Secure patient data sharing systems		

question 3c: "*which contributions of the Healthcare 4.0 digital applications to treat COVID-19 patients did you observe? Please, justify your answer and give examples*". The interview protocol was pre-tested and validated by three experts (two academics and one practitioner). Those experts had at least 5 years of experience in healthcare digitalization and were already involved in previous studies developed by the authors; therefore, they were familiar with the research topic. They verified the face validity (Gravetter and Forzano, 2018) of our interview protocol, and suggested changes in questions' content and wording. Those improvements were implemented before we conducted the semi-structured interviews.

All interviews were audio-recorded and followed the same sequence of questions, lasting from 30 to 90 min. No ideas from earlier interviews were introduced into subsequent ones, as suggested by Guest et al. (2017). Interviews were attended by at least two authors, increasing the ability to handle contextual information confidently (Dubé and Paré, 2003). Leaders were asked to describe the adoption of H4.0 digital applications listed in Table 1 in their healthcare organizations during the past few years, indicating and exemplifying benefits and barriers. They were also asked whether and how those digital applications were contributing during the COVID-19 outbreak. Moreover, during the interviews we tried to restate and summarize the interviewees' answers to confirm their opinions. Idiosyncratic responses were disregarded in the interest of focusing on dominant patterns among interviewees.

3.3. *Content analysis and propositions*

Content analysis is the most common example of qualitative data analysis. It refers to the categorization, tagging, and thematic analysis of qualitative data and may include combining the analysis results with behavioral data for deeper insights (Mayring, 2004). Content analysis was adopted to examine patterns in communication in a replicable and systematic manner. One of the key advantages of using content analysis to analyze social phenomena is its non-invasive nature, in contrast to simulating social experiences or collecting survey answers (Westbrook, 1995; Bell et al., 2018). Practices of content analysis involve systematic observation of texts or artifacts, which are assigned labels (also denoted as codes) to indicate the presence of interesting, meaningful pieces of content (Hodder, 1994). By systematically coding the content of a set of texts, researchers can analyze content patterns using either quantitative or qualitative methods. While methods in quantitative content analysis transform observations of found categories into quantitative statistical data, the qualitative content analysis focuses on the intentionality and its implications (Vaismoradi et al., 2013).

In this step, we carried out a content analysis of transcripts from the interviews to develop a chain of evidence (Carter et al., 2014) that supported the formulation of propositions for theory testing in future studies. The audio-recorded information was transcribed and subsequently analyzed qualitatively and discussed by the authors. The qualitative content analysis allowed us to deal with the intricacies of latent interpretations, looking to patterns more closely and more easily identifying latent meanings (White and Marsh, 2006).

To code our findings, we used excerpts from the transcripts and manually analyzed the information obtained from interviews. The coding of the qualitative data, identification of different themes, and the relationships between them were based on words and short phrases as labels, as they are easier to skim and organize (Hsieh and Shannon, 2005). Codes were then sorted into categories based on how different and related they were, organizing findings into meaningful information blocks. Such qualitative analysis was independently conducted by two authors, who had their codes and arguments conciliated by a third author; summaries were then merged after reaching a consensus on the main findings (Miles and Huberman, 1994). This conciliation allowed to establish consensus and consistency in the findings' reasoning (Tortorella et al., 2019a).

Given our study purpose, descriptive information about the case studies was grouped into two broad topics: (*i*) H4.0 implementation in the organization during the past few years and (*ii*) the role of H4.0 digital applications in the treatment of COVID-19 patients. For topic (*i*), the collected data were classified into six categories, namely: (*a*) adoption frequency of H4.0 according to each application focus (i.e., supply chain, patient diagnosis, patient treatment, and patient follow-up), (*b*) motivation for H4.0 adoption, (*c*) benefits and (*d*) barriers for H4.0, (*e*) stakeholders and (*f*) facilitators of the implementation. For topic (*ii*), information was coded into four categories: (*a*) H4.0 digital applications useful in the treatment of COVID-19 patients, (*b*) direct contributions to fight the pandemic, and (c) indirect contributions to other patients and staff.

While topic (*i*) provided some context for our investigation, results from topic (*ii*) were later framed according to the four main abilities of resilient systems (monitor, anticipate, respond, and learn). In other words, both the direct and indirect contributions of each H4.0 digital application deemed useful in the treatment of COVID-19 patients were associated with corresponding resilience abilities. To support this classification, we also sought additional evidence of H4.0 contributions to hospitals' resilience abilities in comments from interviewees (e.g., details in examples provided, arguments used to justify answers, similarity

Table 5
Consolidated information on H4.0 implementation in Hospital B.

Applications		Frequency[a]	Motivation	Benefits	Barriers	Stakeholders	Facilitators[b]
Supply chain	Remote monitoring of vendor managed inventory	100.0%	Integration of new digital technologies into processes has been a strategic guideline to maintain competitiveness and quality. It is mandatory to digitally transform the hospital so that it can provide high quality and efficiency care. This is a reference hospital in the state. To remain as such, it must adapt to the newest digital trends and procedures.	The integration of an ERP system allowed to better synchronize materials planning and inventory control with most suppliers. Electronic medical records enable more assertive patient diagnosis. The availability of data minimizes misguided medical recommendations. The use of RFID for tracking critical medical devices allows to identify collaboration opportunities, such that common resources may be shared throughout the hospital. The quality of medical procedures is widely recognized. The integration of H4.0 digital applications helps to ensure that and is perceived by patients.	The hospital infrastructure is an issue. Although it has significantly improved over the years, it still has a long way to go to fully digitalize processes and treatments. Few doctors are still skeptical with respect to the benefits of H4.0 digital applications. That has been a barrier for a more extensive implementation. Hospital is learning. This takes time and resources. The biggest issue is to handle the high expectations of stakeholders in face of investments. Technology has helped a lot. However, there may be a point where staff behaviors will determine whether technology can take the hospital further or not.	- Senior management - Local communities - Suppliers - Third parties (e.g. clinical analysis laboratories, sterilization centers and imaging exam clinics)	- ICT - Maintenance - Quality assurance - Purchasing
	Real-time accuracy of inventory status and policies	25.0%					
	RFID for materials' and products' traceability	0.0%					
	Upstream/downstream integration through a common ERP	100.0%					
	Digital platforms to facilitate supplier relationship management	100.0%					
	Automated scheduling and control of patients/materials	50.0%					
	Modular and customized on-demand medical devices and non-consumables	0.0%					
	Real-time demand forecast based on cloud	25.0%					
	Interconnected internal material distribution	75.0%					
Patient diagnosis	Interconnected and real-time electronic medical record of patients	75.0%					
	Augmented reality as clinical decision support	25.0%					
	IoT-based health prescription assistant	0.0%					
	Virtual doctor-patient interaction and examination	50.0%					
	Remote diagnosis through mobile applications	50.0%					
	Digital screening of patients' symptoms	50.0%					
	Real-time medical encyclopedia cloud	50.0%					
	Digital platforms for collaborative sharing of information	75.0%					
Patient treatment	Patient real-time information recorded in electronic database	100.0%					
	Medical devices traceability system	75.0%					
	Wireless body area network	25.0%					
	Collaborative robots for complex medical procedures	50.0%					
	Virtually aided clinical procedures	50.0%					
	Interconnected medical staff, equipment and devices	25.0%					
	Digital non-invasive medical techniques	100.0%					
	Electronic standardization of medical procedures	0.0%					
Patient follow-up[c]	Real-time vital parameters measurement	100.0%					
	Remote monitoring through mobile cloud computing applications	25.0%					
	Virtual customization of drug management	0.0%					
	Cloud-based real-time prediction of patient status	0.0%					
	Secure patient data sharing systems	100.0%					
	Digital nutrition management and data record	25.0%					
	Synthetic medical data generation	50.0%					
	Interconnected medical emergency support	50.0%					

[a] Represents the percentage of interviewees who indicated the H4.0 digital application as being used in the hospital.
[b] Partial consensus items are mentioned by 50%–99% of respondents; full consensus items are mentioned by 100% of respondents.
[c] Hospital departments involved in H4.0 implementation.

in responses between clinician and non-clinician departments), as recommended by Narasimhan (2014). Based on the interviews' qualitative content analysis, contributions of H4.0 to resilience abilities were classified into three classes: 'not explicitly mentioned', 'briefly mentioned', and 'emphatically mentioned'.

Previously mentioned narratives were revisited to establish data documentation, including all data sources and reflections, ideas, and insights. Identifying commonalities allowed us to formulate general propositions that stressed the relationships between H4.0 digital applications and the previously mentioned four main abilities of resilient systems. Those propositions are useful for further theory testing and validation (Meredith, 1998; Gehman et al., 2018). Finally, as Ketokivi and Choi (2014) recommended, attention was paid to idiosyncrasy and transparency of reasoning to rigorously conduct the multiple case study.

4. Results

We now give an overview of the hospitals in our sample and report the main findings from the interviews.

4.1. Case study 1: public hospital (hospital A)

Hospital A, located in Southern Brazil, is a public teaching hospital that provides high complexity care through the Brazilian Unified Health System (SUS). The hospital offers telemedicine and telehealth services as well as distance health education to remote communities. It has 257 inpatient ward beds (75 dedicated to COVID-19 cases) and 45 intensive care beds (10 dedicated to COVID-19 cases). 103 new staff (e.g., physicians, nurses, technicians, and physiotherapists) were hired to provide additional support during the COVID-19 pandemic. Contingency countermeasures were implemented to cope with the pandemic and avoid exposure of other patients and hospital staff to COVID-19 patients; e.g., an exclusive process flow for patients with respiratory problems, and training of assistance teams to provide care to critically ill patients and use of personal protection equipment (PPE).

Regarding H4.0 implementation, although respondents were from different departments, there was some alignment in their responses (see Table 3). The most acknowledged H4.0 digital applications were those focused on supply chain and administrative processes. That may be justified by the implementation of an ERP system, which is focused on such processes and is still undergoing adjustments to meet specific needs. Although the initial utilization of the acronym ERP dates back to 1990s (Wylie, 1990), the ERP software market is still under significant growth. For instance, in 2019, this market grew by 9% and resulted in a worldwide value of approximately US$ 39 billion in total software revenues (Pang and Kostoulas, 2020). Particularly in the healthcare sector, many authors (e.g., Demirkan, 2013; Catarinucci et al., 2015; Wang et al., 2019; Wang et al., 2018a; 2019) have emphasized its increasing relevance to properly integrate upstream and downstream processes in the healthcare supply chain as part of the H4.0 implementation. Wang et al. (2018b) highlighted that information integration is fundamental to successfully implement big data analytics since the challenges involved in integrating information across systems and data sources within the healthcare organizations remain problematic. Most healthcare organizations find it difficult to integrate data from legacy systems into big data analytics frameworks, reinforcing the importance of ERP systems as part of H4.0 digital applications. The integration of the ERP system to processes, materials, and products in Hospital A has been prioritized according to their perceived relevance. As described by the administrative manager, "*We have been adopting a step-by-step approach to implement these new digital applications over the past few years, in order to learn as we advance and ensure the efforts are worthwhile. With that in mind, we have started this implementation with the most expensive materials, whose suppliers are long-term partners*". The adoption of some H4.0 digital applications, such as 'remote monitoring of vendor managed inventory', was initially targeted at large-sized suppliers, and the hospital just needed to go along with it, facilitating the implementation process. Due to existing initiatives in telemedicine at the hospital, the H4.0 digital application' virtual doctor-patient interaction and examination' was also a consensus among all interviewees. In opposition, some other H4.0 digital applications were not identified by any of the interviewees. Most of them were related to patient follow-up, such as 'remote monitoring through mobile cloud computing applications', 'virtual customization of drug management', 'cloud-based real-time prediction of patient status', and 'interconnected medical emergency support'.

Regarding motivation to H4.0 implementation, that was justified two-fold. First, the fact that the Brazilian Unified Healthcare System sets standard policies and guidelines to all public hospitals, which are pushed to comply with them. Second, as a teaching hospital, some of the medical procedures should be constantly updated so that students could learn the latest techniques. That forced the hospital to integrate digital applications (e.g., 'digital non-invasive medical techniques') into specific patient treatments.

When asked about contributions of H4.0 digital applications to treat COVID-19 patients, interviewees identified 8 (out of 33) applications with significant impact (see Table 4). Supply chain (3) and patient diagnosis (3) were the processes that most benefited from H4.0 digital applications, followed by patient treatment (1) and patient follow-up (1). Such a result is expected considering the reported adoption level of H4.0 digital applications in Hospital A (shown in Table 3).

Interviewees justified the perceived contribution of H4.0 digital applications in fighting the COVID-19 pandemic by three main aspects. The first was related to the accuracy of inventory and ease of communication with suppliers responsible for providing critical consumables to treat COVID-19 patients. H4.0 digital applications, such as "remote monitoring of vendor managed inventory" and "digital platforms to facilitate supplier relationship management", supported the constant review of inventory policies of consumables whose demand has drastically increased. During the pandemic, material replenishment became an important issue, and a closer relationship with suppliers was essential to reduce or avoid shortages. Second, since the outbreak began, exposure and higher risk of contagion became constant concerns of hospital staff. The use of digital applications that allowed to remotely diagnose potentially infected individuals mitigated that, enabling safe triage of critical cases. Third, being an unprecedented event, sharing information and knowledge about treatments and follow-up of COVID-19 patients became fundamental. H4.0 digital applications such as 'patient real-time information recorded in electronic database' and 'secure patient data sharing systems' played a key role, enabling more effective and systematic learning.

Some indirect contributions of H4.0 implementation were also reported. The treatment of COVID-19 patients required materials and products that are often used in other treatments, potentially unbalancing their supply. According to interviewees, upstream/downstream integration through a common ERP system helped identify demand issues, enabling a faster reaction to avoid or reduce shortages in other departments. In addition to new hirings to cope with the outbreak, staff was also relocated from their original assignments to support COVID-19 treatment. Interviewees mentioned that H4.0 digital applications, such as 'virtual doctor-patient interaction and examination', allowed doctors to keep contact with patients from their original departments. Finally, interviewees emphasized that sharing of information and knowledge across the hospital was beneficial not only to treat COVID-19 patients but established new information flows throughout the hospital.

4.2. Case study 2: private hospital (hospital B)

Hospital B, also located in Southern Brazil, is a private-owned organization specialized in general clinic, dermatology, urology, and cardiology. It has 119 inpatient ward beds (25 dedicated to COVID-19 cases) and 29 intensive care beds (5 dedicated to COVID-19 cases).

Table 6
Contributions of H4.0 digital applications during the COVID-19 pandemic in Hospital B.

H4.0 applications listed by respondents as useful in the treatment of COVID-19 patients		Direct contributions to fight the pandemic	Indirect contributions to other patients and staff
Supply chain	Remote monitoring of vendor managed inventory Real-time accuracy of inventory status and policies Upstream/downstream integration through a common ERP Digital platforms to facilitate supplier relationship management Automated scheduling and control of patients/materials	Due to sudden demand increase in specific consumables and supplies, these digital applications helped to rapidly rearrange inventory policies. They also allowed to constantly interact with suppliers to identify risks and anticipate material shortages. That was especially relevant with offshore suppliers. H4.0 technologies helped to minimize contagion risks, as individuals' diagnosis was done remotely. Their data was immediately stored in the records, also allowing the identification of trends on different symptoms, generating valuable information to combat the pandemic. Due to the development of a special process flow for patients with respiratory problems, tracking them and some of the associated medical devices used to treat COVID-19 (e.g. mechanical ventilators) helped to better manage the capacity. It enabled quicker countermeasures whenever bottlenecks were identified.	The hospital used to have vendor managed inventory for critical materials and products. However, suppliers needed to visit frequently to check their inventory levels. To reduce staff exposure and contagion risks, this system was improved so that suppliers could remotely monitor their products' inventories. Motivated by the COVID-19 outbreak, the medical encyclopedia was revisited and improved, expanding its access to personnel from different departments. Knowledge management has always been an issue across the hospital. The emphasis on using digital platforms that could foster that to cope with the pandemic had side effects in the entire hospital. People seem to realize how important it is and are willing to adopt this digital application much beyond the treatment of COVID-19. The observed benefits of digital applications to fight the pandemic have helped to demystify their utilization to other departments and personnel that used to be resistant.
Patient diagnosis	Virtual doctor-patient interaction and examination Remote diagnosis through mobile applications Real-time medical encyclopedia cloud Digital platforms for collaborative sharing of information		
Patient treatment	Patient real-time information recorded in electronic database Medical devices traceability system		
Patient follow-up	Real-time vital parameters measurement Secure patient data sharing systems		

Table 7
Contribution of H4.0 digital applications to hospitals' resilience abilities.

H4.0 digital application	Monitor		Anticipate		Respond		Learn	
	Public	Private	Public	Private	Public	Private	Public	Private
Supply chain	++	++	++	++	+	++	N	N
Patient diagnosis	++	++	++	++	+	+	++	++
Patient treatment	N	+	++	++	+	++	++	++
Patient follow-up	+	+	N	N	N	N	++	++

Notes: N: not explicitly mentioned; +: briefly mentioned; ++: emphatically mentioned.

Dedicated facilities (e.g., surgery center, intensive care unit, laboratory, and imaging diagnosis services) serve emergency and urgency cases and staff. Hospital B has also implemented initiatives to face the pandemic, most notably a 5-step healthcare flow for patients presenting respiratory problems, including pre-screening, medical consultation, isolated patient transportation throughout the hospital, image examination, and hospitalization. No additional staff was hired or new equipment purchased to treat COVID-19 patients.

Based on the interviews, H4.0 implementation in this hospital appears to be more pervasive than in Hospital A, reaching more departments and processes and using a wider range of digital applications. In addition to supply chain benefits observed in Hospital A, patient diagnosis, treatment and follow-up were also reported as positively impacted by digitization. As shown in Table 5, there was partial or full consensus among interviewees on the utilization of 20 out of the 33 applications in Table 1. From those, 5 referred to supply chain, 6 to patient diagnosis, 5 to patient treatment, and 4 to patient follow-up. The higher pervasiveness of H4.0 is somewhat coherent with the assumption that private organizations in emerging economies are likely to have more capital expenditure capacity than public ones (Tortorella et al., 2020b), facilitating wider adoption of digital applications. With respect to the motivations to adopt H4.0, unlike Hospital A, which was mainly driven by external requirements (e.g., government and large suppliers), Hospital B acknowledged H4.0 as strategic for achieving higher performance and competitiveness. As stated by the medical director, "*Digitization of our processes, treatments, and routines is a one-way ticket; those who do not get on board will have no place in the healthcare business*". Although interviewees realize that the hospital is far from full implementation, they have perceived significant advances over the past few years. That was emphasized regarding the use of applications associated with surgical procedures, such as 'patient real-time information recorded in electronic database', 'digital non-invasive medical techniques', and 'real-time vital parameters measurement'. Surgeries account for a significant part of the hospital's revenues, justifying the investments in technology.

As expected, benefits of H4.0 adoption have been noticed in a diversified range of aspects, from materials management and supplier relationship to patient diagnostic and information sharing. Interviewees visualize H4.0 adoption as a value-added activity since patients recognize digitization as a promoter of healthcare quality assurance. On the other hand, when discussing the barriers to H4.0 (except for the ICT coordinator), all leaders emphasized sociocultural factors as challenges to more extensive use of digital applications, which is aligned with Pan et al.'s (2019) findings. Such factors include skepticism from medical doctors and difficulties in staff behavioral changes, and handling of short-term expectations of senior management.

Table 6 summarizes the perceived contributions of H4.0 digital applications during the COVID-19 pandemic in Hospital B. Thirteen digital applications were indicated as useful to cope with the pandemic; those associated with supply chain and patient diagnosis were most prominent. Among the direct contributions of H4.0, remote diagnosis and virtual examination of patients with respiratory problems were emphatically mentioned. As observed in Hospital A, those applications reduce the number of individuals coming to the hospital to check their symptoms. Additionally, interviewees emphasized the role of H4.0 digital applications in the effectiveness of the special flow designed to treat patients with respiratory problems. For instance, both patients and medical devices were digitally tracked throughout the flow; with that, management can easily identify queues, idleness, and bottlenecks, addressing these issues with faster countermeasures. That was critical to avoid too many patients in close proximity or excessive waiting times. Finally, H4.0 was also relevant to manage inventories and interact with suppliers, particularly those offshore that provided materials needed to treat COVID-19 patients. Digital applications were perceived as a means to identify risks and anticipate materials shortages.

Indirect contributions of H4.0 adoption reported by interviewees were related to coping with barriers associated with sociocultural factors. For instance, the nurse director argued that knowledge management has always been an issue at the hospital. However, with the pandemic, the use of digital platforms to systematically share knowledge has gained importance, and other departments realized the benefits of this application as a promoter of organizational learning (similar effects were reported as resulting from the digitization of manufacturers by Tortorella et al., 2020c). In other words, the more extensive use of some H4.0 digital applications to fight the pandemic has triggered their adoption by other hospital areas.

4.3. Contributions of H4.0 to the resilient abilities of healthcare and research propositions

We now summarize the main insights derived from each case study framed according to the four main abilities of resilient systems (monitor, anticipate, respond, and learn). Support to abilities varied according to the focus of H4.0 digital applications (i.e., supply chain, patient diagnosis, patient treatment and patient follow-up); however, commonalities in the emphasis given to each resilience ability in both case studies allowed us to formulate general propositions for further theory testing and validation, shown in Table 7.

In our study, *monitor* refers to the ability to observe and check the progress of implications resulting from the pandemic. Based on the information from both case studies, H4.0 digital applications provided support to this ability at different levels. The analysis of the interviews indicated that H4.0 digital applications associated with supply chain and patient diagnosis were emphatically mentioned as contributors to this ability. This finding suggests that these specific H4.0 digital applications may be more likely to contribute with the monitoring ability, regardless of the hospital management context (i.e., public or private). While H4.0 digital applications focused on supply chain allowed remote and real-time monitoring of the status of critical materials and products, the ones focused on patient diagnosis helped to virtually check patients and assess their symptoms and potential contagion risks. In opposition, the emphases observed for the contributions of H4.0 digital applications focused on both patient treatment (e.g., the use of traceability system for medical devices and patients in the private hospital) and follow-up (e.g., adoption of secure patient data sharing systems in both cases) were less prominent and more superficial. In fact, contributions from H4.0 digital applications focused on patient treatment to the monitoring ability were not even mentioned during the interviews with leaders from the public hospital. That suggests that these H4.0 digital applications (i.e., patient treatment and follow-up) may be viewed as less likely to contribute with the ability during the pandemic, or their contribution is less pervasive across different contexts than expected. Thus, because we found strong evidence about the positive contributions from H4.0 digital applications focused on supply chain and patient diagnosis to the monitoring ability of both hospitals during the pandemic, we raised the following proposition:

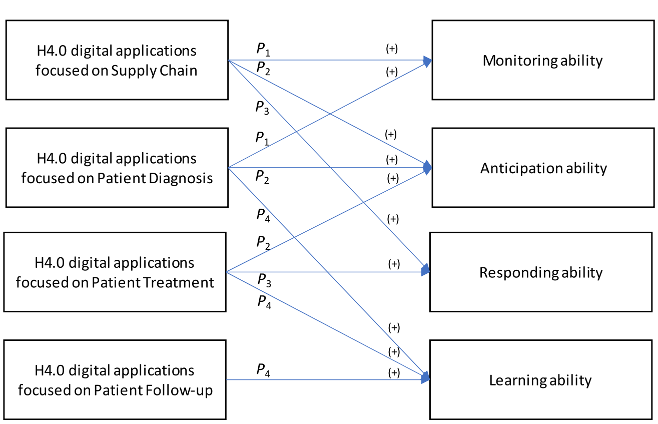

Fig. 2. Proposed contributions of H4.0 digital applications to the resilience abilities of healthcare organizations.

Proposition 1. *The adoption of H4.0 digital applications, especially those oriented to supply chain and patient diagnosis, allows to remotely control and verify the status of materials and equipment, as well as to virtually assess the condition of patients, enhancing the healthcare organization's ability to monitor the implications of the pandemic.*

Anticipate is the ability to predict or know what to expect (Hollnagel, 2011). *In both hospitals investigated, H4.0 digital applications associated with supply chain, patient diagnosis, and patient treatment were emphatically viewed as giving* support *to that ability during the COVID-19 outbreak. In the case of the supply chain, H4.0 digital applications allowed identifying new trends in demands for material and medical consumables and adjusting the inventory system to them through real-time revision of materials' lists and automatic scheduling of deliveries from suppliers. Likewise, anticipation was also possible through the identification of trends in the evolution of symptoms and treatments associated with the disease, supported by H4.0 digital applications such as "digital platforms for collaborative sharing of information" in the case of patient diagnosis and "patient real-time information recorded in electronic database" in the case of patient treatment. However, H4.0 digital applications that anticipated future developments of the disease after patients left the hospital were not reported by the hospitals, most likely due to the lack of resources to promote an efficient patient follow-up. Analyzing* Table 7, *we concluded that H4.0 digital applications focused on supply chain, patient diagnosis, and patient treatment are likely to positively impact the hospital's ability to anticipate during the pandemic, giving rise to the following proposition*:

Proposition 2. *The adoption of H4.0 digital applications oriented to supply chain, patient diagnosis, and patient treatment allows real-time identification of trends in materials, equipment, processes, and patients, enhancing the healthcare organization's ability to anticipate the implications of the pandemic.*

A resilient system is capable to properly respond to disruptions that occur, quickly returning to its original state or improving it (Jüttner and Maklan, 2011). *Both hospitals developed contingency plans to treat COVID-19 patients and minimize the impacts of the pandemic on other treatments. H4.0 digital applications were viewed as key to* support *such adaptation, most notably those related to supply chain and patient treatment in the private hospital. In the case of the supply chain, H4.0 digital applications such as 'digital platforms to facilitate supplier relationship management' and 'automated scheduling and control of patients/materials' helped to establish a closer link with suppliers promoting faster information exchange. In the case of patient treatment, H4.0 digital applications provided support to the special flow of COVID-19 patients and helped to mitigate the indirect negative*

Table 8
Summary of findings relating H4.0 digital applications to resilience abilities during the COVID-19 outbreak.

		Resilience abilities			
		Monitor	Anticipate	Respond	Learn
Focus of H4.0 digital applications	Supply chain	-Remote monitoring of vendor managed inventory -Upstream/downstream integration through a common ERP -Digital platforms to facilitate supplier relationship management	-Remote monitoring of vendor managed inventory -Upstream/downstream integration through a common ERP -Digital platforms to facilitate supplier relationship management	-Remote monitoring of vendor managed inventory -Upstream/downstream integration through a common ERP -Digital platforms to facilitate supplier relationship management	
	Patient diagnosis	-Virtual doctor-patient interaction and examination -Remote diagnosis through mobile applications -Digital platforms for collaborative sharing of information	-Virtual doctor-patient interaction and examination -Remote diagnosis through mobile applications -Digital platforms for collaborative sharing of information		-Virtual doctor-patient interaction and examination -Remote diagnosis through mobile applications -Digital platforms for collaborative sharing of information
	Patient treatment		-Patient real-time information recorded in electronic database	-Patient real-time information recorded in electronic database	-Patient real-time information recorded in electronic database
	Patient follow-up				-Secure patient data sharing systems

impacts on the treatment of other hospital patients. The use of H4.0 digital applications that allowed remote and virtual treatment of patients apparently improved efficiency and reduced the overburden imposed on staff. That was observed in both hospitals, although more explicitly discussed by leaders from Hospital B, which may be justified by size and resource availability. In opposition, no comments or examples were provided considering H4.0 digital applications oriented to respond to patient follow-up disruptions. Analyzing Table 7, *we concluded that respond is the resilience ability less supported by H4.0 digital applications during the pandemic. However, because the contributions of H4.0 digital applications oriented to supply chain and patient treatment to this ability were emphatically evidenced in the private hospital and briefly noticed in the public hospital, we formulated the following proposition*:

Proposition 3. *The adoption of H4.0 digital applications oriented to supply chain and patient treatment allows to automatically and/or remotely develop countermeasures to address issues in materials, equipment, processes, and patients, partially enhancing the healthcare organization's ability to respond to implications of the pandemic.*

Learn is the ability to realize what has occurred and take lessons from those experiences to guide future decisions (Madni and Jackson, 2009). *Facing the COVID-19 pandemic has changed healthcare systems, organizations, society, and economies, leading to what has been commonly named the 'new normal'* (Govindan et al., 2020). *In both case studies, H4.0 digital applications such as 'digital platforms for collaborative sharing of information', 'patient real-time information recorded in electronic database', and 'secure patient data sharing systems' were acknowledged as a means to foster more effective information and communication sharing across the hospital, including even departments not directly involved with the treatment of COVID-19. Those benefits could potentially extend to the healthcare supply chain, although our results indicated otherwise, i.e., learning was more prominently reinforced at a hospital level. This outcome is opposed to previous evidence about the positive association between knowledge management and digitization in supply chain management* (Neumann, 2018; Schniederjans et al., 2020). *Thus, based on the strong emphases mentioned for the contributions of H4.0 digital applications oriented to patient diagnosis, treatment, and follow-up to the development of this ability in both hospitals during the pandemic (see* Table 7), *we formulated the following proposition*:

Proposition 4. *The adoption of H4.0 digital applications oriented to patient diagnosis, treatment, and follow-up allows real-time and secure sharing of information and data on patients, enhancing the healthcare organization's ability to learn from the implications of the pandemic.*

The commonalities found in the case studies also allowed the indication of which H4.0 digital applications are more prone to contribute to the resilience abilities, according to the reported applications' focuses. The proposed contributions are displayed in Fig. 2, *in which the evidenced relationships are schematically illustrated based on the theoretical constructs that grounded our multi-case study. Moreover,* Table 8 *displays H4.0 digital applications that were emphatically mentioned by respondents from both hospitals as direct and indirect contributors to fight the pandemic, as summarized in* Table 6. *As observed, H4.0 digital applications focused on supply chain, patient diagnosis and treatment seem to present a similar level of pervasiveness across the resilience abilities, i.e., each one might consistently contribute to the monitor, respond, and anticipate abilities. However, the number of common H4.0 digital applications oriented to patient treatment appears to be lower than the ones oriented to supply chain and patient diagnosis. Additionally, H4.0 digital applications focused on patient follow-up are more likely to enhance the learning ability than the others.*

5. Discussion

Our findings allow an insightful discussion in light of previous studies. Regarding H4.0 implementation in the healthcare organizations investigated, results indicate that digital applications seem to be more extensively used to improve the healthcare supply chain. Being a highly complex system, healthcare organizations comprise several agents, processes, and value streams (Kumar et al., 2008; Samuel et al., 2010; Mathur et al., 2018). In the face of such complexity, it is somewhat reasonable to expect the utilization of H4.0 digital applications to facilitate and support managerial processes. For instance, Chong et al. (2015) and Özceylan et al. (2018) integrated ICTs, such as RFID and additive manufacturing, into healthcare supply chain processes. In opposition, the adoption of H4.0 digital applications oriented to patient follow-up appears to be less extensive. Such an outcome is surprising considering the profuse evidence on its benefits (e.g., Menachemi et al., 2011; Elhoseny et al., 2018). However, since H4.0 is not fully implemented in any of the hospitals, incorporating digital applications into patient follow-up processes was probably left as a secondary priority.

Second, leaders from both hospitals have acknowledged the direct and indirect contributions of H4.0 to cope with the COVID-19 pandemic. In terms of direct contributions, some common benefits were observed in both cases, e.g., the increased ability to store and share information and the support to safely manage patient flow specially designed to treat COVID-19 patients. These outcomes are aligned with indications from Ohannessian et al. (2020) and Badawy and Radovic (2020). In terms of indirect contributions of H4.0 to other patients and staff (non-COVID-19 related), we observed a generalized cascade effect. The direct benefits from H4.0 to treat the pandemic have incited the hospitals' remaining areas, departments, and staff to adopt it, attenuating existing barriers. In other words, in addition to affecting technical aspects, behavioral changes were also perceived in the direction of facilitating H4.0 implementation, addressing concerns reported in the related literature (e.g., Lin et al., 2012; Pan et al., 2019; Tortorella et al., 2020a). Therefore, we argue that for a successful H4.0 implementation and, hence, development of more resilient healthcare services during the COVID-19 outbreak, leadership does have a vital role in adapting and designing new processes and health treatments. Leaders are also responsible for ensuring adherence to these new procedures and improving them as needed. In this context, H4.0 digital applications act as enablers that support leadership in devising necessary changes to cope with the COVID-19 implications, corroborating to indications from previous studies of similar nature (e.g., Jia et al., 2019; Chen et al., 2021).

Finally, our study provided initial evidence on how H4.0 can contribute to the enhancement of hospitals' resilience abilities. Resilient healthcare has been a topic of growing academic and practical interest. However, studies that explored the link between that topic and innovative ICTs are still scarce (Ellis et al., 2019). In general, results from the interviews showed a positive association between the adoption of new digital applications (i.e., H4.0 implementation) and the resilience of healthcare organizations facing disruptive events, such as the COVID-19 pandemic. Since we examined the contribution in terms of supply chain, patient diagnosis, patient treatment, and patient follow-up, our findings complement those in Rusinko (2020)'s study, who proposed two generic frameworks to illustrate how responses with respect to patient diagnosis and treatment of COVID-19 can be characterized as resilient. Further, as we targeted the resilience of healthcare organizations as the unit of analysis during the COVID-19 outbreak, which is a disruptive event, our research adds to indications by Rubbio et al. (2019) and Mandal (2020). While the former used evidence from inpatient wards to examine how digital applications may support healthcare resilience, the latter explored the moderating role of digital applications on the relationship between healthcare resilience and sustainable performance. In view of all the points above, we may state that the evidence raised here and its derived propositions are unique, supporting the theory-building in healthcare operations management.

6. Conclusions

This article aimed at examining the contributions of H4.0 digital applications to the resilience of healthcare organizations during the COVID-19 outbreak. An empirical qualitative research was carried out with experts from two Brazilian healthcare organizations that have been adopting H4.0 digital applications and providing care to COVID-19 patients. Our findings contribute to both theory and practice, as discussed next.

6.1. Theoretical implications

Although the resilience of healthcare organizations has motivated previous researchers (e.g., Jeffcott et al., 2009; Rosso and Saurin, 2018), more evidence is needed on the impact of H4.0 as a promoter of systems' resilience. H4.0 is a recent topic, and studies offer narrow analyses about its adoption (Azzawi et al., 2016; Munzer et al., 2019), compromising a systemic view of its implications. Such theoretical gap is aggravated when considering the COVID-19 pandemic and the changes it suddenly imposed on healthcare organizations.

From a theoretical perspective, our research approaches three emerging topics (H4.0, resilience engineering, and the disruptions caused by the COVID-19 pandemic), whose relationships are still underexplored. Our study aims at bridging that research gap by providing initial evidence on how H4.0 digital applications may help to increase the resilience of healthcare organizations during the pandemic. Results allowed the formulation of research propositions, suggesting a link between H4.0 and resilience abilities in the situation of a severe disruptive event. Such research propositions are aimed at motivating further empirical research on the topic, allowing testing and validation of hypotheses.

Our findings also indicate that the link between H4.0 and resilience abilities for coping with disruptions may vary according to the focus of the H4.0 digital applications (i.e., supply chain, patient diagnosis, patient treatment, and patient follow-up). When facing severe disruptive events such as the COVID-19 pandemic, hospitals' resilient abilities do not seem to equally benefit from the adoption of H4.0 implementation. That was especially observed in the case of H4.0 digital applications aimed at improving patient follow-up, whose impact on the resilient abilities *anticipate* and *respond* was not evidenced in any of the healthcare organizations investigated. That calls for further research on how the digitization of patient follow-up could improve hospitals' ability to anticipate and respond to the reoccurrence of patient contaminations with the COVID-19 and potential treatment sequelae.

6.2. Practical contributions

With respect to practice, identifying the role played by H4.0 on the enhancement of healthcare organizations' resilience might help establish new policies and guidelines to fight the COVID-19 outbreak. The evidence provided here may also encourage more assertive investments in ICTs, mitigating the negative consequences of future disruptive events. The pandemic has brought different challenges to healthcare organizations, either in their supply chain, patient diagnosis, treatment, or follow-up. Our results indicated that the effect of H4.0 digital applications oriented to supply chain and patient diagnosis is pervasive across all resilient abilities. That provides hospital managers information on the broader impact of H4.0 digital applications, whose contributions for coping with the pandemic direct and indirect implications may be more objectively assessed. Depending on the resilience ability to be improved, different ICTs and digital applications may be prioritized, channeling both financial and human resources to a successful H4.0 implementation that is likely to support the achievement of more resilient healthcare in the face of severe disruptive events.

As observed in our research, a better understanding of the benefits of H4.0 digital applications to cope with the pandemic promoted their use in other areas and departments of the hospital, reducing socio-cultural barriers that might exist. In other words, the urgent changes in healthcare organizations following the pandemic outbreak presented an extreme scenario in which the actual contribution of H4.0 to the resilience of those organizations could be verified. That might help to convince key internal and external stakeholders about the relevance of systematic H4.0 implementation. Moreover, based on the empirical data gathered from both case studies, there was evidence that the integration of H4.0 digital applications supported the improvement of not only the administrative processes (e.g., more effective materials management and inventory control) during the COVID-19 pandemic but also the performance of medical treatments (e.g., remote diagnosis of patients with respiratory problems, and minimization of contagion risks). That indicates a safer, more reliable, and effective healthcare environment in both hospitals due to the adoption of H4.0 digital applications, resulting in improved overall healthcare quality during the severe disruption caused by the pandemic.

6.3. Limitations and future research

This study has some limitations which point to future research directions. First, it is a qualitative study carried out at two Brazilian hospitals, with results that may be only generalizable to other organizations in similar socioeconomic contexts. Additional survey-based studies exploring a sample of hospitals with other contextual characteristics (e.g., number of employees, type of ownership, complexity, socioeconomic location) are due, providing complementary evidence to our findings and empirical validation for the propositions formulated in our study. Moreover, given the worsening of the pandemic in Brazil, our data collection was limited to hospitals with which extensive collaborations have been previously established. Future studies could perform a similar data collection in hospitals that are not adopting H4.0 digital applications, allowing insightful comparisons on the development of resilience abilities during the COVID-19 pandemic. Second, the COVID-19 outbreak is recent, and our research was carried out only four months after its acknowledgment. Thus, short-term perceptions are prevalent in the data collected. Longitudinal research that investigates how H4.0 contributes to coping with the "new normal" implied by the pandemic in the long-run is recommended. Another limitation concerns the protocol used for the semi-structured interviews. Although the design of a semi-structured script with general and open-ended questions allows new ideas to be brought up during the interview, it tends to be less objective and harder to defend when compared with structured interviews. Hence, further research could encompass more specific questions, which could lead to more consistency in the interviews. Finally, the healthcare value chain comprises agents with different characteristics and interests. Our study exclusively focused on the contribution of H4.0 to the resilience of hospitals during the pandemic. However, H4.0 implementation may also impact the resilience of other agents in the value chain; future studies should broaden the analysis to include all healthcare value chain agents.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.technovation.2021.102379.

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